Abrasion resistance of fibre reinforced concrete floors

Vassoulla Vassou

Thesis submitted for the degree of
Doctor of Philosophy

Aston University, Birmingham
April 2003

To my parents

"For you are the wind beneath my wings"

"Knowledge is the food of the soul"
Plato, Greek Philosopher

Aston University, Birmingham

Abrasion Resistance Of Fibre Reinforced Concrete Floors

Vassoulla Vassou

Doctor of Philosophy

2003

Summary

This thesis focuses on the investigation of the abrasion resistance of fibre reinforced concrete floors at both the macro and micro levels. A literature review of the available literature concerning subjects allied to the current project is included. This highlights themes relevant to wear mechanisms and the factors influencing it; factors that affect the abrasion resistance of concrete and several test methods for assessing it; and the historical development of fibres and the properties of different fibre types and their influence on concrete.

Three accelerated abrasion testers were compared and critically discussed for their suitability for assessing the abrasion resistance of concrete floors. Based on the experimental findings one accelerated abrasion apparatus was selected as more appropriate to be used for carrying out the main investigations. The laboratory programme that followed was undertaken to investigate the influence of various material and construction factors on abrasion resistance. These included mix variations (w/c ratio), fibre reinforcement, geometry, type and volume, curing method and superplasticizing agents. The results clearly show that these factors significantly affected abrasion resistance and several mechanisms were presumed to explain and better understand these observations.

To verify and understand these mechanisms that are accountable for the breakdown of concrete slabs, the same concrete specimens that were used for the macro–study, were also subjected to microstructural investigations using techniques such as Microhardness

examination, Mercury intrusion porosimetry and Petrographic examination. It has been found that the abrasion resistance of concrete is primarily dependent on the microstructure and porosity of the concrete nearest to the surface.

The feasibility of predicting the abrasion resistance of fibre reinforced concrete floors by indirect and non-destructive methods was investigated using five methods that have frequently been used for assessing the quality of concrete. They included the initial surface absorption test, the impact test, ball cratering, the scratch test and the base hardness test. The impact resistance (BRE screed tester) and scratch resistance (Base hardness tester) were found to be the most sensitive to factors affecting abrasion resistance and hence are considered to be the most appropriate testing techniques.

In an attempt to develop an appropriate method for assessing the abrasion resistance of heavy-duty industrial concrete floors, it was found that the presence of curing/sealing compound on the concrete surface at the time of accelerated abrasion testing produces inappropriate results. A preliminary investigation in the direction of modifying the Aston accelerated abrasion tester has been carried out and a more aggressive head has been developed and is pending future research towards standardisation.

Keywords: Abrasion resistance
Fibre reinforced concrete
Floor slab
Impact resistance
Scratch resistance
Surface matrix microstructure

Declaration

This is to certify that, except where specific reference is made, the work described in the submitted thesis is the result of my own work (the candidate). Neither this thesis, nor any part of it has been presented, or it concurrently submitted in candidature for any other degree at any other University.

Industrial collaborators

I wish to acknowledge the support of the following industrial collaborators who willingly provided relevant information and/or materials:

- Ardex High Performance Tiling and Flooring Products – Mr S Brooks
- Armorex Ltd – Mr P Newson
- Cem-FIL International Ltd – Mr Brian Marten
- Concrete Floor Testing and Consultancy Services – Mr RG Chaplin
- Concrete Society – Mr R Day and Mr T Hullet
- Don Construction Products Ltd – Mr N Sanders
- English Abrasives and Chemicals Ltd – Mr M Lucket
- FEB MBT – Mr D Firth
- Fibermesh Europe – Mr Andy Gibbs
- Fibrin (Humberside) Ltd – Mr Mark Mitchel
- Fosroc Ltd – Mr I M Smith
- Grace Construction Products Ltd – Mr Richard Young
- National Physical Laboratory – Dr M Gee
- Seamless floors – Mr P Little
- Stanford Industrial Concrete Flooring Ltd – Mr K Louch
- Tarmac Topmix Ltd – Mr K Sutherland
- Tinsley Wire Ltd – Mr Steve Gavigan
- Trefil ARBED Ltd – Mr Philip Ash
- Wexham Developments – Mr S Clements

Vassoulla Vassou – Candidate

Roger J Kettle – Supervisor

April 2003

Acknowledgements

I wish to express my lasting gratitude and sincere appreciation to Professor RJ Kettle, Convenor of the Civil Engineering and Logistics Subject Group at Aston University, for his intellectual contribution, excellent supervision and financial support given willingly throughout the preparation of this project.

I am greatly indebted to the technical staff of the Civil Engineering and Logistics Subject Group at Aston University, in particular Mr D Hall, Mr B Carter, Mr T Hewings, Mr C Tompson, Mr B Curtis, Mr P Green, Mr A Crowcombe, Mr R Neal and Mr R Poole.

Contribution is acknowledged to my parents for their direct and indirect support throughout the past few busy years.

Special thanks are due to Ann, Ian, Maxine and Hayley for their friendship and delicious Sunday dinners.

Finally I would like to thank Massud, Mahvash, Gamini, George and Salman for their helpful advice, consistent encouragement, friendship and unfailing sense of humour.

Contents

List of tables

List of Figures

List of Plates

Notation

AC	Air curing
ACI	American Concrete Institute
AR	Alkali resistant
AT	Aston abrasion tester
BCAT	Original British Cement Association (formerly C & CA) abrasion tester
BRE	Building Research Establishment
C & CA	Cement and Concrete Association
CC	Curing compound
CR	Curing regimes
CT	Chaplin abrasion tester
d	dressing wheels
de	diamond electroplated wheels
f	flat spot wheels
FRC	Fibre reinforced concrete
GFRC	Glass fibre reinforced concrete
ggbs	Ground granulated blast-furnace slag
GRC	Glass fibre reinforced cement
ISAT	Initial surface absorption test
ITZ	Interfacial transition zone
l/d	Aspect ratio
MIP	Mercury Intrusion Porosimetry
NPL	National Physical Laboratory
OECD	Organisation for Economic Co-operation and Development
OPC	Ordinary Portland Cement
PAN	Polyacrylonitrile
PCA	Portland Cement Association
PF	Power finishing
pfa	Pulverised fuel ash
PFRC	Polypropylene fibre reinforced concrete
PS	Polythene sheet

PSD	Pore Size Distribution
PVA	Polyvinyl alcohol
s	standard rolling wheels
SFRC	Steel fibre reinforced concrete
SiC	Silicon Carbide
TiC	Titanium Carbide
TiN	Titanium Nitride
TR	Technical report
w/c	Water-cement ratio

Chapter 1: Introduction

1.1 Background to the project

The original rationale behind this investigation was to explore the links between two overlapping areas of interest. The first was the investigation of abrasion resistance at Aston University during the last fifteen years, with the second being the recent numerous and unsubstantiated claims of many authors and/or manufacturers that the inclusion of fibres into concrete floors results in improved abrasion resistance. These are explained below.

1.1.1 Abrasion resistance

An earlier literature survey (Sadegzadeh, 1985) revealed that there were many different methods for testing the abrasion resistance of concrete, and therefore direct comparison of the reported data was not possible. To overcome this problem, an extensive research on the abrasion resistance of concrete was undertaken at Aston University (Sadegzadeh, 1985). As a consequence, standard portable equipment was developed for measuring the abrasion resistance of concrete. A standardised test method was also adopted and used to determine the principal factors that affect abrasion resistance. Sadegzadeh (1985) based the design of this equipment on the one that had originally been developed by the Cement and Concrete Association, (C & CA, 1980). Comparative work of the two devices was conducted between the two laboratories. It was concluded that there was no significant difference between the original C&CA and the Aston Tester and that they both produced reliable and repeatable results.

The subsequent laboratory testing which followed the initial programme of the project (Sadegzadeh, 1985) was subdivided into three levels, namely:

- Macroscopic,
- Micro-structural and
- Non-destructive testing.

On the macroscopic scale, the investigation studied the influence of mix design, finishing techniques, curing regimes and surface treatments on the abrasion resistance of concrete. For the micro-structural study several techniques were used to demonstrate that the nature of the surface layer of the concrete is of primary importance to abrasion resistance. These techniques included mercury intrusion porosimetry, micro-hardness, scanning electron microscopy and differential thermal analysis. Several non-destructive tests were also carried out in order to establish whether it would be possible to use them to accurately establish the abrasion resistance. Only one of the methods, the initial surface absorption test, proved to be sensitive to the factors shown to influence abrasion resistance. Finally a field study was organised to compare laboratory data with similar information from in-service warehouse floors.

This investigation lead to the development of abrasion criteria for concrete slabs in a medium industrial environment. Co-current research work was undertaken by Chaplin (1987) at the former C & CA, now the British Cement Association (BCA), which produced almost identical criteria for rating floor performance. The values established by Sadegzadeh (1985) and Chaplin (1987) have been related to the floor classifications in BS 8204: Part 2: 1999 and TR-34 of the Concrete Society (1994). Subsequent research work carried out by Phitides (1991) and Webb (1996), as well as the current work, have utilised the basic apparatus and test procedure developed during the project by Sadegzadeh (1985).

The investigation undertaken by Phitides (1991) was concerned with the effects of cement replacements on abrasion resistance. She concluded that appropriate curing was critical for mixes containing these materials, particularly those containing ground granulated blast-furnace slag (ggbs). It was established that for concretes containing pulverised fuel ash (pfa) up to replacement levels of 40 %, the level of cement replacement was not critical providing the mix designs were adjusted to achieve a constant strength level. Finally it was also demonstrated that the 3 and 6 month abrasion depths were less than those obtained at 28 days, implying that the incorporation of cement replacement materials in concrete could lead to better long term performance in floor slabs.

The more recent experimental study (Webb, 1996) was focused on the influence of the quality and hardness of the coarse aggregate, initially by considering the concrete to be a two-phase material. This investigation also substituted crushed rock fines for the sand in order to modify the matrix in this two-phase model. It was concluded that low-grade

(strength) coarse aggregates could be used to provide industrial floors for medium industrial environments although, when used as a fine aggregate, the performance may be insufficient. It was also demonstrated that the presence of water on the wearing surface significantly reduces the resistance to abrasion, this effect being particularly marked with lower grade aggregates.

1.1.2 Fibre reinforced concrete floors

During recent years, floor construction methods involving the addition of polypropylene or steel fibres into the concrete have become commonplace in the UK. With the advent of fast-track systems in the construction industry, concrete flooring has had to meet quicker construction programmes. With the use of laser screeders, fibres are often specified instead of conventional mesh due to the inconvenience of positioning individual mats of mesh immediately in front of the laser screeding machine as the machine progresses (Knapton, 1999).

Some limited experimental data has been reported by Liu, (1980), Alexanderson (1982), Nanni (1989) and Sustersic, Mali, & Urbancic (1991) on the abrasion resistance of fibre reinforced concrete specimens and they have generally concluded that the inclusion of fibres into the concrete matrix positively affects the abrasion resistance. However, the investigators did not use a standard method to assess abrasion resistance, these studies employed different testing methods, different specimen sizes and random selections of fibre materials. In addition they did not assess the role of key contributing factors such as mix design, w/c variations and curing regimes. These reasons explain why the work is different to this study undertaken at Aston University. Indeed, the above researchers represent the only workers that have actually validated their remarks through experimental work. Many other authors (Swamy, 1974; Kukreja, et. al, 1984; Anon, 1985; Malisch, 1986; Hogan, 1987; No author, 1987; Deacon, 1990; Vondran, 1994; Maidl, 1995; Parameswaran, 1996; Carr, 1998; Philip Jones Construction Materials Ltd, 1998 and Knapton, 1999) have claimed that the introduction of fibres into concrete results in a greater surface abrasion resistance as compared to that of conventional concrete, but without any supporting experimental data.

This lack of experimental evidence is considered to be a significant gap in our knowledge. A combination of the two areas of interest presented in sections 1.1.1 and 1.1.2 would not

only investigate the potential use of fibres in ground floor slabs, it would also provide a unique opportunity to explore the effects of the different fibre types and properties on the abrasion resistance of concrete.

1.2 Aims of the project

The main aims of the research project are defined as follows:

- To carry out comparative tests of three abrasion testers (i.e Aston abrasion tester – AT; Commercial abrasion tester – CT; and Original British Cement Association abrasion tester – BCAT) and to select the most appropriate to be used for the main investigations of this project.
- To determine the effect of steel, polypropylene and glass fibres on the abrasion resistance of concrete slabs and their role in the wear process. This phase would include observations on both the macroscopic and microscopic scales.
- To determine the influence of several curing regimes on the abrasion resistance of fibre reinforced concrete floors again with observations on both the macroscopic and microscopic scales.
- To investigate the possibility of assessing the abrasion resistance through indirect and non-destructive methods.
- To study the effect on the abrasion resistance of the presence of a curing compound on the surface of the concrete slab.
- To develop a new testing head to permit assessment of the abrasion resistance of newly constructed concrete floors, which are to be subjected to extremely intensive abrasion loadings.
- To simulate site practices whenever possible so that the results obtained may be considered to provide a good representation of the materials used by industry.

1.3 Report outline

The following sections outline the structure of this report, including the main elements of each chapter.

1.3.1 Literature review

A review of the available literature concerning all aspects of the proposed project. The themes covered include different wear mechanisms, factors which influence wear, factors which affect the abrasion resistance of concrete and test methods for assessing abrasion resistance of concrete. The review also summarises the historical development of fibre use in concrete and evaluates the properties of different fibre types and their influence on concrete with particular emphasis on their inclusion in the construction of industrial floors. The final part details the literature gap in terms of the reported abrasion resistance of fibre reinforced concrete floors and demonstrates the significance of this project.

1.3.2 Scope of investigation

The general goals and objectives of the research work are presented. These include the influence of the concrete mix design on abrasion resistance, the comparative investigations of three accelerated abrasion test apparatus, the macro-study and micro-structural study of abrasion resistance of fibre reinforced concrete, the indirect and non-destructive methods for predicting abrasion resistance of fibre reinforced concrete and the abrasion resistance of heavy duty industrial concrete floors.

1.3.3 Engineering properties of materials

The properties of the materials used to manufacture the test specimens for this work are discussed. The methods applied for material and specimen preparation and/or fabrication are not described in this section but are collectively and individually outlined in the subsequent chapters.

1.3.4 Comparative investigations using three accelerated abrasion testers

It was deemed important to investigate the three existing accelerated abrasion testers to determine whether they produce reliable and repeatable results and establish which one would be most suitable for use during the main investigations of the project. This chapter explains how this was tackled.

1.3.5 Macro-study of abrasion resistance of fibre reinforced concrete

A laboratory programme was designed to study the abrasion resistance of fibre reinforced concrete floors at the macro level. The prime aim is to investigate the influence on the abrasion resistance of variables such as different types, shapes, lengths and volume of fibres, concrete mixes and curing regimes. An assessment of current industrial methods and practices is introduced and subsequently applied wherever possible. Details of the laboratory programme are presented and results of the tests for cube strength and abrasion resistance for all concrete mixes are discussed and compared to each of the variables under investigation.

1.3.6 Micro-structural study of abrasion resistance of fibre reinforced concrete

The results of the micro-structural study of abrasion resistance of concrete are presented and discussed. The techniques used include microhardness, mercury inclusion porosimetry and petrographic examinations. Based on the data obtained from this study a theory has been developed to describe the mechanisms of abrasive wear on fibre reinforced concrete floors.

1.3.7 Indirect and non-destructive testing for predicting abrasion resistance of fibre reinforced concrete

The aim of this part of the programme was to investigate the feasibility of assessing the abrasion resistance of fibre reinforced concrete floors by indirect and non-destructive methods. The particular methods that were investigated have frequently been used for assessing the quality of concrete and they included the initial surface absorption, impact, ball cratering, scratch and base hardness tests. Details of the laboratory programme are presented and the results are discussed and compared to the abrasion resistance data. Based on the two following assumptions, that is (i) the test should be sensitive to the factors affecting abrasion resistance and (ii) the test should not damage the concrete floor slab, a selection of the most suitable test(s) is presented.

1.3.8 Abrasion resistance of heavy-duty industrial concrete floors

In this part of the research project testing heads more aggressive than the standard rolling wheels were examined for their suitability in assessing the abrasion resistance of heavy-duty industrial floors. Three testing heads were investigated namely: dressing wheels, flat

spot wheels and diamond electroplated wheels. These tests were carried out on slabs constructed in the laboratory using typical industrial concrete mixes. The experimental study was extended to investigate the effect of the presence of curing compound on the abrasion resistance of concrete floors and limited tests were carried out on both laboratory samples and on newly built and in-service industrial concrete floors. Given the time constrains of the experimental programme it was only possible to undertake a preliminary investigation but the data can be used to guide future work in this area.

1.3.9 Conclusions and recommendations for future research

This chapter presents the main conclusions of the research project. From the results and discussion of the current project it has been possible to suggest additional research which could expand the existing knowledge in particular areas.

1.3.10 Appendices

The appendices contain information, which is deemed non-essential to the main part of the report. These contain all the original data from the abrasion testing programme and detailed calculations concerning the statistical analysis carried out, as well as data sheets concerning the materials used together with additional data regarding the micro-structural and non-destructive testing.

Chapter 2: Literature survey

2.1 Introduction

This chapter provides a review of the available literature concerning subjects allied to the project. Initially wear mechanisms are examined with an emphasis on brittle materials such as concrete and ceramics. Factors affecting the abrasion resistance of concrete and concrete floors are explored and the different test methods are described. The review summarises the historical use of fibres, describes the various types of fibre that have been used in concrete and outlines their manufacturing processes. Particular emphasis is given to the utilisation of fibres in the construction of industrial concrete floors. The theoretical aspects linked to fibre reinforcement and fibre reinforced composites are discussed. The final section explains the mechanical properties of fresh and hardened fibre reinforced concrete and concentrates on methods for effective preparation and subsequent application.

2.2 Wear

According to the OECD Research Group on the wear of engineering materials (1969), wear can be defined as the progressive loss of material from the operating surface of a body occurring as a result of relative motion at the surface. Further, Lansdown and Price (1986) suggested that the problem of wear is so important because it arises wherever there is loading across surfaces in motion, something which is commonplace in engineering practice. Wear occurs in a wide variety of industries and is a major cause of expenditure (Lansdown and Price 1986, Arnell, et al., 1991).

2.3 Types of wear

Rabinowicz, (1965) suggested that the terminology in the field of wear is quite unsettled and likely to remain so for some time since apparently nothing is being done to produce standardisation. Lansdown and Price (1986) also support this view since they believe that the subject of wear is complicated by a confusion of nomenclature and the lack of clear definitions of the different types of wear found in engineering.

However, in 1957, Burwell published an excellent "Survey of possible wear mechanisms" where he listed four distinct or major mechanisms: (1) adhesive wear; (2) abrasive wear; (3) corrosive wear and (4) surface fatigue. He also included a fifth classification under the heading "Minor types of wear", which covered erosion and cavitation. Burwell's (1957) terminology is adopted and presented in the following sections because it seems to be simple and logical and seeks out the primary cause of each form of wear. Nevertheless, since this paper was written the subject has been developed further by research and therefore it was necessary to include a third type of minor wear known as "fretting" which has been described by Waterhouse (1988). Fretting wear is discussed in more detail in section 2.5.1

2.4 Distinct types of wear

2.4.1 Adhesive wear

The theory of adhesive wear was originally proposed by Bowden & Tabor (1950 and 1964) and formulated as a semi-empirical law by Archard (1953). Rabinowicz (1965) believes that adhesive wear arises from the strong adhesive forces set up whenever atoms come into intimate contact. During sliding, a small patch on one of the surfaces comes into contact with a similar patch on the other surface and there is a probability, small but finite, that when this contact is broken the break will occur not at the original interface, but within one of the materials. In consequence, a transferred fragment will be formed.

Further, Lansdown & Price (1986) suggested that when two surfaces are loaded against each other the whole of the contact load is carried on a very small area at the asperity contacts. The real contact pressure at these asperities is very high, and adhesion takes place between them. If one of the surfaces is moved sideways over the other, the adhesive junctions will break. As sliding continues, fresh junctions will form and be ruptured in turn. If the adhesive strength of the junction is less than the cohesive strengths of the materials forming the asperities, then the junction will rupture at the original point of contact and there will be no loss of material from either of the two surfaces. If, on the other hand, the adhesive strength is greater than the cohesive strength of either of the two materials, then the junction will rupture within the weaker asperity. The two possibilities are shown in Figure 2.1, where Path 1 represents rupture along with the original contact and Path 2 represents rupture within the weaker asperity.

Figure 2. 1 Alternative rupture paths for an asperity junction (Lansdown and Price, 1986)

Lansdown & Price (1986) go on to explain that it would seem reasonable to expect that rupture would normally take place at the original contact, since this is the shortest path and is weakened by contaminants and mismatching of the crystal or grain structures. In practice, some direct investigations showed that a typical junction break took place very close to, but not at, the original contact surface, so that small numbers of atoms were transferred from one surface to the other. Although this transfer represents a form of wear, more typical wear results in the formation of separate particles, or wear debris. The process by which debris is formed in adhesive wear probably involves a weakening of an asperity tip due to repeated compression and tension. Eventually the impact against the opposing asperity is sufficient to break the weakened particle away from the surface and hence form a wear particle. The rate of wear debris formation and the size of the wear particles depend on the severity of the adhesion place between the asperities.

2.4.2 Abrasive wear

From an economic point of view, abrasive wear caused by ploughing or gouging of a hard surface, hard particles or debris, against a relatively softer mating surface is probably the most serious single cause of wear in engineering practice (Scott, 1983).

By the early 1960s, it had become "traditional" (Rabinowicz et al., 1961; Misra & Finnie, 1980) to divide abrasive wear into two-body and three-body groups. In light of the above background the term "three-body abrasion" would seem to mean wear caused by free abrasive particles present as interfacial elements between a solid body and a counter-body (Zum Gahr, 1961). "Two-body abrasive wear" was originally intended to denote the wear of a metal surface sliding against a rough, harder body (Rabinowicz et al., 1961). The term does not, however, appear in standard lists of wear definitions (OECD, 1969; Kajdas et al., 1990; ASTM G40-95, 1995). Two-body abrasion involves hard asperities on a relatively

massive body (Zum Gahr, 1982) and can be understood by the analogy of a hard metal file cutting into a soft metal body. This view is sometimes attributed (Misra & Finnie, 1980; Spero et al. 1991) to Burwell & Strang (1952) and Burwell (1957), but the cited documents do not actually use the terms two-body or three-body. Burwell (1957), however, does differentiate between "cutting wear" and "abrasive wear" as explained below.

Burwell's (1957) cutting wear is where the hard material that causes damage to the softer surface is the counterface itself. Burwell's (1957) examples of such counterfaces are restricted to rough hard metal surfaces rather than rock or a rock face. Consequently, he dismissed this type of wear as being industrially unimportant, industry had long recognised the need for machined sliding surfaces to be smooth and so could produce the requisite finish. Burwell's abrasive wear is where the hard material that causes damage to the softer material is a third body, usually a small particle of grit, caught between two closely mating material surfaces. Burwell's (1957) discussion includes not only cases of machinery where fine abrasives come between two closely mating metal surfaces, but also cases such as rock crushers, "where the hard sharp abrasive is in fact the second of the two rubbing surfaces". Two-body abrasion is thought by some to encompass not only Burwell's cutting wear, in which a hard metal cuts softer metal, but other forms including the cutting action of bonded abrasive papers (Misra & Finnie, 1981; Stachowiak & Batchelor, 1993; Wang & Hutchings, 1989), grinding as a deliberate metal removal process (Misra and Finnie, 1980), cases where the hard second body is rock (Zum Gahr, 1961; Burwell, 1957) and cases where abrasive particles become embedded in a softer counterface (Stachowiak & Batchelor, 1993). The consequence being that Burwell's abrasive wear effectively became three-body abrasion.

Misra & Finnie, (1980) felt that the two-body case was relatively simple, but proposed further subdivision of three body abrasion into "closed" and "open" groups. The closed group covers the cases of fine abrasives between closely mattering surfaces. Open three-body abrasion covers cases where there is a thick bed of abrasive, or the particles are large, so that the two-metal surfaces are too far apart for the mechanical properties of one to have any influence on the other (Misra & Finnie, 1980; Spero et al. 1991; Zum Gahr, 1989). Misra & Finnie, (1980) proposed that in open three-body abrasion it is not necessary to have a second metal counterface. Thus cases like impact pulverisers, where there is no backing surface and the forces are generated via inertia alone, shovels digging into a pile of loose rock, and solid particle erosion can all be regarded as examples of three-body

abrasion. This means that the "third body" is defined as any loose abrasive material, whether backed by a counterface or not. On this basis the primary connotations of two-body and three-body abrasion can be formulated. Two-body abrasive particles or asperities are rigidly attached to the second body and are therefore able to cut deeply into the first body. In contrast, three-body abrasive particles are loose and free to roll and therefore spend only part of their time actually cutting into the material being exposed (Gates, 1998). As a consequence, two-body abrasion tests are considered (Stachowiak & Batchelor, 1993; Rabinowicz et al., 1961; Zum Gahr, 1961; Tylczak, 1992) to produce wear rates one to three orders of magnitude higher than three-body abrasion under comparable loading conditions.

The abrasive wear theory may be applied to brittle solids such as ceramics and concrete as well as metals, although the subject has not been researched as thoroughly as the wear of metals. Moore & King (1980) have studied a wide range of engineering ceramics and brittle solids. Their investigation showed that fracture mechanisms might cause the rate of material removal to be about ten times that due to plastic deformation mechanisms. They concluded that fracture mechanisms predominate when the depth of indentation of the abrasive is high, the abrasive is sharp and the ratio of fracture toughness to hardness of the material is low. Naghash et al. (1994) suggested that there appears to be a trend indicating that the abrasion resistance increases with increasing material hardness, but microstructural effects were also considered to be important insofar as the grain size is concerned. They found that the effects of grain size and porosity are unrelated in the sense that certain samples showed small grain size but high wear loss. This was attributed to the effect of the high level of porosity. In addition Deuis et al. (1998) compared the three-body abrasive wear of ceramic coatings in both wet and dry environments and found that the environment significantly influenced wear behaviour. The wet environment produced a higher wear rate than the comparable dry conditions.

2.4.3 Corrosive wear

Corrosive wear has been defined as the wear process in which sliding takes place in a corrosive environment (Rabinowicz, 1965). In the absence of sliding, the products would form films on the surface which would tend to slow down, or even arrest, the corrosion, but the sliding action wears the films away so that the corrosive attack can continue. According to Lansdown & Price (1986) the chemical reactions which contribute to

corrosive wear are generally similar to those which would take place with the same materials in the same environment, but often the corrosion is greater when wear occurs and the wear is greater when corrosion occurs.

It follows that corrosive wear should often be suspected where the environment is known to be chemically reactive. It may not be easy to recognise because the surfaces may be bright and not obviously corroded but the total rate of loss of material in corrosive wear can be high and the resulting problems can be very serious. Technically any definition of corrosive wear includes the re-oxidation of exposed metal in a worn surface and, in general, this is a beneficial phenomenon. The same is true of the action of extreme pressure additives in lubricants. In addition, the chemical reactions take place more rapidly at higher temperatures and a rough rule of thumb is that the reaction rate doubles for a 10°C rise in temperature. Therefore, there is a general tendency for corrosive wear problems to be more serious at high temperatures (Arnell et al., 1991; Lansdown & Price, 1986).

2.4.4 Surface fatigue wear

Two types of surface fatigue wear are common. The first is that observed in rolling applications, namely gears and rolling contact bearings, and the second is observed in brittle, ceramic material under rolling or sliding conditions (Rabinowicz, 1965).

Several authors have described fatigue theories of wear. Halling (1975) derived a wear equation based on the Manson-Coffin fatigue equation (Tavernelli & Coffin, 1959), which relates fatigue life to the plastic strain increment during each cycle. Others (Kragelsky, 1965; Soda et al., 1977) have suggested fatigue as a predominant process at low wear rates. Arnell et al. (1991) believe that fatigue is probably one of the more important contributory factors in almost all mechanical wear processes.

2.4.4.1 Rolling contact fatigue

The useful life of rolling elements is limited by surface disintegration pits or fracture being caused by a fatigue process dependent upon the properties of the material, the nature of the lubricant and the environment. The phenomenon of rolling contact fatigue is characterised by the sudden removal of surface material or fracture due to repeated alternating stresses. The process has three phases, preconditioning of the material prior to crack initiation, crack initiation and crack propagation (Scott, 1983).

The experimental study of surface fatigue wear is rather difficult (Rabinowicz, 1965). Until spalling occurs few useful observations can be made, although some investigators have made metallographic studies of rolling contact materials and discovered that the crack which initiates spalling is sometimes located at the surface and at other times below the surface (Figure 2.2) (Rabinowicz, 1965).

Figure 2. 2 *Appearance of typical surface fatigue failures in their early stages: (a) Surface crack; (b) subsurface crack. (Rabinowicz, 1965).*

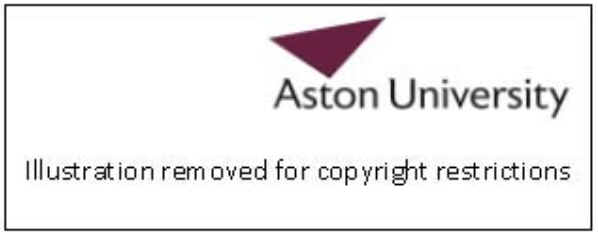
The occurrence of subsurface cracks is probably related to the fact that the point subjected to the maximum shear stress and hence the point with the maximum tendency for plastic yielding is located a small distance below the surface (Figure 2.3) (Davies, 1949).

Figure 2. 3 *Zone of stress maximum during rolling contact fatigue (Davies, 1949)*

2.4.4.2 Brittle fracture wear

According to Rabinowicz (1965) this form of wear occurs in brittle materials (e.g. glass, ceramic, hard coatings, concrete etc). During sliding, a characteristic series of cracks is observed in the wear track (Figure 2.4). Subsequently, large wear particles tend to be produced by fracture of the surface layer.

Figure 2. 4 *Characteristic appearance of wear track of brittle material showing tensile cracks (Rabinowicz, 1965).*



The formation of wear particles is usually considered (Rapoport, Salganik & Gotlib, 1995) as being determined by the attainment of a critical situation. The critical situations may be governed by strain or fracture parameters for brittle-dominated wear. For brittle materials the wear particle formation is predominantly controlled by fracture of a surface layer and so may be described by the fracture mechanics approach. Over the past 25 – 30 years this approach has been applied to tribology (Rosenfield, 1980; Hills & Ashelby, 1979; Hornbogen, 1975).

Hornbogen (1975) proposed a model to explain the increasing relative wear rates with the decreasing toughness of metallic and brittle materials. It was based on a comparison between the strain that occurs during asperity interactions and the critical strain at which crack growth is initiated. He suggested that if the applied strain is smaller than the critical strain, the wear rate is independent of toughness. However, if the applied strain is larger than the critical strain of the material, it would result in an increased probability of crack growth and therefore lead to a higher wear rate. Rosenfield (1980) calculated the stress intensity associated with a subsurface crack. He reported that the crack is driven by shear stresses associated with an asperity contact but its growth is retarded by the friction between the opposing faces. He suggested that this latter factor is important in determining the ease of debris formation.

Rabinowicz (1965) suggested that the wear rate in brittle materials is usually quite high and rather variable, depending on the exact way the specimen had been produced. The wear seems to become especially high for such materials whose tensile strength is less than one-third their compressive strength, which appears to be due to the fact that the maximum tensile stress behind a typical junction is about one-third the compressive stress under the junction (Figure 2.5). Thus, with a compressive stress of σ_y, if the tensile stress is less than σ_y /3, then tensile failure will take place behind the junction.

Figure 2. 5 *Schematic illustration showing the position of maximum tensile stress behind the region of contact. In brittle materials cracking may be produced there. (Rabinowicz, 1965).*

In the discussion Rabinowicz (1965) implied not only that very brittle materials are subject to poor wear behaviour, but that somewhat less brittle materials also show fairly poor wear properties. Thus chrome plate, sintered alumina and many ceramic composite materials are too brittle for most structural applications, but perform satisfactorily under sliding conditions. For structural applications it is generally desirable that the material is capable of some plastic yielding under tensile loading so that stress concentrations do not lead to failure. This implies that the tensile strength will be as great as the compressive strength. For sliding applications it is necessary merely that the tensile strength is greater than one-third of the compressive strength (Arnell et al., 1991; Rabinowicz, 1965).

2.5 Minor types of wear

Fretting, erosion and cavitation are other phenomena which are often classified as types of wear (Scott, 1983; Arnell et al., 1991; Rabinowicz, 1965). Fretting is seen as not a primary

form of wear, but rather as a phenomenon which occurs when other wear mechanisms act together under oscillatory sliding conditions. Whether erosion or cavitation are admitted as forms of wear depends on whether damage by impacting particles or by the sudden boiling of a liquid are accepted as falling within the category of "mechanical action".

2.5.1 Fretting

Fretting is a specific form of wear which occurs when there is slight vibratory movement between the loaded surfaces in contact and it is manifested by pitting of the surfaces and the accumulation of oxidised debris (Scott, 1983). Fretting can combine many of the wear processes already described. The oscillatory sliding causes fatigue wear, which may be enhanced by adhesion. Most commonly this wear is combined with the effects of corrosion, by oxygen or some other medium, and as many corrosion products are harder than their parent metals, this can also lead to abrasion. To sum up, this is a case where adhesive, corrosive, and abrasive forms of wear are all present (Arnell et al., 1991; Rabinowicz, 1965; Barnett, 1955). This form of wear was originally referred to as fretting corrosion (Halliday & Hirst, 1956) because it was felt that the formation of an abrasive oxide was the key step in causing fretting. Fretting has been observed, however, with materials that do not oxidise, such as cupric oxide (Godfrey & Bailey, 1954), so this nomenclature is best abandoned (Rabinowicz, 1965).

2.5.2 Erosion

Erosion is the term applied to the damage produced by the impingement of sharp particles on an object and is closely analogous to abrasion. The main difference between the two types of wear is that with erosion the resulting surface roughness may be relatively more severe than with abrasion, due to the removal of material from low points on the surface by the striking particles (Arnell et al., 1991; Scott, 1983; Hammit, 1980; Rabinowicz, 1965; Bitter, 1963; Finnie, 1960).

Ductile materials undergo weight loss by a process of plastic deformation, the material being removed by the displacing or cutting action of the eroding particles. However in brittle materials, the material is removed by the intersection of cracks, which radiate out from the points of impact of the eroding particles. There are obviously materials which fall between these two categories and so damage would involve some combination of these two wear processes (Lansdown & Price, 1986).

2.5.3 Cavitation

When a portion of a liquid is under tensile stresses, it may boil. Later, the bubble may collapse suddenly, producing a mechanical shock. A nearby solid surface may be damaged by this shock, leading to the removal of material. This process is known as cavitation (Arnell et al., 1991; Scott, 1983; Rabinowicz, 1965).

2.6 Principal factors influencing wear

In the following sections a number of factors, which can cause considerable variation in the wear rates of rubbing surfaces, are examined.

Although it is convenient to consider these different factors under different headings, it will be seen that they interact and it is difficult to separate one from another (Halling, 1975). For instance high loads and speeds will generate high temperatures at the surface. The temperature influences surface film formation which in turn can cause changes in the surface structure and hardness.

2.6.1 Lubrication

Lansdown & Price (1986) have defined a lubricant as "any substance interposed between two surfaces in relative motion for the purpose of reducing the friction and/or wear between them". In fact many solids or liquids can be effective lubricants, even though they have not been interposed for that purpose, such as wet clay on a ploughshare, the liquid component of a process slurry or even fine dust in a milling process. Obviously the effect of a lubricant is usually to reduce wear, but sometimes wear will be increased by a lubricant and there are situations in which wear is unchanged, or where the type of wear is changed without influencing the amount of wear (Lansdown & Price, 1986).

Rabinowicz (1965) subdivided lubrication into two types, fluid and boundary lubrication. Fluid lubrication occurs when a thick film of some liquid or gas completely separates two solids, whereas boundary lubrication occurs where the lubricant forms a thin film of the order of magnitude of one monolayer, interposed between the contacting surfaces. Most lubricants are introduced into a sliding system with the aim of reducing the amount of interaction between the contacting surfaces. Thus a lubricant may be used to reduce the friction force, or the amount of wear, or the degree of surface adhesion. Sometimes,

however, the prime task of the lubricant is to reduce the interfacial temperature, which otherwise might produce some harmful change, for example melting, in one of the contacting materials. In some specialised applications, for example metal cutting, the task of the lubricant may be to influence the way that chips are formed or the nature of the surface finish. In a few applications, particularly those concerned with wearing-in mechanisms, it is the function of a special wearing-in lubricant to produce fast wear during running-in, after which this lubricant is removed and a more normal lubricant substituted (Rabinowicz, 1965).

2.6.2 Hardness

In general increasing hardness decreases the wear of a material, but there is no simple relationship between the two (Lipson, 1967; Lansdown & Price, 1986). Holm (1950) suggested that the wear increased if the hardness values for the members approach each other. It gets excessive when both surfaces are of the same material, this has been established for a long time. The reason is that the members have the same tendency to deform so that the amplitude of the deformation waves becomes great (Holm, 1950).

Many metals show a transition from mild to severe wear when the nominal contact pressure (that is the load divided by the apparent area of contact) becomes greater than some fraction of the hardness. For many metals this fraction has a value of about one-third. This transition is generally attributed to the interaction of the plastic zones beneath contacting asperities, so that gross plastic deformation can take place. To avoid this effect it is clearly desirable to choose materials which have hardness values several times greater than the apparent contact pressure (Halling, 1975).

2.6.3 Load and speed

It is convenient to consider rubbing speed and applied load together. Burwell (1950) suggested that superficially it might appear that the rubbing speed is the speed with which the applied load moves over one of the two surfaces, but this is not always true and so two types of tangential speeds must be distinguished. The first is the relative rubbing speed at which the two surfaces traverse each other, and the second is the speed at which the point of application of the mutually applied load passes over each surface. The rolling speed is the speed at which the normal load moves over the surfaces of the test rolls, but the relative rubbing speed on the surfaces of the rolls may vary from zero under pure rolling to a high

value if a large amount of slip is present. Burwell (1950) explains that there may be a further speed component of the two surfaces normal to each other, namely the rate at which a load is applied, as under impact loading. In such a case the tangential rubbing speed may be zero.

The relative rubbing speed may affect the wear process in at least three ways. Initially, it determines the frequency with which potential surface-to-surface contact may occur, since the same area is traversed more often. Secondly, it enters into the frictional power consumption and hence into the local temperature rise. It affects the power consumption both because it is a primary factor in the product of friction force and speed, and also because the friction force itself (even in the boundary lubrication region) often depends on the speed. Thirdly, if a sufficient supply of a viscous lubricant is present, the tangential speed can determine the thickness of an interposing fluid film – which, in turn, reduces the possibility of metal-to-metal contact. (Also the frictional heating can change the lubricant's viscosity.) For these reasons, the dependence of some types of wear on rubbing speed can be extremely complicated.

The velocity of the surfaces normal to each other, the velocity of the point of application over the surface and the frequency and magnitude of the load all have the same effect on wear. They determine the speed and frequency with which a compressive stress is applied to a point on the surface. In soft materials such loads produce plastic deformation. Bowden & Tabor (1950) have discussed this situation, in particular they show that such normal or impact loads can be transmitted with high intensity even through a bulk film of lubricant. In hard materials this type of loading may lead to little surface damage, but it can produce a deep-seated (type of) fatigue failure resulting in the spalling off of relatively large particles from the surface, leaving deep pits (Buckingham & Talbourdet, 1950). Like all fatigue phenomena it depends on the total number of cycles of stress application, so that frequency affects lifetime in service. As regards the magnitude of the load itself, there seems to be no exception to the conclusion that the higher the load in a given type of operation, the greater the type of wear which that operation will produce (Burwell; 1950).

2.6.4 Surface films

According to Lipson (1967) the presence of surface films is particularly beneficial in reducing adhesive wear. These surface films can be of the following types: oxides, chemical reaction films (chlorides, sulphates, etc.), metals, fluid lubricants, etc.

The two important functions of contaminating films are to reduce the shear strength and to act as an anti-flux to reduce welding or adhesion of the asperities. This will decrease both the friction force, which is necessary to break these welds, and the wear, which results from the breaking off and metal transfer of these asperities. The better the bond between the film and the surface and so, the greater the resistance to rupture of the film and surface, the greater the protection from welding.

2.6.5 Temperature

In general an increase in temperature tends to produce an increase in the wear rate, because with increasing temperature the materials involved become softer (Lansdown & Price, 1986) and this has its greatest effect on the wear of metals (Halling, 1975). The hardness of metals is temperature dependent, the higher the temperature, the lower the hardness. Thus as the tendency for asperities to adhere and the wear rate to increase with decreasing hardness, in the absence of the effects, they also increase with increasing temperature (Hordon, 1967). In order to counteract this effect it is necessary to use metals with high hot-hardness for bearing materials operating at high temperatures. Metals commonly used at high temperatures include tool steels and alloys with base compositions involving cobalt, chromium and molybdenum.

Welsh (1957) reported another effect of frictional heating when rubbing ferrous materials in normal atmospheres. He found that at low loads wear was high but at higher loads the wear rate dropped to a very low value. A metallographic study indicated that this fall in the wear rate was due to the formation of a hard surface layer, which Welsh attributed to interaction with the atmospheric nitrogen at the temperatures generated under the higher loads.

2.6.6 Presence of abrasive materials

Abrasive wear also arises when hard, abrasive particles are introduced between sliding surfaces and abrade these materials. The mechanism of this form of abrasive wear seems to be that the abrasive grain adheres temporarily to one of the sliding surfaces, or else is embedded in it, and plows out a groove in the other. The two forms of wear, one involving a hard, rough surface and the other hard, abrasive grains, are generally referred to as the two-body and the three body abrasive wear process respectively (Burwell, 1957).

Abrasive wear of the two-body kind does not take place when the hard sliding surface is smooth. Similarly, three-body abrasive wear does not occur when the particles in the system are small or when they are softer than the sliding materials. Hence it is usually possible to arrange matters so that a sliding system is, initially at any rate, free from abrasive wear. However, once sliding has commenced, abrasive wear may become a problem as wear debris, often made harder by oxidation, begin to accumulate in the system as result of other wear processes. In other cases contaminating particles may be introduced into the sliding system from the environment (Rabinowicz, 1965).

Many investigators (Rabinowicz et al., 1961; Avient et al., 1960; Kruschov & Babihev, 1960; Mulhearn & Samuels, 1962), have found that when the materials and the abrasive remain fixed, but the size of the abrasive is varied, there is a critical abrasive particle size such that the wear rate becomes independent of abrasive particle size above this critical value. When the particle size is below this critical value there is a strong dependence of the wear rate on particle size, thus the reduction of wear rate when small particles are used has received a number of different explanations. They resolve themselves into two main categories, one being that with small particles the indenter geometry is different, the other suggesting that, with small abrasive particles, clogging of the system by abraded debris (Rabinowicz, 1965).

2.7 Abrasion resistance of concrete floors

One of the most important properties of a concrete floor is its resistance to abrasion from traffic. The type of traffic and its intensity vary widely for floors, while some are subjected to high impact stresses or abrasion by heavily loaded steel-wheeled trolleys, in contrast others may only be subjected to wear by rubber-tyred vehicles or pedestrian traffic. The abrasion resistance required of a floor will, therefore, depend upon its usage (Chaplin,

1972). In addition, Hester (1986) stated that the repeated vigorous washing of floors with high-pressure hoses, movement and turning of heavy equipment with hardened tyres and the dragging of pallets over the floor surface are additional sources of abrasion. With abrasion, as the floor erodes, the debris is carried away to expose new surfaces to attack, and the debris itself frequently acts as a grinding agent. As a consequence it is probably the most serious durability problem experienced by floors.

The ACI Committee 116 (1967) has defined abrasion resistance as "the ability of a surface to resist being worn away by rubbing and friction". Nevertheless, Prior (1966) and Taylor (1977) suggested that on different surfaces, wear is brought about in various ways as in:

- Concrete floors and heavily trafficked foot-ways, where wear is caused by the rubbing action of foot traffic, light trucking and the skidding of objects over abrasive particles.
- Concrete road surfaces, where the exposure factor is a rubbing and impact-cutting action of heavy trucking and automobiles (with or without chains) and accelerated by the presence of abrasive particles.
- Airport runways, because of the impact and abrasion of high-pressure tyres during landing operations.
- Jet-engine warm-up aprons and rocket-launching platforms, where disintegration takes place by blast and heat.
- Hydraulic structures, where impact abrasion or erosion occurs through cavitation.
- Underwater construction-inverts, where a cutting action is caused by the abrasive materials carried by flowing water.
- Concrete bunkers and chutes in heavy industry, where the movement of raw material sets up intense grinding, shearing and impact forces.
- The lining of rotary kilns, where both rubbing and impact cutting by clinker aggregate take place at elevated temperature.

For the purposes of this discussion, the definition employed by Sadegzadeh (1985) with regards to wear of a concrete floors by abrasion has been adopted. Therefore, "the abrasion resistance of a concrete floor in an industrial environment may be defined as the ability of the concrete surface to resist being worn away by rubbing, rolling, sliding, cutting and impact forces".

2.8 Test methods for abrasion resistance of concrete

An earlier literature survey (Sadegzadeh, 1985) revealed that a number of test methods have evolved over the years to simulate the wide range of wear situations on concrete surfaces. Comparison between results obtained from different research programmes is extremely complex, because there are distinct differences with regards to the test apparatus and the procedures adopted by each investigation. The following sections summarise this initial review and also provide additional sources of information relating to the methods used by several investigators to assess the abrasion resistance of concrete.

2.8.1 Rattler test

The research programmes of Abrams (1916 and 1921), Jackson & Pauls (1924), Scofield (1925) and Scholer & Allen (1928) investigated rattler equipment, such as the Deval test and the Los Angeles and Talbot-Jones rattlers. In this test method, concrete cylinders or cubes are placed in a rotating steel drum and are tumbled with steel balls for a set period of time. The abrasion resistance is then determined by visual observation and by weight loss.

The rattler test is considered to be more suitable for testing aggregates than concrete because is a rather severe test, involving a pounding action, not commonly associated with abrasion. A hard, brittle concrete might break up in this test, whereas a softer but tougher material might perform better. However, in practice, it is likely that the harder concrete would resist the abrasive forces much better than a relatively softer material. Nevertheless, the above mentioned investigators have used this type of tests in their work on the abrasion resistance of concrete. In fact Senbetta (1992) has recently re-employed this method in a slightly modified form as a test for impact resistance of concrete, rather than for abrasion resistance.

2.8.2 Reciprocating test

A'Court (1949) originally designed a reciprocating test apparatus to study the dust nuisance associated with concrete floors. He subsequently used (A'Court, 1954) the same apparatus to establish the effect of mix design on the abrasion resistance of concrete. The reciprocating apparatus consisted of a frame into which a concrete specimen of 150 x 100 x 25 mm was fitted. The frame was given a reciprocating motion by means of suitable gearing driven by an electric motor. Held in a separate frame, but resting on the sample,

was a deep cast-iron pan having a slot in the bottom. The pan was filled with sand, which leaked out through the bottom and formed an abrasive medium acting between the sample and the bottom of the pan. Abrasion was measured in terms of the sample weight loss. Taylor (1977) has reported the use of a similar test by Imperial Chemical Industries in Britain to test the abrasion resistance of tiles.

2.8.3 Cavitation apparatus

Vapour bubbles are formed in water flowing trough a slot-shaped Venturi throat and are carried downstream, where an increase in pressure causes them to collapse. Upstream and downstream pressures are adjusted to cause the centre of the area of collapse to coincide with the exposed area (75 x 270 mm) of a concrete specimen. The flow velocity is about 30 m/s and the period of exposure is 3 hours. From the measured volume of erosion, the erosion resistance is expressed as a number of hours required to erode 2.5 cm^3/cm^2 of exposed surface (Price & Wallace, 1950; ACI Committee 210, 1955; Watkins & Samarin, 1975).

2.8.4 Ball-bearing test

The "Davis" (United States) or the "Ebener" (Germany) apparatus causes abrasion by rolling steel balls under pressure over a test surface. The concrete surface is prepared for testing by wood floating and light steel trowelling (Smith, 1958; Fentress, 1973). In the Davis apparatus, a 4.5 kN load is applied to a 300 mm diameter, rubber-covered head rotating at 60 rev/min. The head bears on 41, 25 mm steel grinding balls in annular formation over the test surface. The load is applied for 5 minutes and the weight loss of a dry specimen is determined. In the Ebener apparatus, as described by Plassmann (1954), a loaded grinding head and a turntable rotate in opposite directions. The depth of wear of the specimens is determined from the weight lost in each of five test cycles. Several researchers (Sawyer, 1957; Smith, 1958; Soroka, 1965; Fentress, 1973; Lane, 1978; Liu, 1981) have used a similar method in their investigations. A slightly modified form of this test is specified as one of the test methods in ASTM Standard C-779 (1998) for assessing the abrasion resistance of concrete. It was suggested (Chaplin, 1972) that its action (high impact and high compressive forces) may reproduce the conditions of wear experienced under very severe conditions. In fact, a recent investigation (Sonebi & Kahayat, 2001) suggested that this method may be effectively used to assess the abrasion resistance of high strength concrete, where the compressive strength can take values of up to 120 MPa.

2.8.5 Shot-blast test

Several investigators (Meissner & Smith, 1938; Kennedy, 1946; Witte & Backstrom, 1951; Smith, 1958) have used the shot-blast test to assess the abrasion resistance of concrete. In a "Ruemelin" shot-blast apparatus, broken steel shot or zirconium oxide (2000g passing a 1.18 mm sieve and retained on a 0.30 mm sieve) is ejected by compressed air at 20 kPa from a 65.5 mm diameter nozzle. The jet is directed against the surface of a 300 x 300 x 50 mm concrete test specimen, located 100 mm from the end of the nozzle. The shot is discharged at the rate of 500 g per minute. Eight tests are made at different locations on the specimen and, by weighing it dry before and after the operation, the weight loss per test is determined (United States Army Corps Engineers, 1949; Smith, 1958). The test simulates the abrasive effect of solids in flowing water and it may be used for testing the abrasion resistance of the mortar matrix of concrete or of a protective film over the surface. Its effectiveness is reduced on a highly resilient surface film, which causes the shot to rebound without cutting the surface. A slightly modified form of this test is specified in the ASTM Standard C418 – 90 (1998) for assessing the abrasion resistance of concrete.

2.8.6 Rotating disk test

Stones for road building have been tested in the past by means of a machine known as the Dorry apparatus (Page, 1913; Goldbeck & Jackson, 1912). Cylindrical cores are cut from a sample and submitted to a given amount of abrasion by silica and sand, carried on cast steel. A test similar to this was exhibited in 1878 at the World's Fair at Paris. Professor Johann Bauschinger (1844) made rather extensive tests by means of an apparatus of this nature and reported them in his "Communications".

The standard test for stone was deemed to be too severe as it cut too deeply into the flooring specimens. Shank (1935) suggested that the test for flooring materials should not be carried to depths greater than what may reasonably be expected for floorings as determined from practice. The Dorry road-stone test was modified in order to suit flooring materials and was used in this altered form by many investigators (Kessler, 1928; Shank, 1935; Schuman & Tucker 1939; Scripture, et al., 1953).

This test method is one of the three methods currently specified by the ASTM Standard C-779 (Method A, 1998). The apparatus consists of three 60.3 mm diameter, cold-rolled steel revolving disks, each attached to motor-driven vertical shafts which revolve about a

vertical axis. The disks are free floating inasmuch as they are self-supporting and are driven transversely along a circular path at 12 rpm while being individually turned on their own axis at 280 rpm. Cups attached at the top of the shaft of each disk are loaded with lead shot to produce a uniform total load of 22 N on the face of each abrading disk. The abrasive grit is silicon carbide fed through a 3.2 mm orifice from a storage cup mounted on the revolving circular plate. The abrasive falls at the mid-width of the circular abraded track, and midway between two of the disks. The abrasion is measured using a depth micrometer. The machine is designed to accommodate approximately test specimens with an approximate face area of 305 x 305 mm.

Kettle & Sadegzadeh (1991) suggested that this test method is the least aggressive of the three methods in the ASTM Standard C-779 (1998) and as such closely compares to the Aston abrasion tester, i.e. rolling wheels (see section 2.8.9). Nevertheless direct comparison is not possible due to the vast operational differences of the two testers.

2.8.7 Reamer

The test uniquely simulates the type of wear that exists in ore bunkers and chutes and is applied to both concrete and wood for comparative testing (Taylor, 1977). The reamer of 40 mm diameter is ground to a blunt, eccentric chisel face and cross-fluted with three 4 mm indentations. The tool is rotated counter-clockwise at 134 rpm in a modified drill press, under a load of 1.35 kN, the load being checked by a spring balance. The test specimen, 150 x 150 x 60 mm, is fastened to a turntable, which rotates clockwise at 23 rpm and with an eccentricity of 40 mm in relation to the reamer. Debris is blown off by compressed air. The depth of the grove, which is produced during successive runs of 1 minute, is measured with a depth micrometer at four points. The rate of wear is represented by the average increase in depth per minute taken over three runs following the first.

2.8.8 Dressing wheels test

The dressing wheel machine is the second test method detailed in ASTM Standard C-779 (1998) for assessing the abrasion resistance of a horizontal concrete surface. This method is dependent upon the abrasive action of three sets of loaded steel dressing wheels riding in a circular path over a test surface (Scripture 1936, United States Army Corps Engineers 1949, Smith 1958, Montgomery, Long and Basheer, 1989). The action of the dressing wheels on a concrete surface results in a rough circular path the depth of which is

measured to determine the abrasion resistance. The average of three tests is believed to represent the wear that may be caused by heavy foot or wheeled traffic in service (ASTM Standard C-779 Method B).

2.8.9 Rolling wheel test

Over the years, several researchers have used the rolling wheel method to investigate he abrasion resistance of concrete. Amongst the early workers were Covell (1928), Ahlers et al., (1929), Emley & Hofer (1937) and Wastlund & Erikson (1946) who have utilised the same basic technique but with considerable variations. Essentially they have used the same principle which incorporates a frame supporting a motor which drives a test head containing a number of steel wheels. The unit as a whole is loaded and acts upon a prepared concrete surface. Some researchers used rubber wheels (Wastlund & Erikson, 1946), but most used steel wheels (Covell, 1928; Ahlers et al., 1929; Emley & Hofer, 1937; Chaplin, 1987; Sadegzadeh & Kettle, 1987).

The equipment devised by Chaplin, (1987) and Sadegzadeh & Kettle (1987) consists of a rotating plate carrying three case-hardened steel wheels. The rotating plate was designed so that it would accept three different abrasion heads: (a) revolving pads, (b) rolling wheels or (c) dressing wheels. A dead load of 40 kg was placed around the machine, so that the total load passing down the drive shaft to the plate was 65 kg. Each head leads to the development of a circular groove in the concrete surface and the depth of this groove provides a measure of abrasion resistance. During the test the machine is kept in position by two bolts, which pass through the legs of the machine into oversize holes in the slab. They prevent the machine from moving laterally, without restricting the vertical movement as the wheels pass over the concrete surface. The test head rotates approximately 190 rpm so that the test exposure totals approximately 2850 revs which is the standard value now specified in BS 8204: Part 2 (1999). Abrasion resistance is determined by depth of wear in the wheels' path after a 15 minute period of exposure to the rotating wheels. This test method has several different wear mechanisms interacting together. Rolling contact fatigue and brittle fracture occur together with a small amount of abrasive wear.

It was observed that of all the wear tests described, only the cavitation tests investigates the role of water on the abrasion resistance of concrete. Considering the important effect that moisture has on many other concrete properties, such as compressive strength, tensile

strength and coefficient of thermal expansion, very little research has been applied to investigating its effect on concrete wear mechanisms.

2.9 Factors affecting the abrasion resistance of concrete

Concrete abrasion resistance is markedly influenced by a number of factors, including concrete strength, aggregate properties, cement replacement materials, curing, surface finishing and surface treatments (Naik et al., 1995, Sadegzadeh, 1985). A large number of earlier studies (Lane, 1978; Chaplin, 1972; Prior, 1966; Witte & Backstrom, 1951) have indicated that concrete abrasion resistance is primarily dependent on the compressive strength of concrete. Therefore, factors such as air-entrainment, water cement ratio and types of aggregates and their properties that affect concrete strength should also influence abrasion resistance. Nevertheless, factors such as surface finishing, surface treatments and the microstructure of the surface matrix are more significantly related to the characteristics of the surface which has to directly withstand abrasion (Chaplin, 1980; Sadegzadeh, 1985).

2.9.1 Compressive strength of concrete

Numerous studies (Naik, Singh & Hossain, 1995; Naik, Singh & Hossain, 1994; Taylor, 1977; Schuman & Tucker, 1939) have suggested that compressive strength is the single most important factor governing the abrasion resistance of concrete, with the abrasion resistance increasing as the compressive strength increases. Neville (1999) suggested that almost any factor, which influences the compressive strength, would also affect the abrasion resistance of concrete. Many investigators have reported that the abrasion resistance decreased with increase in the water-cement ratio (Laplante et al., 1991; Kunterding & Hilsdorf, 1990; Sadegzadeh, 1985; Smith, 1958). Witte & Backstrom (1951) demonstrated that air content (or density) influences the abrasion resistance of concrete but only so far as it affects the compressive strength, in other words air-entrained concrete is as resistant to abrasion as plain concrete providing they are of equal strength. Sawyer (1957) and Abrams (1916) established that the abrasion resistance of concrete increased with increased cement content. However, Troxtell et al. (1968) concluded that lowering the water-cement ratio through improvement of the aggregate grading and by employing the lowest practicable slump is more effective in improving wear resistance than the same reduction in w/c ratio from an increase in the cement content.

Abrasion resistance, like compressive strength, is a mechanical property of concrete and this has led to the generally accepted view that abrasion resistance increases proportionally with strength. However, it was found (Dhir et al., 1991) that slabs which have undergone different curing, but which have equal strength, could possess very different abrasion resistances, and so other factors may have more influence on the abrasion resistance of concrete. Similarly, Sadegzadeh (1985) reported that particular finishing techniques could significanlty increase the abrasion resistance of relatively low strength concrete. Further, Langan et al. (1990) and Omoregie et al. (1994) concluded that compressive strength does not have a significant effect on abrasion resistance while A'Court (1954) could not establish a very clear relation between abrasion resistance and compressive strength. Nanni (1989) indicated that compressive strength is a poor parameter to evaluate abrasion resistance because of the influence of factors such as surface finishing and curing conditions. Very often, compressive strength has been used as a convenient factor to rank concrete performance though several investigators have reported results contrary to the general view.

2.9.2 Aggregates

A great deal of research has been undertaken to determine the influence of both coarse and fine aggregates on the abrasion resistance of concrete. The effects of coarse and fine counterparts are considered separately.

2.9.2.1 Coarse Aggregates

Numerous papers have been published (Abrams, 1921; Jackson & Pauls, 1924; Scripture et al., 1953; Smith, 1958; Liu, 1981; Laplante et al., 1991; Omoregie et al., 1994; Webb et al., 1996) reporting the influence of different types of coarse aggregates on the abrasion resistance of concrete. Smith (1958) suggested that no conclusive correlation exists between abrasion resistance and the quality of coarse aggregate as determined by the ASTM tests for the Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate (C88) and the Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine (C131). However, the abrasion resistance of concrete can be increased appreciably by the use of dense, hard coarse aggregates such as traprock, granite, or metallic aggregate near the surface (Lane, 1978). Smith (1958) has also shown that while concrete of compressive strength below 55 MPa greatly benefited from the use of

hard aggregate, above this strength level, the effect of the coarse aggregate on wear resistance was reduced greatly.

Several researchers, among them Abrams (1921), Jackson & Pauls (1924), Scripture et al. (1953), have specifically investigated the abrasion characteristics of stone and with respect to pavement surfaces. Abrams (1921) stated that the wear of these parameters was not dependent on the qualities of the coarse aggregate in the wearing surface. He also suggested that the wear of concrete is, in general, not materially affected by the quality of the fine aggregate so long as it is structurally sound, clean and does not contain an excess of very fine material. Jackson & Pauls (1924) and Pogany (1935), concluded that the rate of wear of concrete is in general not affected by the coarse aggregate provided that the coarse aggregate is equal or superior to the mortar matrix in its resistance to wear. Further, Jackson & Pauls (1924) established that excessive wear would result from the use of very soft stone as the coarse aggregate even when used with a mortar of satisfactory quality. Scripture et al. (1953) by adopting the ASTM test for the Scratch Hardness of Coarse Aggregate Particles (1968), concluded that there is no correlation between the hardness of the coarse aggregates and the abrasion resistance of the resulting concrete mixes. Omoregie et al. (1994) concluded that the abrasion-erosion resistance of cement-hardened materials is primarily a function of the aggregate hardness.

Although it seems quite reasonable that the type of aggregate used should significantly affect the wear resistance of a concrete floor, Sadegzadeh (1985) stated that initially it is the surface matrix that resists the abrasive forces. As such the aggregate becomes involved only when there has been sufficient wear to expose the coarse aggregate. In addition, as explained in Section 2.8, many techniques have been used to assess the abrasion resistance of concrete with the mechanisms of wear depending on the particular technique. These factors are likely to influence the conclusions derived by different investigators.

Interestingly, Laplante et al. (1991), Ozturan et al. (1987) and Liu (1981) reported results conducted from tests on sawn specimens, although each employed a different testing method – the ASTM C779-95 (1998) ball baring test, the Böhme abrasion test (DIN 52108, 1968) and an underwater abrasion test respectively. Clearly, in all these investigations, the surface exposed to the particular test head contained both coarse and fine aggregate as well as the cement matrix. Not surprisingly the findings from these three studies are identical

and conclude that the coarse aggregate is the most important factor affecting the abrasion resistance of sawn concrete specimens.

Some investigators (Schuman & Tucker, 1939; Witte & Backstrom, 1951; Dhir et al., 1991) have studied the effect of aggregate shape and maximum size on the abrasion resistance of concrete. Schuman & Tucker (1939) pointed out that the shape of the aggregate particles, rounded or angular, regulates the water requirements for the placing and finishing operations and so has a direct influence on the wear resistance of concrete. Witte & Backstrom (1951) reported that the maximum size of aggregate appears to have little effect on the concrete resistance to abrasion when they compared concrete mixes with equal compressive strength. On the contrary, Dhir et al. (1991) concluded that the maximum aggregate size affects the abrasion resistance of concrete in that concretes having a maximum aggregate size of 5 and 40 mm had an inferior abrasion resistance to concretes having a maximum aggregate size of 10 and 20 mm, but such changes may also be attributed to the consequent changes in the amount of fine aggregate.

2.9.2.2 Fine aggregates

Several researchers, among them Schuman & Tucker (1939), Smith (1958), Li (1959), Ozturan et al. (1987), Chaplin (1987) and Laplante et al. (1991), have investigated the influence of fine aggregates on the abrasion resistance of concrete. They have generally reached identical conclusions:

- An increase in the percentage of fine aggregates in a concrete mix results in increased abrasion resistance.
- The use of superior quality fine aggregates in a concrete mix results in increased abrasion resistance.
- Specimens containing crushed rock fines have significantly reduced abrasion resistance than those containing natural sand.

During an investigation of the factors influencing the abrasion resistance of concrete floor slabs, Chaplin (1987) considered three types of fine aggregates of widely differing gradings, including two types of natural sands. One of these sands was available in three gradings corresponding to the limits for F, M and C sands (BS 882) and the second sample was available in two gradings corresponding to the F and M requirements (BS 882). The

third fine aggregate was crushed carboniferous limestone with a grading corresponding to the C requirement (BS 882). He found that the specimens containing the crushed limestone fines produced significantly greater depths of wear than those with the natural sands. Although it is commonly assumed that the grading of the sand has a large influence on the quality of the surface mortar, Chaplin (1987) showed that the grading of the natural sands used in this study did not produce significant differences in the abrasion resistance. He therefore concluded that it is the particle shape of the crushed rock fines and possibly its lower resistance to crushing which is of greater significance with regards to abrasion resistance.

A'Court (1954) reported that the rate of abrasion is not necessarily related to the degree of exposure of the coarse aggregate and concluded that it is the mortar quality which is of outstanding importance. He also suggested that the increasing the fineness of the sand led to a decrease in the abrasion resistance.

More recent studies (Webb et al., 1996; Kettle & Webb, 1999) have generally confirmed the findings of the previous investigators and concluded that low-grade aggregates, in carefully designed mixes, may produce concrete that is suitable for flooring used in light or medium industrial environments. Webb et al. (1996) reported that in dry conditions the properties of the fine aggregate fraction have greater influence on the abrasion resistance than the coarse aggregate. In wet conditions the properties of the coarse aggregate fraction have a major influence on the abrasion resistance with the role of the fine aggregate being less influential (Kettle & Webb, 1999).

2.9.3 Cement replacement materials

Increasing energy costs and the depletion of the required high quality natural materials for Ordinary Portland Cement (OPC), and the resultant variability of its properties with respect to durability of concrete, has lead to the increased use of low cost replacement minerals in cement and concrete. During the last thirty years, the inclusion of replacement materials in both cement and concrete products has increased dramatically (Langan et al., 1990). The most commonly used materials include fly ash, pulverised fuel ash (pfa), ground granulated blast-furnace slag (ggbs) and silica fume (Neville, 1999). The energy crisis of the late 1970s and early 1980s formed the basis for several previous investigations, carried out to establish the properties of concrete when less energy-intensive materials were used.

Numerous researchers (Langan et al., 1990; Fernandez & Malhotra, 1990; Kettle & Yassim, 1995; Naik et al., 1994; Naik et al. 1995; Chaplin, 1987; Dhir et al., 1991) have reported the effect of these materials on the abrasion resistance of concrete.

Langan et al. (1990) concluded that 50% of fly ash cement replacement decreased the abrasion resistance at all ages when compared with plain concrete, even though the abrasion resistance tended to increase as the age at testing increased. Fernandez & Malhotra (1990) conducted abrasion resistance tests on concrete specimens that contained ggbs as a replacement for normal Portland cement at percentages of 0, 25 and 50 % by cement mass and their w/c ratios varied between 0.45 to 0.70. They found that, regardless of the w/c ratio and irrespective of the slag content, the abrasion resistance of concretes incorporating slag was lower than that of the plain concrete. Kettle & Yassim (1995) used pfa for their study and showed that at a constant replacement range of 30 % the abrasion resistance is inversely related to the w/c ratio. Further, within a replacement range of up to 40 % the abrasion resistance of plain concrete could be achieved with an appropriate mix design. They reported a significant increase in abrasion resistance with age up to 6 months for well-cured concretes.

In contrast, Naik et al. (1995) concluded that fly ash concrete with up to 30 % cement replacement levels exhibited abrasion resistance similar to that of plain concrete at 28, 91 and 365 day ages. During an earlier investigation Naik et al. (1994) found that plain concrete showed higher abrasion resistance than high-volume (40, 50 and 70 %) fly ash concrete mixes when tested at 28 days. However when these concretes were tested at 91 days they exhibited excellent abrasion resistance. Chaplin (1987) reported that, provided good curing is achieved, there is no significant reduction in the abrasion resistance of concrete mixes produced from the use of OPC blended with ggbs with a replacement level of up to 50 %, compared to plain concrete mixes. The same was true for concrete mixes produced from OPC blended with pfa with a replacement level of up to 35 %. Dhir et al. (1991) also concluded that there is no significant difference in the abrasion resistance of pfa and microsilica concretes when compared to OPC concretes.

2.9.4 Curing

Curing is widely perceived as being an important factor in achieving durable concrete (Plowman, 1956; Buenfeld & Yang, 2001). This seems reasonable in that curing allows

hydration of the cement to continue which reduces capillary porosity, and thereby increases the compressive strength and the resistance to abrasion (Buenfeld & Yang, 2001). In constructing concrete floors and slabs the quality of the concreting operation determines the properties of the surface. Well-cured concrete can produce a highly wear-resistant surface (Lane, 1978). Murdock et al. (1991) suggest that for maximum durability and abrasion resistance, curing should start as soon as possible after the concrete has been finished and be continued preferably for a minimum of 7 days.

A correlation of curing time and wear reported by Sawyer (1957) involved a series of tests comprising a wide range of cement contents, w/c ratios and incremental curing. From this study it is apparent that marked improvement in abrasion resistance can be expected with extended curing time. Fentress (1973) observed that the application of a curing compound immediately after finishing gave the best results. When the application of the curing compound was delayed for one day, the particular specimens had very poor wear resistance. When the application of the curing compound was delayed it was ineffective, specimens receiving no positive curing gave better results than those receiving the curing compound the following day.

Several other investigators (Sadegzadeh et al., 1989; Chaplin, 1987; Schuman & Tucker, 1939) have reported that efficient curing is reflected in increased abrasion resistance. Sadegzadeh et al. (1989) stated that proper curing significantly increases the abrasion resistance of concrete floors. They found that curing becomes more critical as the w/c ratio of the concrete mix is increased. During this study it was also noted that of all the curing methods, then routinely used on site, plastic sheeting was the most reliable and easy to perform. An even more efficient method of curing is to use curing compounds, as these improve abrasion resistance further, with resin-based types resulting in the highest abrasion resistance (Chaplin, 1987). However, the effectiveness of curing compounds is dependent on the smoothness of the surface on to which they are applied (Chaplin, 1987).

2.9.5 Surface finishing

Poor finishing procedures cause many of the problems associated with the performance of concrete floors. During compacting, levelling and power floating of a slab, a layer of cement-rich mortar is brought to the surface. This surface laitance can become too thick through excessive working of the over-wet concrete. Where this condition occurs the

surface laitance will wear rapidly, possibly crazing and dusting badly. The use of fully compacted, low-slump concrete followed by the floating and trowelling operations at the correct times, will help avoid the formation of the excessively thick laitance and result in a durable floor surface (Kotzé, 2000; Bury et al., 1994). The correct procedures for carrying out these operations are described in detail in a number of publications (Gatfield, 1998; Concrete Society's TR34, 1994; Perkins, 1993; ACI 302.1R-89, 1989). Finishing techniques have also been compared with the wear resistance of concrete in a study by Fentress (1973). In this investigation, abrasion forces were imparted on wood float, magnesium float, steel trowel, and hard steel trowel finishes. The wood float tends to tear the surface and displace the aggregate. The magnesium float, despite its ease of finishing, caused a rough-textured surface which led to a reduction in the wear resistance. Both the steel and hard-steel trowels produced smooth surfaces, closing any existing imperfections which produced an excellent resistance to abrasion. Some workers in this field (Scripture, 1936; Sawyer, 1957; Liu, 1981; Dhir et al., 1991) have produced specimens, which have been finished using a wooden float followed by steel trowel. They suggested that although this method improves abrasion resistance compared to no finishing at all, it could be further improved by employing power plant for the floating and trowelling processes.

The timing of the trowelling operations is dependent upon the surface condition of the plastic concrete and long delays, to allow for the evaporation of bleed water, often cause quality control problems as well as increasing the cost (Chaplin, 1980). Vacuum dewatering is a proprietary method, which has been used to enable trowelling to begin sooner after placing. This process significantly increases the abrasion resistance (Baxter, 1975; Pickard, 1981) by reducing the w/c ratio of the concrete near the surface.

The trowelling process may be replaced by early grinding, 36 to 48 hours after placing, which removes the surface laitance to expose the harder concrete underneath. This makes monolithic construction possible and leads to improved abrasion resistance (Fairweather, 1980). The key to durable, cleanable concrete slabs according to Ytterberg (1971) can be found in proper finishing procedures and in a reduction in the w/c ratio. Combining these demands in one application, he demonstrates that a deferred topping finish from which the surface water is removed by a vibratory absorption process yields higher abrasion resistance. The technique requires that after the excess water has been removed, the surface is blade floated and, upon stiffening, trowelled. In Ytterberg's (1971) study the deferred

topping finish significantly exceeded the wear resistance of a comparable monolithic finish.

In a comprehensive study of finishing techniques, Sadegzadeh (1985) confirmed the significant benefits obtained from power finishing with regard to abrasion resistance, and stated that the workability and compressive strength of the concrete became less critical when power finishing was utilised. It was emphasised that the finishing applied to the surface of the slab was the primary means of altering the surface microstructure, the principal factor found during this work governing concrete abrasion resistance.

2.9.6 Surface treatments

The applications of materials such as dry-shakes or chemical solutions onto the concrete surface are considered to be two separate forms of surface treatments. Dry shakes consist of a mixture of cement with various types of hard aggregate in either metallic or mineral form and they may be applied directly onto the plastic concrete following the specific requirements of timing for power floating and then given a repeated power trowelling finish for surface density. Chemical treatments on the other hand are substances such as magnesium or zinc fluosilicate, sodium silicate and linseed oil and may be spread over the surface of hardened concrete.

Several investigators (Tyo, 1991; Fentress, 1973; Schuman & Tucker, 1939; Scripture, 1936; A'Court, 1949; Ahlers et al., 1929) have studied the effect of dry shakes on the abrasion resistance of concrete. They have generally concluded that the higher concentration of aggregate and the lower w/c ratio near the surface provides increased abrasion resistance over conventional concrete. Some workers (Sadegzadeh & Kettle, 1988; Scripture, 1936) reported that the abrasion resistance of concrete slabs treated with metallic aggregate dry shake is superior to concrete slabs treated with mineral aggregate or cement dry shakes. Even though Tyo (1991) came to the same conclusion, he also suggested that as these dry shakes are only present on the top 3 mm of the concrete surface they may have little effect in heavily trafficked areas.

Chemical treatments, which employ surface hardeners, based on sodium silicate or magnesium or zinc fluosilicate react with the free lime in the pore structure of the concrete to produce calcium or sodium silicate and calcium fluoride respectively (Concrete

Society's TR34, 1994). These glass-like materials were found (Schuman & Tucker, 1939; A'Court, 1949) to improve the surface hardness of concrete slabs by blocking the surface pores and hence resulting in higher abrasion resistance. Sadegzadeh & Kettle (1988) concluded that concrete liquid hardeners, based on aqueous solutions, were more effective in improving the abrasion resistance of mixes with low w/c rather than those with higher w/c. Further, they reported that treatments with penetrating hardeners, these largely being resin based, significantly increased the abrasion resistance of all types of concrete mix. The abrasion resistance obtained by the use of these specific treatments ranked highest when compared with other treatments applied to air-cured specimens. In addition, the application of these penetrating sealers and hardeners reduced the influence of the concrete mix design on the abrasion resistance of concrete slabs.

2.9.7 Addition of fibres

The ACI Committee 544 (1986) reported that unpublished laboratory data, from the United States Steel Corp., show that slab test samples with 2.5 % by volume of fibre reinforcement and pea gravel abraded to a depth of 27 % less than a corresponding plain concrete with gravel. Further tests by the Corps of Engineers suggest that the abrasion resistance of steel fibre concrete, with respect to scour from all types of debris contained in water flowing trough and over structures, was no better than that of plain concrete (Liu, 1980).

Nanni (1989) suggested that the addition of steel or synthetic fibre does not affect the abrasion resistance of the surface layer subjected to the action of an abrasive tool. However, benefits can be seen in the case of pavements subjected to vehicular traffic. Improper moist curing conditions severely affect surface quality more so than compressive strength. He claims that it is possible to use abrasion testing to monitor surface performance as a function of curing time.

In contrast to Liu (1980), Sustersic et al. (1991) reported that steel fibres are adequate for applications requiring erosion-abrasion resistant concretes. They reported that the abrasion resistance, according to the Böhme test method, was not improved by an increase in compressive strength, but was improved by the addition of steel fibres. They found that the erosion-abrasion resistance was improved by an increase in compressive strength with or without steel fibres. Furthermore, for mixes with a constant w/c (0.30), where the values of

compressive strength were essentially constant, this resistance was increased by an increase in the volumetric percentage of steel fibres. If the abrasion resistance is improved, the erosion-abrasion resistance does not necessarily improve too, as shown by the results of concrete at different w/c, with and without constant content of steel fibres. Nevertheless, the erosion-abrasion resistance was generally improved by the presence of steel fibres.

Febrillet et al. (2000) suggested that the addition of steel fibres at several volumes into ultra-high strength concrete had little or no influence on the resulting abrasion resistance. They have also shown that the abrasion depth decreased with increasing compressive strength, suggesting that the abrasion resistance is primarily dependent on the compressive strength of the mortar rather than fibre addition.

Form the recovered literature it is apparent that only a handful of researchers (Liu, 1980; Alexanderson, 1982; Nanni, 1989; Sustersic, Mali, & Urbancic, 1991; Eren et al., 1999) have carried out experimental work on the abrasion resistance of fibre reinforced concrete specimens. They have generally concluded that the inclusion of fibres into the concrete matrix positively affects abrasion resistance. It was almost surprising to find that the above researchers are the only ones that have actually validated their remarks through limited experimental work. As briefly explained in Chapter 1, Section 1.12, many other authors (Swamy, 1974; Unwalla, 1982; Kukreja, et. al, 1984; Anon; 1985; Malisch, 1986; Hogan, 1987; Anonymous, 1987; Deacon, 1990; Vondran, 1994; Maidl, 1995; Parameswaran, 1996; Carr, 1998; Philip Jones Construction Materials Ltd, 1998 a & b; Knapton, 1999) only claim that the introduction of fibres into concrete results in a greater abrasion resistance as compared to that of conventional concrete. This lack of experimental data was considered to be a significant gap in the literature and was deemed important to examine these issues in detail through this research work.

2.10 Historical use of fibres

Historically fibres have been used to reinforce brittle materials since ancient times; straw was used to reinforce sunbaked bricks, horse hair was used to reinforce plaster and more recently, asbestos fibres have been used to reinforce portland cement (ACI Committee 544, 1986). Patents have been granted since the turn of the century for various methods of incorporating wire segments or metal chips into concrete. The low tensile strength and brittle character of concrete have been bypassed by the use of reinforcing rods in the

tensile zone of the concrete since the middle of the nineteenth century (ACI Committee 544, 1986).

Research by Romualdi & Batson (1963) and Romualdi & Mandel (1964) on closely spaced wires and random fibres in the early 1960s was the basis for US patents based on fibre spacing (Patent No. 3,429,094, 1969, and No. 3,500,728, 1970). The Portland Cement Association (PCA) investigated fibre reinforcement in the late 1960s (Monfore, 1968) and another patent, based on the bond and aspect ratio of the fibres, was granted in 1972 (Patent No. 3,650,785, 1972). In the early 1960s, experiments using plastic fibres in concrete with and without steel reinforcement were conducted (Goldfein, 1963; Williamson, 1965). Experiments using glass fibres have been conducted in the United States (Goldfein, 1963; Abbud-Klink, 1967), the United Kingdom (Majumdar & Ryder, 1968; Grimer & Ali, 1969; Majumdar, 1970; Majumdar & Ryder, 1970) and Russia (Biryukovich, Yu & Yu, 1965). Similarly, over the past 40 years, a number of applications have been recommended for the use of fibre reinforced concrete including road and floor slabs, refractory materials and concrete products (ACI Committee 544, 1986).

Most of the experience with steel fibres in both the United States and the United Kingdom has been with mixes using normal weight aggregate and OPC as the binder. Present mechanical methods of producing and handling plain concrete may or may not be appropriate for fibre reinforced concrete depending on the many mix parameters involved. The volume and type of fibres selected determine the maximum aggregate size and volume of paste, with these factors known, the techniques of good concrete proportioning can be applied to obtain workable and economical mixes (Kesler & Halvorsen, 1979). Methods for mixing, placing, consolidating and finishing steel fibre reinforced concrete have been developed, particularly for pavements. The greater difficulty in handling steel fibre reinforced concrete requires more deliberate planning and better workmanship than normal concrete construction procedures.

To date, the fibres finding greatest use have been three man-made fibres, namely steel and polypropylene, principally in concrete, and glass in cement mortar for thin section applications. The reinforced matrix is generally based on OPC but alternative less straightforward matrices have also been used (Keer, 1984). More recent references have been made to the use of metallic and non-metallic fibres in hybrid systems (Ohama et al., 1985; Qian & Stroeven, 2000) and their advantages over single fibre matrices (Bentur &

Mindess, 1990) though the research work carried in this area is somewhat limited. Ohama et al. (1985) concluded that the fibre hybrid reinforced concrete using steel and polyethylene fibres has much better properties such as flexural toughness and maximum tensile strain than the concretes reinforced only with the individual fibres.

Qian & Stroeven (2000) investigated the optimisation of fibre size, fibre content and fly ash content in hybrid polypropylene-steel fibre reinforced concrete (with low fibre content) based on general mechanical properties. Their research results showed that a certain content of fine particles such as fly ash is necessary to evenly disperse fibres. They found that fibre size of the steel fibres influenced a number of mechanical properties but this influence varied with the individual property. For example additions of a small fibre had a significant influence on the compressive strength with only limited influence on the splitting tensile strength. In contrast, a relatively large fibre produced the opposite effects on these parameters.

2.11 Types of fibres

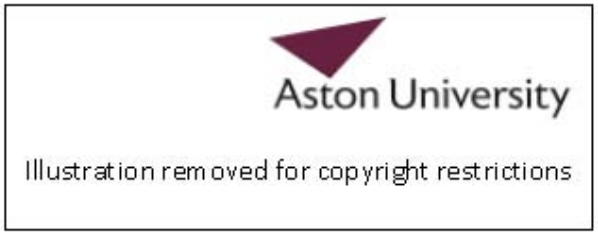
The ACI Committee 544 (1986) defined fibres as reinforcing elements that have a discontinued and discrete nature. Continuous meshes; woven fabrics and long rods are not considered to be discrete fibre reinforcement in this respect. A convenient numerical parameter describing a fibre is its aspect ratio (l/d), defined as the fibre length (l) divided by the fibre diameter (d). In the case of non – circular fibres the equivalent diameter may be used (ACI Committee 544, 1986; Ramakrishnan, 1988). Typical aspect ratios range from 30 to 150 for length dimensions of 6.4 to 76 mm.

A wide variety of fibre materials in various sizes and shapes have been developed over the years for use in fibre reinforced concrete (FRC) and they are commercially available for use in the construction industry (ACI Committee 544, 1986; Ramakrishnan, 1988; Maidl, 1995; Knapton, 1999). Currently, steel, polypropylene and glass fibres are commonly used for a wide range of applications. However, there are also limited applications of fibres made of carbon, ceramics, asbestos, and plant cellulose (Ramakrishnan, 1988; Maidl, 1995).

2.11.1 Steel fibres

Many efforts have been made in recent years to optimise the shape of steel fibres to achieve improved fibre-matrix bond characteristics, and to enhance fibre dispersibility in the concrete mix. Many more types of fibres are used today than just the straight-round ones as illustrated in Figure 2.6. Steel fibres now available in many deformed shapes are claimed to produce better mechanical bonding to concrete matrices than straight round wires (Soroushian & Bayasi; 1991).

Figure 2. 6 Various types of steel fibres (Soroushian & Bayasi, 1991; Knapton, 1999)



Currently, steel fibres are produced by the application of three different manufacturing processes. These have been described in detail by a number of investigators (Swamy, 1974; Ramakrishnan, 1988; Soroushian & Bayasi, 1991; Maidl, 1995) and include the following:

- A sheet of metal is cut or slit, producing a square or rectangular fibre.
- Cold-drawn wire is chopped to specific length. Some are collated with water-soluble glue into bundles of 10 to 30 fibres to facilitate more effective handling and to increase their bond and anchorage parameters.
- Melt-extracted fibres are produced by a process whereby a rotating, cooled disc with indentations the size of the fibre is dipped in the surface of a molten pool of high quality metal.

The ultimate strength of the steel fibres range from 345 to 2070 MPa whereas the size ranges from 13 x 0.25 mm to 64 x 0.76 mm. The steels used for making steel fibres are generally carbon steels or alloy steels (stainless steel), the latter are used primarily for corrosion resistant fibres, in refractory applications and marine structures (Swamy, 1974; Ramakrishnan, 1988; Bentur & Mindess, 1990). However, in one investigation brass-plated cut steel wire tyre cord has been used successfully (Ramakrishnan et al., 1981).

2.11.2 Polypropylene fibres

Two important reasons which make polypropylene attractive as a reinforcing fibre are the low price of the raw polymer material and the existing high production capacity (Keer, 1984; Bentur & Mindess, 1990). Due to their high alkaline resistance, polypropylene fibres are gaining in significance (Maidl, 1995). Further, they are resistant to most chemicals and it would be the cementitious matrix, which would deteriorate first under aggressive chemical attack (Keer, 1984; Bentur & Mindess, 1990). The melting point of polypropylene is high enough (165°C) that a working temperature of 100°C may be sustained for short periods without detriment to the fibre properties (Keer, 1984).

Polypropylene fibres are available in two forms i.e. monofilament or fibrillated, manufactured in a continuous process by extrusion of a polypropylene homopolymer resin (Keer, 1984; Knapton, 1999). Monofilament fibres are manufactured from extruded sheet/film material which is subject to molecular alignment, coated and cut to the appropriate length. This type of fibre is usually much finer than the fibrillated fibre and the properties of concrete resulting from the addition of monofilament fibres depend on the large number of fibres present. A smoother surface finish may be achieved from the use of monofilament fibres as opposed to the fibrillated type. Monofilaments do not provide any mechanical bond to the cement paste, but rely on their greater number per cubic metre of

concrete and their chemical bond in order to achieve their proven qualities in both the plastic and hardened states (Knapton, 1999). Fibrillated fibres are manufactured from extruded sheet/film material, which is subject to molecular alignment, fibrillated, coated and cut to the appropriate length. Clustering of fibres is overcome by mixing the aggregates in the concrete mix. Fibrillated fibres have a rough surface texture, which gives each fibre a high degree of mechanical bond to the concrete. Monofilament fibres achieve enhanced plastic shrinkage control and trowel workability, while fibrillated fibres impart a higher degree of abrasion resistance to the resulting concrete (Keer, 1984; Knapton, 1999).

The modulus of elasticity of both the monofilament and the fibrillated polypropylene is usually in the range of 1 to 8 GPa and the tensile strength is about 300 to 400 MPa. The monofilaments can be made in different diameters, ranging from about 50 μm to 0.5 mm (Ramakrishnan, 1988; Bentur & Mindess, 1990). The geometry of the fibrillated polypropylene is more difficult to quantify. It can be described in terms of the thickness of the film (ranging from ~ 15 to 100 μm) and the width of the individual filaments or fibrils which range from ~ 100 to 600 μm. Alternatively, the fibrillated geometry can be quantified by the measurement of the specific surface area by absorption techniques, where values in the range of ~ 80 to 600 mm^2/mm^3 have been reported (Hughes, 1984). The chemical structure of polypropylene make the fibres hydrophobic, which can be advantageous in the mixing process since the fibres do not absorb part of the mixing water and need only be dispersed evenly through the mix (Keer, 1984; Ramakrishnan, 1988; Bentur & Mindess, 1990; Knapton, 1999).

2.11.3 Glass fibres

Glass fibres are produced using either the spinning or the rod drawing process. During the former, the processed glass is added to a melting basin, at the base of which there are two thousand 1 – 2 mm openings. The fluid glass flows out of these openings and is drawn into threads (Keer, 1984; Maidl, 1995). The second process involves heating glass rods in a furnace so that beads of glass form on the ends of the rods which eventually drop off the rod drawing a thread with them which can then be reeled (Maidl, 1995).

A wide range of glass types is available and they differ only in the proportioning of their constituents. E, S and R type of glass are most commonly used for the production of glass fibres (Keer, 1984; Maidl, 1995). However, E glass fibres have an inadequate resistance to

the alkalis present in Portland cements and which destroy the glass network and so reduce the strength of the fibres. In addition, these fibres are prone to an ageing process, which gives rise to the same effects and can be accelerated by humidity (Majumdar & Ryder, 1968; Majumdar, 1970; Majumdar & Nurse, 1974). As a consequence many investigators worked on the development of alkali-resistant (AR) glass fibres (Biryukovick et al., 1966; Majumdar & Ryder, 1968; Majumdar, 1970; Majumdar & Nurse, 1974; Larner et al., 1976; Chakraborty et al., 1979; Proctor & Yale, 1980; Majumdar, 1980a; Franke & Overbeck, 1987). It was generally concluded that the most efficient method for enhancing the alkali resistivity is the incorporation of ~ 16% zirconium oxide (ZrO_2) in the glass composition (Majumdar & Ryder, 1968; Majumdar, 1970). The properties and composition of E and AR glass are presented in Tables 2.1 and 2.2 respectively.

Table 2. 1 Properties of single filaments of glass (Majumdar & Nurse, 1974)

Property	E glass	AR glass
Density (kg/m^3)	2540	2780
Tensile strength (MPa)	3500	2500
Modulus of elasticity (GPa)	72.5	70.0
Elongation at break (%)	4.8	3.6

Table 2. 2 Chemical composition of E and AR glass (Majumdar & Nurse, 1974)

Ingredients	E glass (%)	AR glass (%)
SiO_2	52.4	71
$K_2O + Na_2O$	0.8	11
B_2O_3	10.4	–
Al_2O_3	14.4	18
MgO	5.2	–
CaO	16.6	–
ZrO_2	–	16
Li_2O	–	1

2.11.4 Other types of fibres

In the interest of providing a comprehensive overview the following sections contain a brief description of organic, carbon, ceramic and asbestos fibres. Technological developments in recent years have led to a considerable improvement in the properties of these fibres and in many cases these have been accompanied by considerable reductions in their production costs (Maidl, 1995).

2.11.4 .1 Organic fibres

A wide range of organic fibres is available and these include polypropylene (see 2.11.2), polyvinyl alcohol (PVA), polyester, polyacrylonitrile, polyaramide and plant fibres.

PVA fibres are produced by wet or dry spinning and boron is added to achieve high strength and stiffness by forming intermolecular bonds (Hikasa & Genba, 1986). To enhance their compatibility with the cement matrix and to enable efficient dispersion, the PVA fibres are surface treated (Bentur & Mindess, 1990). They are available in several diameters with modulus of elasticity up to 25 GPa. With a density of 1300 kg/m^3 they can achieve tensile strength up to 1000 MPa (Maidl, 1995). These fibres are particularly resistant to alkalines and to the effects of ageing (Hikasa & Genba, 1986; Zhijiang & Tian, 1986). In addition, they are thermally stable, with no strength loss after exposure to temperatures of 150 °C and are insensitive to biological attack (Zhijiang & Tian, 1986).

Polyester fibres have very low bond strength in the cement matrix but are stable in both acid and alkaline environments (Wang, Backer & Li, 1987). Their modulus of elasticity is below 19 GPa and their tensile strength is approximately 1000 MPa (Maidl, 1995).

Polyacrylonitrile fibres are very compatible with the requirements of fibrous cement products. Their modulus of elasticity is relatively high at 20 GPa with tensile strengths up to 1000 MPa. This type of fibre has good alkali resistance and good interfacial bonding and the resulting matrix has a reduced shrinkage tendency and improved energy absorption and flexural strength (Maidl, 1995).

Polyaramide fibres are distinctive among the organic fibres due to their significantly superior mechanical properties (modulus of elasticity is relatively high at 70 – 130 GPa, tensile strength up to 3000 MPa). In addition they are resistant to chemical corrosion (Maidl, 1995).

Several investigators have reviewed the types and properties of ***natural fibres*** (Cook, 1980a; Cook, 1980b; Aziz et al., 1981; Aziz et al., 1984; Subrahmanyam, 1984; Balaguru & Shah, 1985). Cook (1980a & 1980b) has suggested four classes of fibres based on their morphology: stem, leaf, surface and wood.

Stem fibres are obtained from the stalks of plants and are freed from the substances surrounding them by a process known as retting, which involves the combined actions of bacteria and moisture. Jute and flax fibres are included in this category.

Leaf fibres are obtained from the leaves of plants by a process in which the leaf is crushed and scraped to remove the fibres, followed by drying. The most common fibres in this category are sisal, henequen and abaca.

Surface fibres are found as single cell fibres on the surface of stems, fruits, and seeds of plants. Cotton and coir (coconut fibre) are included in this group.

Wood (cellulose) fibres are the most popular amongst the types of plant fibre. Wood chips are processed into various solutions and subjected to mechanical treatment to extract good quality cellulose fibres. They are relatively short and inflexible, but are usually strong and perform better during long ageing in the cement environment. Both theoretical and practical tests have been carried out on cellulose fibres (Foerdoes & Tram, 1986; Nagaraja, 1986). A wide range of tensile strength of between 200 to 1500 MPa was reported and the moduli of elasticity varied between 5 to 40 GPa (Maidl, 1995). Wood fibres derived from bamboo or sugar cane have been used in the past for the production of low cost cement composites. There is a particular interest in bamboo reinforcement (Subrahmanyam, 1984; Nagaraja, 1986), which can be used in the form of fibres after appropriate processing or as reinforcing rods. Subrahmanyam (1984) has extensively reviewed this topic.

2.11.4.2 Carbon fibres

Carbon fibres exhibit a variety of good mechanical properties. These fibres are light and very resistant to the effects of chemicals and high temperatures. They are particularly well suited for the strengthening of plastics and metals (Maidl, 1995). However, limited reports have been published with regards to their application in cement bound matrices (Nishioka et al., 1986; Brown & Hufford, 1986; Ramakrishnan, 1988).

Carbon fibres are produced through two main processes that are based on different starting materials. Polyacrylonitrile is used to produce PAN carbon fibres whereas petroleum and coal tar pitch result in the production of pitch carbon fibres (Bentur & Mindess, 1990; Maidl, 1995). A variety of carbon fibre grades may be achieved depending on the

combination of heat treatments, stretching and oxidisation during the production process (Bentur & Mindess, 1990).

The properties of both PAN and pitch fibres are presented in Table 2.3, reproduced from previous investigations (Hull, 1981; Nishioka et al., 1986). The PAN carbon fibres are subdivided into two categories or types, I and II, and both possess higher modulus of elasticity and strength in comparison to the pitch carbon fibres (Hull, 1981). However, pitch carbon fibres have superior properties to many other synthetic fibres, and their modulus of elasticity is equal to or greater than that of the cement matrix (Bentur & Mindess, 1990). A lot of the work on reinforcing cement with pitch carbon fibres was carried out by Nishioka et al. (1986) as they had initiated the development of these fibres.

Table 2. 3 Properties of carbon fibres (Hull, 1981; Nishioka et al., 1986)

Properties	**PAN**		**Pitch**
	Type I	Type II	
Diameter (μm)	7.0 – 9.7	7.6 – 8.6	18
Density (kg/m^3)	1950	1750	1600
Modulus of elasticity (GPa)	390	250	30 – 32
Tensile strength (MPa)	2200	2700	600 – 750
Elongation at break (%)	0.5	1.0	2.0 – 2.4

2.11.4.3 Ceramic fibres

Ceramic fibres were initially developed for thermal insulation purposes. Aluminium silicates and various aluminium oxides are used to produce ceramic fibres. They are manufactured through splitting the molten mass followed by spinning, centrifugal or jet-blowing processes. Short fibres, made of pure Al_2O_3, with a diameter of 3 μm have a tensile strength of 2000 MPa and a modulus of elasticity of 300 GPa (Maidl, 1995). When appropriately processed these fibres may be used as a reinforcing material.

However, it is only during recent years that these fibres have been used in cement bound matrices. Ma & Tan (2000) studied the mechanical properties and durability of ceramic fibre reinforced Portland Cement composites. They found that when the length and content of ceramic fibres are 5 mm and 5% (by mass of cement), respectively, the flexural strength of ceramic fibre mortar can increase by approximately 40%. In addition they reported that, if the particle size of the matrix is reduced by adding 40% silica fume, the flexural strength can increase by about 100% at the same fibre length and content. Further, a patent by Ward

(Patent No. GB 2 308 592 A, 1997) described a lightweight load-bearing slab or panel suitable for use as a flooring slab and a ceiling or a wall panel. This is cast from a flame-resistant mortar consisting of calcium aluminate cement and inorganic ceramic fibres, where the mortar contains 60 – 85 % by weight of the fibres.

2.11.4.4 Asbestos fibres

Asbestos is a naturally occurring mineral that is collected as a stone in open-cast mining, split into fibres and separated according to fibre length by sieving (Parratt, 1972; Bentur & Mindess, 1990; Maidl, 1995). Natural asbestos is a low cost fibre and because it has twice the stiffness of normal E glass fibre it is a useful form of reinforcement that is still frequently used in a variety of commercial products (Parratt, 1972; Feric et al., 1997; Gibbs et al., 1998; Savastano & Agopyan; 1999). This type of fibre has a high fire resistance due to its high melting point of 1550°C and with only one exception it is also very resistant to aggressive solutions. Asbestos fibres have a high tensile strength (up to 3500 MPa), a high modulus of elasticity (160 GPa) and excellent electrical insulating capacity (Bentur & Mindess, 1990; Maidl, 1995; Feric et al., 1997). However, insight into the carcinogenic effect of asbestos fibres, resulted in the significant reduction in their use as a building material (Parratt, 1972; Schneider & Woitowitz, 1997; Gibbs et al., 1998; Grosse et al., 1998; Gibbons, 1998).

2.12 Theoretical principles of fibre reinforcement

In general, the purpose of fibre addition to cement or concrete is to improve the mechanical properties of the matrix (Keer, 1984). This section therefore examines the theoretical approaches leading to an appreciation of the way in which these improved properties are achieved. Numerous publications (Swamy et al., 1974; Swamy, 1975; Hannant, 1978; Keer, 1984; Mallick, 1988) have profoundly discussed the mechanics of fibre cement composites and these are summarised in the following sections.

2.12.1 The modulus of elasticity of the uncracked composite

It is generally accepted that the "law of mixtures" (Holister & Thomas, 1966; Holiday, 1966; Kelly, 1973; Hannant, 1978; Keer, 1984) governs the modulus of elasticity, E_c, of a fibre reinforced cement or concrete. Hence, prior to the matrix cracking it may be assumed that:

$$E_c = \eta_1\eta_2 E_f V_f + E_m V_m \qquad (2.1)$$

Where

E: the modulus of elasticity

V: the volume fraction

$_c$: composite

$_f$: fibre

$_m$: matrix

η_1: efficiency factor depending on the fibre orientation

η_2: efficiency factor depending on the fibre length

Some typical values of the efficiency factor, η_1, are given in Table 2.4. For continuous fibres aligned in the direction of applied stress $\eta_1 = \eta_2 = 1$. For a random orientation of fibres in two dimensions the reported values of η_1 are 1/3 and 3/8; in three dimensions η_1 may be as small as 1/6 or 1/5 (Hannant, 1978).

For practical composites, the length efficiency factor, η_2, is likely to be nearly unity in the region prior to matrix cracking. For a practical composite, the addition of fibres is unlikely to significantly improve its stiffness, considering V_f in equation 2.1 is generally small (<0.1) compared to V_m (~0.9) (Keer, 1984).

Table 2. 4 *Efficiency factor, η_1, for fibre orientations relative to stress direction (Hannant, 1978)*

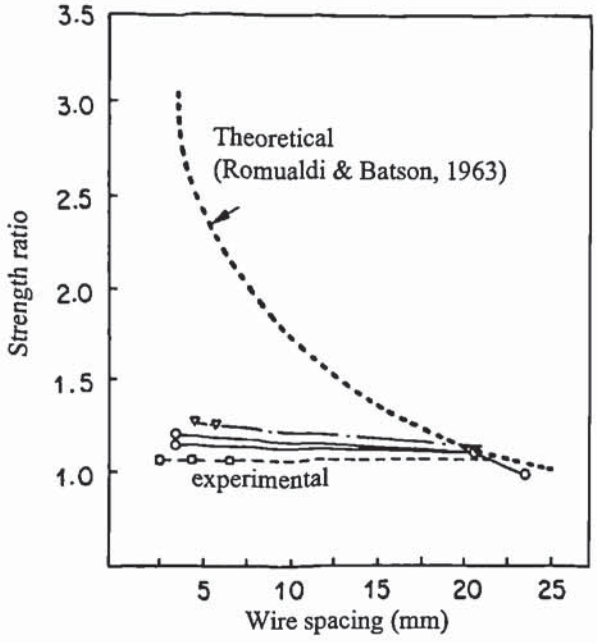
Fibre orientation	η_1 according to	
	Cox (1952)	Krenchel (1964)
1 – D aligned	1	1
2 – D random in plane	1/3	3/8
3 – D random	1/6	1/5

2.12.2 The failure strain of the matrix

The failure strain of the matrix is defined as the strain at which cracks propagate unstably across the cross-section of a tensile specimen (Keer, 1984). Hannant, (1978) believes that the failure strain of the matrix is not affected by the presence of fibres and consequently the cracking stress of a fibre cement or concrete is not significantly increased by the presence of fibres.

Over the years, there has been a continuing controversy over the actual effect of fibres on the matrix failure strain. The work by Romualdi & Batson (1963) provided the initiative for the development of fibre cements and concretes. They adopted a fracture mechanics approach and theoretically predicted that the tensile strength of concrete would be considerably increased by the inclusion of closely spaced fibres. However, the supporting experimental work was based on flexural testing. Subsequently, a number or researchers (Shah & Rangan, 1970; Johnson & Coleman, 1974; Edgington, Hannant & Williams, 1974) concluded that there is either slight or no improvement of the cracking strengths when tested specimens in direct tension (Figure 2.7). Kelly (1974) observed that Romualdi & Batson's (1963) theoretical approach resulted in high bond stresses, which in practice, could not be sustained.

Figure 2. 7 *Effect of spacing of reinforcement on cracking strength of concrete (Edgington, Hannant & Williams, 1974)*



Aveston et al. (1971) examined the energy requirements for a crack to form in the matrix and suggested that the matrix will fail either when it reaches its normal cracking strain, ε_{mu}, or when the strain reaches a value ε_{muc}, whichever is greater. ε_{muc} is give by:

$$\varepsilon_{muc} = \left\{ \frac{12\tau\gamma_m E_f V_f^2}{E_c E_m^2 r V_m} \right\}^{1/3} \qquad (2.2)$$

Where τ: the fibre-matrix frictional stress transfer

γ: the work of failure

r: the fibre radius

Aveston et al. (1974) carried out an investigation on cement paste reinforced with continuous steel wire and carbon fibres and established a good correlation between this theory and their experimental results. Using Equation 2.2 Aveston et al. (1974) concluded that about 0.5 % of continuous steel wires would be sufficient for crack suppression whereas, for randomly oriented 3-D wires, the beginning of crack suppression would require a steel fibre content of around 3 %. The latter is on the upper limit of the volume of short fibres that can be effectively incorporated into concrete. Despite these conflicts concerning the mechanics of crack growth and the stabilising effects of fibres on crack development further theories have been produced to describe the increase in the failure strain of brittle matrices reinforced by fibres (Korczynskyj et al., 1981; Hannant et al., 1983).

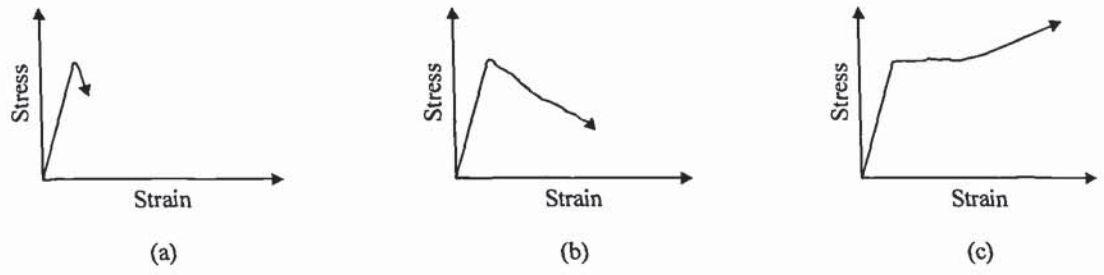
The theory by Aveston et al. (1974) is now considered to give a lower limit to the strain that must be exceeded for cracking to occur. According to this theory the failure strain of the unreinforced matrix (0.022%) would not be increased until the fibre volume exceeded some 16 %. In contrast the other theories (Korczynskyj et al., 1981; Hannant et al., 1983), more correctly, predict enhancement in matrix failure strain as the fibre volume increases from zero. Hannant et al. (1983) suggested that the inclusion of about 6 % by volume of glass fibres or about 10 % by volume of aligned polypropylene fibres might enhance the matrix cracking strain by about 50 %. However, experimentally, there is likely to be a considerable scatter of results either side of such an increase, so that care must be taken in using these enhanced cracking strains for design purposes (Hannant et al., 1983).

2.12.3 Post-cracking behaviour in tension

The failure strain of a reinforcing fibre is generally substantially higher than that for the matrix. Consequently, significant benefits can be gained if full use is made of the ductility of the fibre component (Keer, 1984). Once the brittle matrix cracks, a fibre cement or concrete, as illustrated in Figure 2.8, may exhibit three types of post-cracking behaviour in tension:

- The composite fails as the fibres fracture immediately under the increased stress (Figure 2.8 (a)).
- The composite can carry a decreasing load as the fibres pull out from the cracked surfaces (Figure 2.8 (b)). After the matrix cracks, the tensile strength of the composite is not increased. However, the strain at complete failure is increased and there can be a considerable increase in the toughness of the composite as measured by the area under the complete stress-strain curve. This type of behaviour is typical of some short, randomly orientated steel or organic fibre composites (Keer, 1984).
- The composite continues to carry an increasing tensile stress. Multiple cracking of the matrix occurs and the material behaves in a pseudo-ductile fashion with a high impact strength (Figure 2.8 (c)). Cement or mortar matrices with a sufficient volume of continuous (or long) steel fibres and glass-fibre reinforced cement may exhibit this type of behaviour (Keer, 1984).

Figure 2. 8 *Types of behaviour in tension exhibited by fibre cements or concrete: (a) composite fails when matrix cracks; (b) composite carries a decreasing load as fibres pull out and crack; (c) composite can carry an increasing load after matrix cracking (Keer, 1984)*



Multiple cracking may occur when the fibre volume is greater than the critical volume, Hannant (1978) defined this as the volume of fibres which, after the matrix cracks, will carry the load that the composite sustained before cracking and is given by:

$$V_{fcrit} = \frac{E_c \varepsilon_{mu}}{\sigma_{fu}} \tag{2.3}$$

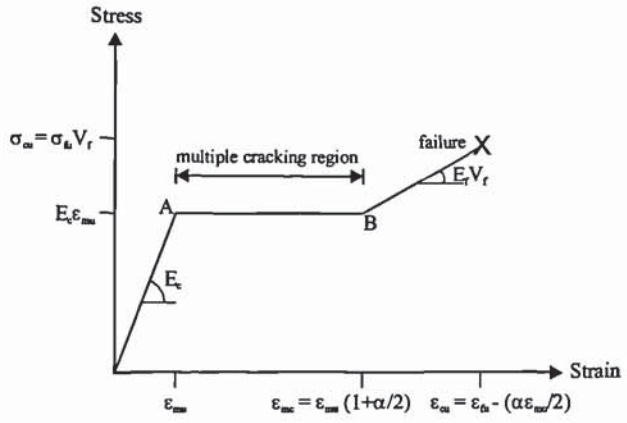
Where ε_{mu}: the strain at which the matrix cracks

σ_{fu}: the failure stress of the fibres

Keer (1984) suggested that the critical fibre volume may significantly increase with time since, in the long term, the modulus and cracking strain of the matrix may increase while the fibre strength may decrease. For example, a composite that is initially tough and ductile, with a stress-strain characteristic as shown in Figure 2.8(c), may change to a characteristic such as in Figure 2.8(a) with a brittle failure when a single crack forms.

Aveston et al. (1971) presented the idealised form of the tensile stress-strain curve, for a composite exhibiting multiple cracking, shown in Figure 2.9. They assumed that the fibres are continuous and aligned, the bond between the fibres and matrix is purely frictional and the matrix has a well-defined, single-valued breaking stress.

Figure 2. 9 *Idealised tensile stress – strain curve of fibre cement or concrete (Aveston et al., 1971)*



If V_{fcrit} is exceeded the matrix cracks, and the additional load is transferred back into the matrix over a transfer length x'. This is given by:

$$x' = \frac{V_m \sigma_{mu} A_f}{V_f \tau P_f} \tag{2.4}$$

Where σ_{mu}: ($= E_m \varepsilon_{mu}$) the matrix failure stress

A_f: the fibre cross – sectional area

P_f: the fibre perimeter

Eventually the matrix will be broken down into a series of blocks of lengths between x' and 2x'. Hannant (1978) explains that when the crack spacing is 2x', the additional stress

on the fibres due to cracking of the matrix varies between $\sigma_{mu}V_m/V_f$ at the crack and zero at distance x' from the crack. Consequently the average additional strain in the fibres, $\Delta\varepsilon_c$, is equal to the extension per unit length of composite at constant stress, $E_c\,\varepsilon_{mu}$, and is given by:

$$\Delta\varepsilon_c = \tfrac{1}{2}\sigma_{mu} \cdot \frac{V_m}{V_f} \cdot \frac{1}{E_f}$$

$$\text{i.e. } \Delta\varepsilon_c = \alpha\frac{\varepsilon_{mu}}{2}$$

Where $\alpha = E_mV_m/E_fV_f$

When the formation of multiple cracks is completed at stress $E_c\varepsilon_{mu}$, further increase in stress on the composite results in fibres sliding relative to the matrix and the tangent modulus becomes E_fV_f (Aveston et al., 1976). The composite fails when the stress in the fibres at a crack reaches the ultimate fibre stress. Hence the ultimate strength of the composite, σ_{cu}, is given by:

$$\sigma_{cu} = \sigma_{fu}\,V_f \tag{2.6}$$

and the ultimate strain, ε_{cu}, by:

$$\varepsilon_{cu} = \varepsilon_{fu} - \alpha\varepsilon_{mu}/2 \tag{2.7}$$

when the crack spacing is 2x', ε_{fu} is the fibre failure strain ($= \sigma_{fu}/E_f$)

The ultimate strength will be reduced if the fibres are randomly aligned and/or short so they pull out before they break. Fibre pull-out is the dominant failure mode for concrete with short, random fibres such as steel or chopped, fibrillated polypropylene (Keer, 1984).

A fibre will pull out before fibre fracture when the fibre length, l, is less than that of the critical length, l_c, defined as twice the length of fibre embedment which would cause fibre failure in a pull-out test (Keer, 1984; Aveston et al., 1976), i.e.

$$l_c = \frac{\sigma_{fu}r}{\tau} \tag{2.8}$$

According to Aveston et al. (1974), the strength of a composite reinforced with short randomly oriented fibres may be estimated from the product of the number of fibres, N, crossing unit area of a crack and the average pull-out force per fibre. If the mean pull-out length is l/4, then:

$$\sigma_{cu} = 2\pi r\tau N(l/4) \tag{2.9}$$

N can be determined from:

$$N = \frac{\eta_l V_f}{\pi r^2} \tag{2.10}$$

η_l is the fibre orientation efficiency factor, with proposed values (Aveston et al., 1974) of 1.0 for aligned fibres, $2/\pi$ for a random 2-D array and ½ for random 3-D array.
Hence,

for aligned fibres, $$\sigma_{cu} = V_f \tau \frac{l}{d} \tag{2.11}$$

for a random 2-D, $$\sigma_{cu} = \frac{2}{\pi} V_f \tau \frac{l}{d} \tag{2.12}$$

for random 3-D , $$\sigma_{cu} = \tfrac{1}{2} V_f \tau \frac{l}{d} \tag{2.13}$$

where d: the fibre diameter

Therefore, for a 3-D short fibre concrete, if the ultimate strength, σ_{cu}, is to exceed the strength at which the composite cracks, then from Equation 2.13:

$$V_{fcrit} > \frac{2\sigma_{mc}}{\tau(l/d)} \tag{2.14}$$

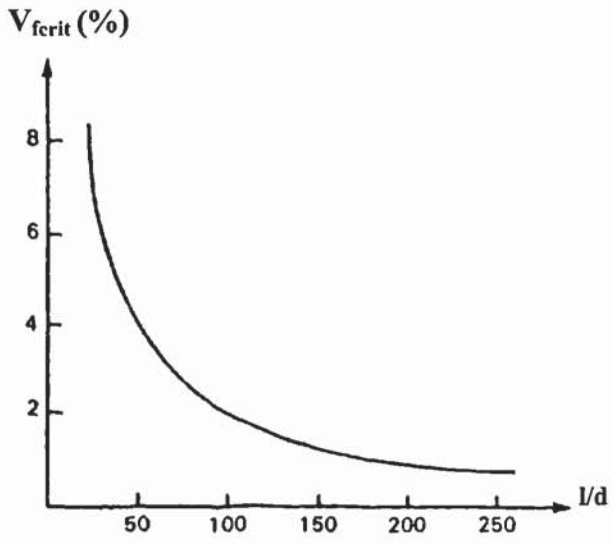
For a steel fibre concrete, for example, values of τ measured (Keer, 1984) have varied, but a reasonable value of σ_{mc}/τ might be unity. The relationship between V_{fcrit} and l/d for Equation 2.13 is illustrated in Figure 2.10, overleaf. V_{fcrit} is difficult to achieve in steel

fibre concrete because mixing and compaction problems increase with increasing V_f and with increasing l/d ratio.

Aveston et al. (1976) suggested that the ultimate strength, σ_{cu}, would be less than the value $\sigma_{fu}V_f$ even when the fibre length is greater than the critical length. This is because a proportion, l_c/l, of fibres will have one end less than $l_c/2$ from a crack and will therefore pull out instead of breaking. The average stress in the fibres that pull out is $\sigma_{fu}/2$ and hence the ultimate tensile strength (for aligned fibres) will be reduced to:

$$\sigma_{cu} = \left(1 - \frac{l_c}{2l}\right)\sigma_{fu}V_f \tag{2.15}$$

Figure 2. 10 *Critical fibre volume fraction, V_{fcrit} against fibre aspect ratio, l/d, from equation 2.14 for $(\sigma_{mc}/\tau) = 1$ (Keer, 1984)*



when $l = l_c$, Equation 2.15 becomes:

$$\sigma_{cu} = \sigma_{fu}V_f/2 \tag{2.16}$$

It should be emphasised that Equations 2.2 to 2.16 are based on several simplifying assumptions (Hannant, 1978) and the realities of composite behaviour and the practicalities of fabrication are likely to produce wide scatter in test results compared to the predicted

values. These factors should therefore be considered when designing composite materials to carry stresses.

2.12.4 Flexural behaviour

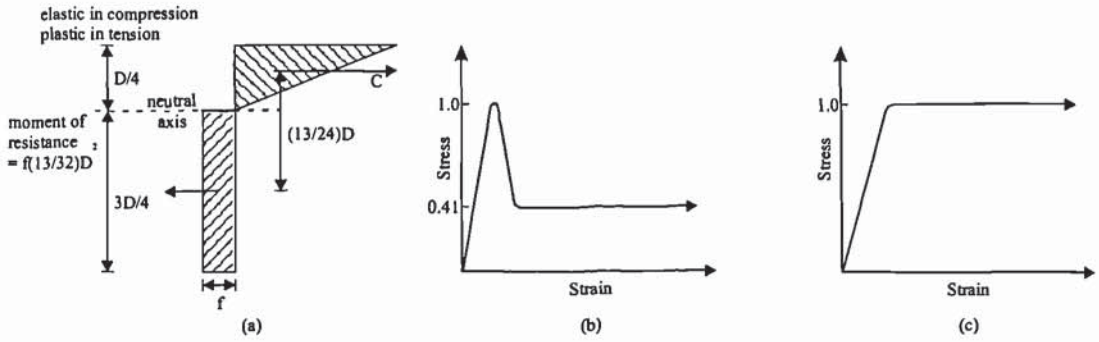
Similarly to the tensile case, the properties of the unreinforced matrix of flexural members may be enhanced by the addition of fibres. Therefore, the load at which matrix cracking is observed, the load deflection and failure and the toughness may all be increased (Keer, 1984). The following points are considered to be important when examining flexural behaviour:

- In general, flexural strength is expressed as a surface stress, which is calculated assuming elastic behaviour to failure with the neutral axis at mid-depth, with the extreme stress at failure commonly referred to as the modulus of rupture (MOR). The MOR is a nominal stress, since prior to failure, the neutral axis moves towards the compression surface as cracking propagates in the tensile zone. The MOR may be up to three times the direct tensile strength of the material.
- An increase in moment may be accompanied by a movement of the neutral axis, therefore flexural strengthening may occur even if in direct tension. However, there is no increase in strength after the matrix cracks.

Several investigators have proposed theories relevant to the evaluation of the flexural tensile strength of fibre-cement composites (Swamy, 1975; Swamy et al., 1974). The simplified stress distribution proposed by Hannant (1975) is presented (Figure 2.11). It illustrates the method to be adopted for the calculations depending on the type of stress distribution assumed and other simplifying assumptions made in formulating the equations.

Figure 2.11(a) presents the ultimate flexural behaviour. Here the stress in the tensile zone is assumed uniform, with the neutral axis positioned at one – quarter of the depth from the compression surface. Figure 2.11(b) suggests that flexural strengthening may occur, provided that the post – cracking tensile strength exceeds 41 % of the matrix cracking strength and there is adequate ductility in tension. It follows from this argument that the critical fibre volume for flexural strengthening is 41 % of the critical volume for direct tension.

Figure 2. 11 *Flexural strengthening: (a) assumed stress distribution at ultimate load; (b) stress – strain curve in uniaxial tension for no decrease in flexural load capacity after cracking; (c) stress – strain curve in uniaxial tension yielding modulus of rupture relationships in equations 2.17 – 2.19 (Hannant, 1975)*



As for the tensile strength, the apparent modulus of rupture, σ_{MR}, for a fibre composite failing by fibre pull-out rather than fracture, is a function of $V_f\tau l/d$ and the fibre orientation. Hannant (1975) proposed the following relationships for a composite with a tensile stress-strain curve similar to that shown in Figure 2.11(c):

$$1-D: \quad \sigma_{MR} \approx 2.44 V_f \tau (l/d) \tag{2.17}$$

$$2-D: \quad \sigma_{MR} \approx 1.55 V_f \tau (l/d) \tag{2.18}$$

$$3-D: \quad \sigma_{MR} \approx 1.22 V_f \tau (l/d) \tag{2.19}$$

Therefore, the critical factors affecting the modulus of rupture for composites in which the fibres pull-out, rather than break, are the volume, shape and orientation of the fibres and the bond strength between fibre and matrix.

2.13 Fibre reinforced concrete

The inclusion of fibres in concrete may significantly alter its properties in both the fresh and hardened states. However, it is very well documented (Maidl, 1995; ACI Committee 544, 1988; Keer, 1984) that the main contribution of fibres is to the enhancement of the properties of the hardened concrete, such as compressive, tensile and flexural strengths, flexural toughness, impact and abrasion resistance, shrinkage and creep. The extent to which the addition of fibres alters the mechanical properties of concrete is influenced by

the fibre type, geometry, volume, and orientation and the bonding between the concrete matrix and the fibres (ACI Committee 544, 1988a).

In the following sections the important effects of fibres (principally steel, polypropylene and glass) upon the properties of fresh and hardened concrete are discussed. The basic concepts regarding the preparation and handling of fibre reinforced concrete are also considered.

2.13.1 Mechanical properties of fresh fibre reinforced concrete

Achieving adequate workability (flowability and compactability) is one of the most important problems generated when using fibre reinforced concrete (FRC). This is because an adequate workability is essential for the concrete to be placed, compacted and finished with ease and ensure a uniform fibre distribution (ACI Committee 544, 1988a; Ramakrishnan, 1988). Other significant problems associated with fresh fibre reinforced concrete include fibre balling, mix segregation and excessive bleeding during placing and compaction (Maidl, 1995; Ramakrishnan, 1988). All of the above factors may severely influence the concrete strength as well as other properties and therefore knowledge of the fresh concrete properties is considered to be essential for proper design and application of fibre reinforced concrete mixes (Ramakrishnan, 1988).

2.13.1.1 Workability

The ACI Committee 544 (1988b) defines workability as the measurement of the ability of wet concrete to be mixed, handled, transported, placed and consolidated with a minimal loss of homogeneity and minimal entrapped air. Over the years several tests have been specified to assess the workability of fibre reinforced and plain concrete, namely, slump test, time of flow through inverted slump cone test and Vebe (V-B) test. These and other relevant tests have been described in more detail elsewhere (Hannant; 1978, ACI Committee 544; 1988b).

Many investigators have used these tests (Swamy, 1974; Edgington et al., 1974; Hannant; 1978; Balaguru & Ramakrishnan, 1988; Soroushian & Bayasi, 1991) to assess the workability of steel fibre reinforced concrete (SFRC). They generally concluded that inclusion of steel fibres into the concrete mix, influences its workability, with increases in the fibre volume and aspect ratio leading to decreased workability. In addition, several

researchers (Edgington et al., 1974; Swamy, 1974; Ramakrishnan, 1988; Vondran, 1994; Khayat & Roussel, 2000) suggested that the slump test is a poor indicator of relative workability of SFRC, since the addition of fibres to the mix changes the slump out of proportion to the absolute change in workability. Edgington et al. (1974) found that many of their fibrous mixes responded satisfactorily to vibration even though their slump was zero. As a result the V-B test, which simulates the effects of vibration, was found to give a more realistic assessment of the workability of fibre concretes (Edgington et al., 1974; Swamy, 1974; Ramakrishnan, 1988).

As with any other type of concrete, the mix proportions of SFRC depend upon the requirements of each project, in terms of strength, workability etc. Several procedures for proportioning SFRC mixes, with emphasis on good workability, are available (Ounanian & Kesler, 1976; Schrader & Munch, 1976; Ahuja et al., 1982; ACI Committee 544, 1986; Schrader, 1989). The ACI Committee 544 (1993) advises that the usual amount of steel fibres ranges from 0.25 % to 2 % by volume, with the low end applied to lightly loaded slabs on grade, some precast applications and composite steel deck toppings. The upper end of the range is common for security applications like safes, vaults etc. However, there are some considerations that relate specifically to the workability of SFRC.

Edgington et al. (1974) showed that for a particular fibre type and orientation, the workability of the mix decreased with an increase in the amount and particle size of the coarse aggregate. In contrast the presence of aggregate particles less than 5 mm in size had little effect on the compaction characteristics of the mix. They proposed an equation to estimate the critical percentage of fibres at which the concrete would just become unworkable:

$$PWc_{crit} = 75\frac{\pi SG_f}{SG_c} \cdot \frac{d}{l} \cdot K \qquad (2.20)$$

Where

PWC_{crit} = critical percentage of fibres (by weight of mix)

SG_f = specific gravity of fibres

SG_c = specific gravity of concrete matrix

d/l = inverse of fibre aspect ratio

$K = W_m / (W_m + W_\alpha)$

and where

W_m = weight of mortar fraction (particle size < 5 mm)

W_α = weight of aggregate fraction (particle size > 5 mm)

Edgington et al. (1974) recommended that to minimise the effects on workability, the fibre content should not exceed 0.75 PWC_{crit}. Apart from the maximum aggregate size and the fibre content, another factor that has a major effect on workability is the aspect ratio (defined in section 2.11) of the fibres. Overall Edgington et al. (1974) reported that the workability decreased with increases in the fibre concentration and aspect ratio. Further it was also shown that a reduction in the maximum aggregate size facilitated the introduction of fibres, although this behaviour was largely eliminated when the maximum particle size was below 5 mm.

The workability of polypropylene fibre reinforced concrete (PFRC) has not received the same attention in the literature as SFRC. The volume fraction of polypropylene fibres in concrete generally ranges from 0.05 to 0.3 %. Some investigators claim that at these relatively low volumes, no additional precautions are needed for mix proportioning and manufacturing techniques due to the inclusion of fibres (Zollo, 1984; Naaman et al., 1984; ACI Committee 544, 1986; Alwahab & Soroushian, 1987; Ramakrishnan et al, 1987). However, for higher fibre volumes, Hannant (1978) suggested that the workability of PFRC may be measured by the utilisation of standard tests such as the slump test, the V-B consistometer test and the compacting factor.

Limited work (Ritchie & Al – Kayyali, 1975) was carried out on the effect of increasing fibre volume on the workability of both normal and lightweight aggregate concrete. Ritchie & Al – Kayyali (1975) reported that the compacting factor test gave a useful measure of the observed reduction in the workability of PFRC. In more recent years, Bayasi & Zeng (1993) used the slump and inverted slump cone tests to study the effect of increasing fibre length and volume on the workability of PFRC. They concluded that polypropylene fibres have no detectable effect on the workability of fresh concrete at volumes below 0.3 %. For fibre volumes of 0.5 %, however, the fibres seemed to adversely affect fresh mix workability with longer fibres having a more pronounced effect.

2.13.1.2 Compactability

The major difficulty in FRC mixes is a practical one: ensuring adequate flowability and compactability to enable the concrete to be placed and compacted with ease and retain its uniform fibre distribution, particularly in structural members containing rebars (Swamy,

1974; Swamy, 1975; ACI Committee 544, 1986). It is generally accepted that SFRC requires more compaction energy than plain concrete (Swamy, 1974; Maidl, 1995). Even though several types of vibration may be employed (Hannant, 1978) external mould vibration is preferable to internal vibration (Swamy, 1974; ACI Committee 544, 1986). The type and direction of vibration can have a critical effect on the fibre orientation relative to the future direction of loading (Edgington & Hannant, 1972; Edgington et al, 1974; Hannant & Spring, 1974; Swamy & Stavrides, 1975) and hence on the properties of the hardened state (Swamy, 1974; Hannant, 1978; Maidl, 1995). Preferential orientation of the fibres under vibration (Edgington & Hannant, 1972) may be assisted by magnetic fields and increases in the modulus or rupture of more than 50 % at 1.5 % by volume of fibres have been reported (Bergström, 1975). However, magnetic orientation is likely to be limited to precast applications under factory conditions.

Though in the early days of using SFRC, compactability was a major issue, in more recent years this problem has almost been eliminated (Swamy, 1986) by the use of the following:

- A slight excess of fines in the mix in conjunction with water reducing plasticisers (Swamy, 1986).
- Air entrainment with low w/c ratios and the incorporation of compatible plasticisers (Ramakrishnan & Coyle, 1983).
- Partial cement replacement (up to 30 %) with pfa or fly ash in conjunction with adequate water reducing plasticisers (Swamy, 1982; Swamy et al., 1983).
- External / mould vibration (Swamy, 1986).

Fortunately polypropylene concrete and mortar respond well to conventional vibrating tables or pokers and presses, as the fibres, due to their low specific gravity, do not easily segregate from the mix (Hannant, 1978).

In the case of glass fibre reinforced cements it was reported (Grimer & Ali, 1969) that the addition of fibres results in considerable air entrapment. Since air reduces the strength of concrete Grimer & Ali (1969) have undertaken an investigation of the air content of compacted glass fibre reinforced specimens. They concluded that provided the composite was capable of compaction on a vibrating table, the air content of the matrix within fibre reinforced concretes is no greater than that of the matrix without the fibres. They also

found that in the case of fibre reinforced mortars, there was a trend of decreasing air content with increasing fibre content.

2.13.1.3 Fibre orientation and distribution

When the properties of SFRC are considered it is generally assumed that the fibres are both uniformly distributed throughout the matrix and randomly orientated. Even though these may be true whilst the SFRC is still in the mixer, neither assumption is likely to be correct after vibration and compaction have taken place (Bentur & Mindess, 1990; Hannant, 1978). For example, when using table vibration, the fibres tend to align in planes at right angles to the direction of vibration or gravity as shown schematically in Figure 2.12. Internal vibration has a less marked effect on fibre alignment. A few studies (Edgington & Hannant, 1972; Swamy & Stavrides, 1975) were carried out on the effect of these two compaction techniques on the flexural strength of SFRC. It was concluded that the type and direction of vibration has a considerable effect on the flexural strength with increasing fibre volume resulting in increased flexural strength.

Figure 2. 12 The effect of table vibration on fibre alignment (Edgington & Hannant, 1972)

Steel fibres will in general show some preferential alignment as well as random distribution along the length of a beam. Uomoto & Kobayashi (1984) have clearly demonstrated this by electro-magnetic measurements of fibre content of SFRC. Potrebowski (1983) and Knoblauch (1979) suggested that in any cross-section of a beam, the steel fibres are unlikely to be truly randomly distributed, and this would depend on the orientation of the cross-section with respect to the direction of casting. It follows from the above that if fibres can be aligned uniaxially, either mechanically (Hannant & Spring,

1974) or magnetically (Bergström, 1975; Sikorski, 1982) then the mechanical behaviour of SFRC may be profoundly enhanced, as long as the stress acts in the appropriate direction.

2.13.2 Mechanical properties of hardened fibre reinforced concrete

Ramakrishnan (1988) suggested that the most significant consequence of fibre addition to concrete is the delay and control of tensile cracking in the composite material. Consequently an inherently unstable crack propagation in plain concrete is transformed into slow controlled crack growth. The ductile properties of plain concrete and FRC are significantly different since the fibres act as ductile elements within the brittle matrix (Hannant, 1994; Ramakrishnan, 1988; Edgington et al., 1974; Swamy, 1974). This is the predominant feature of FRC since dynamic properties, like energy absorption (flexural toughness) and fracture toughness, distinguish the material from plain concrete. Overall all modes of failure are affected by the presence of fibres in concrete. As presented in the following sections many significant improvements have been documented (Knapton, 1999, Hannant, 1994; Ramakrishnan, 1988; Edgington et al., 1974; Swamy, 1974) in properties such as ductility, toughness, impact resistance, tensile and flexural strengths, abrasion resistance, shrinkage and durability.

2.13.2.1 Compressive strength

Many investigators (Soroushian & Bayasi, 1991; Nanni & Johari, 1989; Ramakrishnan, 1988; Fanella & Naaman, 1985; Magnat & Azari, 1985a; Magnat & Azari, 1984a; Morris & Garrett, 1981; Atepegba & Regan, 1981; Shah, 1978; Hughes & Fattuhi, 1977; Halvorsen, 1976; Edgington et al., 1974; Johnston, 1974; Williamson, 1974) have studied the influence steel fibres on the compressive strength of concrete. It has generally been concluded that steel fibres do little to enhance the compressive strength of concrete with increases in strength ranging from zero to a maximum of 30 % (Febrillet et al., 2000; Magnat & Azari, 1984a; Morris & Garrett, 1981; Halvorsen, 1976; Johnston, 1974; Williamson, 1974). Even when steel fibres are used as secondary reinforcement, in conjunction to the conventional rebars, they have little effect on the compressive strength (Magnat & Azari, 1985a; Shah, 1978). However, the steel fibres do provide increased ductility (energy absorption), which may prove advantageous in a compressive failure (Fanella & Naaman, 1985; Hughes & Fattuhi, 1977; Swamy & Al – Noori, 1975).

Compressive strength comparisons between plain concrete and PFRC have been reported in several studies. Some researchers (Knapton, 1999; Dahl, 1985; Litvin, 1985) have concluded that there are no significant compressive strength differences between mixes with or without polypropylene fibres. Others (Bayasi & Zeng, 1993; Fibermesh Company, 1985 – 1988; Hanna, 1981) have found a modest increase in compressive strength when fibres are added. However, the majority of the above studies were commercially driven and so there exists a (high) degree of bias in the resulting data.

Even though no publications were retrieved on the influence of glass fibres on the compressive strength of concrete, a few investigators (Cian & Della Bella, 2001; Liang et al., 2002) have studied their influence on the compressive strength of glass fibre reinforced cements (GRC). It was generally concluded that glass fibre enhance the compressive strength of GRC with increases in strength ranging from 0 to 50 % (Liang et al., 2002). In addition it has been shown (Cian & Della Bella, 2001; Liang et al., 2002) that the increase in the curing age and glass fibre content, up to 2.0 %, resulted in a moderate increase in the compressive strength of GRC.

2.13.2.2 Tensile strength

As discussed in Section 2.12, the tensile strength of steel fibre reinforced mortar and concrete has been measured by several authors (Li & Li, 1997; Hannant, 1994; Nanni, 1985; Visavanich & Naaman, 1983; Hughes, 1981; Shah, 1978; Johnson & Coleman, 1974; Edgington et al., 1974; Swamy, 1974; Shah & Rangan, 1971) for various fibre shapes and volumes. Overall a modest increase in tensile strength due to steel fibre reinforcement has been reported. In contrast, Shah & Rangan (1971) suggested that fibres aligned in the direction of the tensile stress may bring about very large increases in the tensile strength, as high as 133 % for 5 % of smooth, straight steel fibres. However, for randomly distributed fibres, the increase in strength is much smaller, ranging from no increase in some instances (Hughes, 1981) to a maximum of 60 % (Johnson & Coleman, 1974). Splitting tension tests of SFRC carried out by Nanni (1985) produced similar results. Nevertheless, like compression, the inclusion of steel fibres led to significant improvements in the post cracking behaviour of composites by 1 to 2 orders of magnitude (Visavanich & Naaman, 1983; Shah, 1978).

Although research work on the tensile strength of PFRC is somewhat limited, it has generally been found that this property is essentially unaltered by the presence of a small volume (0.1 %) of short polypropylene fibres (Hannant, 1994; Litvin, 1985; Keer, 1984).

The tensile strength of glass fibre reinforced cement (GRC) composites rather than glass fibre reinforced concretes (GFRC) has been investigated (Marikunte et al. 1997, Majumdar, 1980a; Majumdar, 1980b; Ali et al., 1975; Ali et al., 1974) mostly in thin sheet components produced by a vacuum-dewatering spray-up system. In these components the glass fibres are dispersed in two dimensions, and they may reach contents of up to 5 % by volume. With this range of reinforcement, the 28 – day tensile properties of GRC generally conform to the stress – strain relationship presented in Figure 2.8c (Keer, 1984). Ali et al. (1974) studied the effects of fibre content and length on the 28-day properties of GRC composites for two storage conditions, air and water. They found that the increase in fibre content resulted in increases in the first crack stress, tensile strength and ultimate strain as well as flexural strength and impact resistance. Increases in fibre length also led to improvements in most of the mechanical properties of the GRC composites but not at the same extent as the increases in fibre content. It was reported (Majumdar, 1980a; Ali et al., 1975) that the tensile and flexural strength may reach values of up to 15 and 40 MPa respectively, with fibre contents of ~ 5 % and lengths of ~ 20 mm. These values are significantly higher than the matrix strength. The tensile strength of air stored composites is considerably lower than that of the water stored composites (Ali et al., 1975). This was also true for other properties such as first crack strength, flexural strength and impact resistance.

2.13.2.3 Flexural strength

Various surveys (Knapton, 1999; Bentur & Mindess, 1990; ACI Committee 544, 1986; Keer, 1984; Swamy et al., 1974; Swamy, 1974; Johnston, 1974) have been published on the flexural strength (or modulus of rupture), mainly relating to SFRC, and as discussed in Section 2.12, detailed experimental work has been carried out by several investigators (Febrillet et al., 2000; Lok & Pei, 1997; Soroushian & Bayasi, 1991; Nanni & Johari, 1989; Ramakrishnan, 1988; Ramu, 1983; Ramakrishnan et al., 1980; Edgington et al., 1974; Lankard, 1972). Overall, steel fibres were found to have a much greater effect on the flexural strength of SFRC than on either the compressive or tensile strengths, with increases of more than 100 % having been reported (Johnston, 1974). Furthermore, the

various surveys have shown that the two most important factors affecting the flexural strength are the volume fraction and the aspect ratio of the fibres, with increases in these parameters leading to higher flexural strength. Other parameters such as fibre orientation and bond strength have also been investigated (Hannant, 1978) but it was reported that they did not significantly influence the flexural strength of SFRC. Many of these investigators reported a general trend suggesting that flexural strength increases linearly with both fibre volume and the aspect ratio of the fibres, although a unique relationship could not be established between these parameters due to the wide variability in the published data, such as differences in matrix strength, bond strength or fibre orientation. More recent studies (Soroushian & Bayasi, 1991; Ramakrishnan, 1988; Sri Ravindrarajah & Tam, 1984; Ramu, 1983) have suggested that deformed (hooked) steel fibres produce similar increases in flexural strength but at lower fibre volumes due to their improved bond characteristics.

Most researchers (Bayasi & Zeng, 1993; Litvin, 1985; Zollo, 1984; Hanna, 1981; Ramakrishnan et al., 1987) have concluded that polypropylene fibres have either little or no effect on the flexural strength, although Alwahab & Soroushian, (1987) reported significant improvements on the flexural strength of PFRC. They have agreed however that the post cracking behaviour of PFRC is of much greater importance due to its ability to continue to absorb energy as the fibres pull out.

Limited experimental work has also been carried out on the flexural strength of GFRC (Marsh & Clarke, 1974). When using 12 mm long glass fibres, it was found that the flexural strength increased with increasing fibre volume of up to 2 %. They also used 38 mm long glass fibres in their study and these fibres generally produced higher flexural strengths for a given fibre volume than the 12 mm long fibres. However, their results on the effect of fibre length were not very consistent, possibly because of the conflicting effects of decreased workability and increased bond area.

2.13.2.4 Flexural toughness

As was implied in the previous sections, steel fibres are generally added to concrete not necessarily to improve the strength, but rather to improve its toughness or energy absorption. Like flexural strength, the volume fraction and the aspect ratio of fibres also affect the flexural toughness (Bindiganavile & Banthia, 2001; Barros & Figueiras, 1998;

Vondran, 1994; Beckett, 1990; Ramakrishnan, 1988; Ramu, 1983; Hannant, 1978). A few researchers have reported that fibres with better bond characteristics (i.e. deformed fibres, or fibres with greater aspect ratios) gave higher toughness values than smooth straight fibres at the same volume concentrations (Ramakrishnan, 1988; Ramu, 1983; Ramakrishnan et al., 1980).

Limited experimental work (Barr & Liu, 1982) has revealed that the addition of polypropylene fibres into the concrete mix generally increases the toughness of the material. A recent study (Sadegzadeh et al, 2001) confirmed this and also suggested that at low dosage rates (1 and 5 kg/m^3) glass fibres are less effective at imparting toughness when compared to the benefits delivered from steel and polypropylene fibres. However, at higher dosage rates (10 kg/m^3 or more) glass fibres outperformed the steel and polypropylene concretes in terms of their flexural toughness.

2.13.2.5 Impact resistance

Several authors have reported alternative techniques that may be used to quantify the impact resistance of concrete. These include explosive tests (Robins & Calderwood, 1978; Williamson, 1965) and projectile impact tests (Luo Xin et al., 2000; Balasubramanian et al., 1996) on structural members as well as standard Charpy tests on beams and cubes (Dellaripa & Reddy, 1987; Hibbert & Hannant, 1978; Edgington et al., 1974) and drop-weight test on cylinders, beams and slabs (Bindiganavile & Banthia, 2001; Eren et al., 1999; Banthia et al., 1998a; Ramakrishnan, 1988; ACI Committee 544, 1988b; Schrader, 1981; Swamy, 1974).

The Charpy and drop weight tests were used to assess the impact resistance of SFRC beams (Gopalatatnam & Shah, 1986; Gopalatatnam et al, 1984; Naaman & Gopalatatnam, 1983; Suaris & Shah, 1983). It was observed that the total energy absorbed by the SFRC beams can be as much as 40 to 100 times that of the corresponding unreinforced beams. It has also been reported that the type and volume of steel fibre are considerable influences on the impact resistance of the composite (Eren et al., 1999; Ramakrishnan, 1988; Ramakrishnan et al., 1980). The use of steel fibres with hooked ends has a far greater influence in this context than increasing the fibre volume (Ramu, 1983; Ramakrishnan et al., 1980). In contrast, Bindiganavile & Banthia (2001) concluded that the flexural strength of concrete reinforced with steel and polymer fibres is higher under impact load regardless

of fibre type and geometry. They also found that the toughness is high under impact but only for concrete reinforced with polymeric fibres. Sadegzadeh et al (2001) reported that the impact resistance of GFRC is superior to that of PFRC and SFRC at higher fibre volumes.

Though it is generally accepted that the strength of FRC under impact is significantly higher than that of plain concrete, it is clear from the above studies that the reported improvements in impact resistance vary widely. It is likely that some of the particular improvement is a function of the test procedure (i.e. energy and velocity of impacting mass, the size of specimen, the rigidity of the supports, the type of test, and even the definition of failure) rather than of the material descriptors.

2.13.2.6 Abrasion resistance

The influences of steel, polypropylene and glass fibres on the abrasion resistance of concrete were discussed in detail in Section 2.9.7.

2.13.2.7 Shrinkage cracking and creep

The reported data on the shrinkage or creep of FRC are not only limited but also contradictive. Hannant (1978) reported that the shrinkage of concrete over a period of 3 months on specimens subjected to various curing environments was not affected by the presence of steel fibres. Similarly, comprehensive creep tests were carried out over a loading period of 12 months and it was reported that the addition of steel fibres in concrete did not significantly reduce the creep strains of the composite (Hannant, 1978). Though Magnat & Azari (1985b) showed that steel fibres have only a small effect on the creep of concrete, others have however reported (Grzybowski & Shah, 1990; Magnat & Azari, 1988; Magnat & Azari, 1984b) that deformed fibres may lead to reductions of up to 40 % in free shrinkage of the concrete. It was suggested (Magnat & Azari, 1988) that the restraint depended on the fibre geometry, with deformed fibres being more effective than straight, smooth fibres. Magnat & Azari (1988) have developed an equation (2.21) to predict the shrinkage of SFRC, in terms of the shrinkage of the corresponding plain concrete.

$$\varepsilon_{fs} = \varepsilon_{os}\left(1 - 2.45\mu V_f \frac{l}{d}\right) \tag{2.21}$$

Where ε_{fs} = free shrinkage of SFRC

ε_{os} = free shrinkage of plain concrete

μ = coefficient of friction between the fibres and the concrete (ranging from 0.04 for plain fibres to 0.12 for deformed fibres)

V_f = volume (%) of fibres

l/d = aspect ratio

It is believed (Bentur & Mindess, 1990) that free shrinkage is not an appropriate measure of the fibre efficiency in reducing shrinkage problems. More important than any reduction in shrinkage strain is the reduction in the cracking associated with restrained shrinkage. A few researchers (Banthia et al., 1996; Grzybowski & Shah, 1990; Swamy & Stavrides, 1979; Malmberg & Skarendahl, 1978) have suggested that, for restrained shrinkage, steel fibres reduce the amount of cracking and the crack widths.

Balaguru & Ramakrishnan (1988) reported that the shrinkage strains were generally smaller for SFRC as compared to plain concrete. Even though they concluded that the differences were more distinct after about 150 days, they were not significant. The shrinkage rate decreased more rapidly in the SFRC, so while the shrinkage ceased after approximately 500 days for SRFC it continued up to 600 days for plain concrete. Therefore, it is apparent that shrinkage characteristics of fibre reinforced concrete are a little more favourable that those of plain concrete. It was also reported (Balaguru & Ramakrishnan, 1988) that the creep strains were consistently higher for SFRC and the differences were more pronounced for the mixtures with higher cement content and lower water-cement ratio.

To enhance the concrete matrix, Sun et al. (2001) mixed steel fibres of different types and sizes with PVA fibres and polypropylene fibres and these hybrid fibres were efficient in reducing shrinkage strains. Their experimental results have shown that when the concrete matrix was kept the same, the shrinkage-resisting effect of hybrid fibres was primarily related to factors such as fibre volume fraction, fibre size and fibre elastic modulus. Sun et al. (2001) have shown that irrespective of the fibre type, shrinkage strains reduced with increased fibre volume fraction. Furthermore, the combined effect using both steel fibre and PVA fibre was more effective in reducing shrinkage than the separate use of either steel fibre or polypropylene fibres.

2.13.3 Formulation and fabrication of fibre reinforced concrete

Compared to plain concrete, FRC mixes generally have higher cement and fine aggregate contents and usually smaller coarse aggregates (Bentur & Mindess, 1990; ACI Committee 544, 1986). As a result, the mix design procedures that apply for conventional concrete may not be entirely applicable to FRC. Very often pozzolans such as fly ash are added to reduce the quantity of cement, with an optimum 25 – 35 % replacement. Furthermore water reducing admixtures, such as superplasticizers, are commonly used in conjunction with air entrainment to improve the workability of high fibre volume mixes and to control shrinkage (ACI Committee 544, 1986; Swamy, 1974). The composition ranges for typical normal weight SFRC mix is shown in Table 2.5. Most of the discussion in this section applies to steel fibres in concrete due to the limited amount of such information concerning polypropylene and glass fibres mixes.

Table 2. 5 *Range of proportions for normal weight fibre reinforced concrete (ACI Committee 544, 1986)*

Materials	Mortar	9.5 mm maximum aggregate size	19 mm maximum aggregate size
Cement (kg/m^3)	415 – 710	355 – 590	300 – 535
w/c ratio	0.3 – 0.45	0.35 – 0.45	0.40 – 0.50
Fine/coarse aggregate (%)	100	45 – 60	45 – 55
Entrained air (%)	7 – 10	4 – 7	4 – 6
Fibre content (%) by volume			
smooth steel	1 – 2	0.9 – 1.8	0.8 – 1.6
deformed steel	0.5 – 1.0	0.4 – 0.9	0.3 – 0.8

2.13.3.1 Mix design

As was pointed out in Section 2.13.1.1 several procedures are available for proportioning SFRC mixes, with emphasis on good workability (Killeen & Dalgleish, 1997; Schrader, 1989; ACI Committee 544, 1986; Ahuja et al., 1982; Ounanian & Kesler, 1976; Schrader & Munch, 1976; Edgington et al., 1974). However, in many projects, steel fibres in particular have been added without any changes to the conventional mixture proportions although, where large percentages of fibre volume are used, some adjustments are advisable (ACI Committee 544, 1986; Swamy, 1974). To provide better workability, FRC demands more paste and in essence a greater proportion of fine material than plain concrete. Normal concrete contains between 25 – 35 % of paste of the total volume of concrete, whereas for FRC this becomes 35 – 45 %, depending on the fibre geometry and

fibre volume (ACI Committee 544, 1993; Swamy, 1974). In early applications, coarse aggregate larger than 19 mm was not recommended for SFRC. However, a few applications have successfully used aggregate as large as 38 mm (Tatro, 1987; Rettburg, 1986).

Aggregate size and volume

According to Hannant (1978) when steel fibres are introduced to concrete rather than mortar, they are not separated by fine grained material which can move easily between them, but by particles which will often be of a larger size than the average fibre spacing, assuming the fibres were uniformly distributed. This leads to bunching and greater interaction of fibres in the spaces between the large aggregate particles, and this effect becomes more pronounced as the volume and maximum size of the particles increases (Figure 2.13).

Figure 2. 13 Effect of aggregate size on fibre distribution within a square of side length = fibre length (40 mm), (Hannant, 1978)

Figure 2.13 shows that uniform fibre dispersion is more difficult to achieve as the aggregate size increases from 5 mm to 10 mm to 20 mm. It should be stressed, however, that the above is a simplified diagram. In reality, the fibre and aggregate dispersion is three dimensional and there may be up to 200 fibres in any given cube of mortar of side length equal to the fibre length before fibre interaction becomes excessive (Hannant & Edgington, 1974).

Fibre length and diameter

Edgington et al. (1974) have shown that the fibre aspect ratio has a crucial influence on the volume of fibres which can be included in the mix while retaining relatively easy

compaction. Hannant (1978) suggested that if a number of long thin fibres of aspect ratio greater than 100 are shaken together, they will interlock to form a mat or a type of bird's nest from which it is very difficult to dislodge individual fibres by vibration alone. On the other hand, short stubby fibres of aspect ratio less than 50 are not able to interlock and can easily be dispersed by vibration. Similar effects were observed when fibres were dispersed in mortar or concrete (Hannant, 1978).

Fibre content

The factors affecting the maximum quantity of a particular fibre which can be included in a mix whilst maintaining adequate workability for site compaction have already been discussed in Section 2.13.1.1.

Edgington et al. (1974) established a simplified equation which enables an approximate estimate to be made of this fibre content for mixes containing aggregates of normal density.

$$W_f < \frac{600(1 - A_g)}{l/d} \tag{2.22}$$

Where $W_f =$ weight of steel fibres, as a percentage of the concrete matrix, which can be compacted with normal site techniques

$A_g =$ $\dfrac{\text{weight of aggregate greater than 5 mm}}{\text{total weight of concrete}}$

$l/d =$ fibre aspect ratio

Swamy (1974) suggested that for SFRC, fibre addition in excess of 4 % by volume is difficult to achieve, but most practical mixes rarely contain more than 2 % by volume of fibres. For PFRC, volume fractions of polypropylene less than 1 % have been used (Knapton, 1999; Ritchie & Al – Kayyali, 1975; Dardare, 1975; Majumdar, 1975; Nanda & Hannant, 1969). Marsh & Clarke (1974) used glass fibres in concrete during their research work at volumes between 0.5 – 2.5 %.

Plasticising admixtures and cement replacements

The plasticity of the mix is important to insure the proper dispersion of fibres. The cohesive properties of the matrix can be improved by the incorporation of liquid

admixtures or pfa or other crushed fines, which also reduce the inter-particle friction between the steel fibres, and between the steel fibres and aggregates (ACI Committee 544, 1986; Swamy, 1974).

The introduction of superplasticizers has lead to trials to determine whether a higher volume of steel fibres can be included in a given mix by the use of these materials. It was found (Hannant, 1978) that, although compaction is easier for a given steel fibre volume, the maximum fibre volume which the mix will carry is not greatly altered. This is because the cement paste becomes more fluid with the addition of superplasticizers and tends to run out of the fibre clusters as they start to form. Segregation or clumping of steel fibres therefore occurs at about the same fibre volume as for the unplasticised matrix (Hannant, 1978). Consequently, superplasticizers should be used mainly as an aid to increase the workability of standard mixes, or to reduce the w/c ratio of a high workability mix in order to achieve adequate strength and durability in the hardened state (ACI Committee 544, 1986).

It has been shown (Kesler, 1972; Kesler & Schwarz, 1972) that SFRC mixes with improved workability and without any loss in strength can be obtained if a portion of the cement is substituted by fly ash, up to 50 % of the cement content, along with a water-reducer and air entrainment. The presence of fly ash also retards setting, which aids placing and finishing, and it provides a mix of higher paste content with a lower cement content. Tests have also shown that the presence of pfa reduces the required water content while maintaining strength and workability.

2.13.3.2 Fibre addition, dispersion and mixing

It is important that fibres are dispersed uniformly throughout the concrete mix in order to prevent fibre balling. A variety of methods are available for introducing steel fibres into the concrete mixer, either to the dry constituents or to the wet mix, and these have been described in detail by several authorities (Cao & Chung, 2001; Knapton, 1999; Maidl, 1995; ACI Committee 544, 1993; Unwalla, 1982; ACI Committee 544, 1986; Swamy, 1974). These techniques range from charging the aggregate conveyor with fibres (Gregory et al., 1975; Gray & Rice, 1972), sieving fibres directly into the mixer drum (Johnson & Nephew, 1975), sieving the fibres and blowing them into the drum (McCurrich & Adams, 1973) or alternating sieves for laboratory use (Edgington et al., 1974). The development of

fibres glued together with a water-soluble adhesive, into units similar to staples (Bekaerts NV Ltd, 1998), enables the fibres to be dispersed into the mixer as a normal aggregate and subsequently they separate in the mixing process.

According to (Hannant, 1978) the critical factor in whatever technique is used for steel fibre addition is that the fibres reach the mixer individually and be immediately removed from the point of entry by the mixing action. Segregation and balling of steel fibres during mixing is influenced by the fibre geometry, the relative volume proportions of fibre and coarse aggregate, the mixing procedure and the duration of mixing (Unwalla, 1982). It is essential that no fibre balls are introduced into the mixer as these are unlikely to be broken by the mixing action (Unwalla, 1982; Hannant, 1978).

Experience in mixing large batches of polypropylene fibres is limited (Zonsvelt, 1976; Williamson, 1966; Williamson, 1965; Goldfein, 1963). However, the ACI Committee 544 (1986) suggested that for small batches in the laboratory, polypropylene fibres can be added to the rotating drum charged with cement, water and aggregates. The same procedure can be used for large batches, but a method of blowing the fibres into a previously charged, rotating drum is preferred. Satisfactory mixes can also be achieved by adding the fibres along with the fine and coarse aggregate to a weigh hopper, and then charging the mixer by a conveyor belt. The cement and water should be added last and the mixing time can remain the same as for ordinary concrete (Knapton, 1999; ACI Committee 544, 1986).

Glass fibres have less tendency to ball compared to steel fibres. According to the ACI Committee 544 (1986) the following procedures may be used:

- For laboratory mixes, the glass fibres may be added directly to the mix containing all the other ingredients, including water.
- For batch plant and ready-mixed concrete trucks, the conventional mixing procedures should be followed with the glass fibres added last. Glass fibres can be dumped directly, or chopped and blown into the truck.

2.13.3.3 Placing, finishing and curing

Conventional tools, equipment and procedures may satisfactorily be used for placing and finishing SFRC (Knapton, 1999; Killeen & Dalgleish, 1997; ACI Committee 544, 1993; Unwalla, 1982; ACI Committee 544, 1986; Swamy, 1974). The fibrous nature of the mix makes the use of shovels very difficult, therefore forks and rakes may be used to facilitate manual handling of the mix. Electrically powered surface vibration, hand-floating and power-operated surface finishings can also be satisfactorily used with SFRC (ACI Committee 544, 1993; Swamy, 1974). Textured surface can be formed by brooming with a stiff brush, but this should be delayed as long as possible to prevent pulling of fibres to the surface and uneven drying (ACI Committee 544, 1993; Unwalla, 1982; Swamy, 1974). It is good concrete practice to place concrete as near to its final position as possible. This is even more true for SFRC because of its reduced flow characteristics (Unwalla, 1982; Swamy, 1974).

Depending upon the workability of the mix and the placing and finishing procedures, some steel fibres may still protrude from the concrete surface. However, with adequate mix design and compaction, the protruding fibres may be minimised (Swamy, 1974). Those fibres that are not firmly embedded in the concrete soon break away under the action of weathering and traffic. SFRC should be cured and protected by the same methods and techniques as plain concrete. Faulty or inadequate curing methods can produce the plastic and shrinkage cracking encountered in conventional concrete (Knapton, 1999; ACI Committee 544, 1993; Swamy, 1974).

PFRC mixes can be transported by normal methods and flow easily from the hopper outlet. No special precautions are necessary when pouring and PFRC will flow around an obstruction such as reinforcement in the same manner as a conventional concrete mix of similar proportions. Conventional means of tamping or vibration can be used to provide the necessary compaction (Knapton, 1999). Like SFRC, PFRC must be cured and protected by the same methods and techniques as conventional concrete. Placed PFRC may be floated and trowelled using all normal hand and/or power plants. Occasional fibres protruding through the surface will again quickly wear away (Knapton, 1999).

2.14 Fibres as a reinforcing material for concrete floors

This is by far the most popular application of FRC at present (Banthia, 1997). In fact, nearly 65 % of the fibres produced world-wide is currently used in industrial floors, road pavements and other slabs-on-grade.

In the European industrial building industry, steel and polypropylene fibres have been used in place of conventional reinforcement for the past 20 years (Tantall & Kuitenbrouwer, 1992). In the UK with the advent of fast-track systems in the construction industry, concrete flooring has had to meet quicker construction programmes. With the use of laser screeders, fibres are often specified instead of conventional mesh because of the inconvenience of positioning individual mats of mesh immediately in front of the laser screeding machine as it progresses. These machines cannot construct long strip mesh reinforced floors effectively, because both the mesh and the formwork impede the machine (Banthia, 1997; Knapton, 1999). Consequently, fibre based concrete is often specified for laser screeded floors (Robinson et al., 1991; Banthia, 1997; Knapton, 1999). It has been shown that industrial floors are the kind of structures where the application of SFRC is advantageous mainly because it has the ability to support loads even after the formation of cracks (Nanni & Johari, 1989; Robinson et al., 1991; Tantall & Kuitenbrouwer, 1992; Banthia, 1997; Barros & Figueiras, 1998).

The construction and use of SFRC floors has grown steadily over the past 20 years in many European countries like Germany, Belgium and the Netherlands as well as other parts of the world like Australia, Canada and the USA (Anonymus, 1987; Robinson et al., 1991; Tantall & Kuitenbrouwer, 1992; Falkner et al., 1995; Falkner & Henke, 1998). However, only a few studies have been devoted specifically to SFRC floors (Robinson et al., 1991; Tantall & Kuitenbrouwer, 1992; Falkner et al., 1995; Bischoff et al., 1997; Masuya et al., 1997; Barros & Figueiras, 1998; Falkner & Henke, 1998) and these have been mostly carried out on the initiative of the fibre manufacturer (Tantall & Kuitenbrouwer, 1992). In addition, the above researchers did not pay particular attention to the abrasion resistance of concrete.

Limited research findings have been published (Hannant, 1994; Hardmeier, 1997; Cian & Della Bella, 2001) of investigations concerning floors reinforced with polypropylene or glass fibres but, like the SFRC floor research programmes, they did not cover concrete properties like abrasion and/or impact resistance. Hannant (1994) examined the uniaxial

tensile forces that can be sustained at 7 days by various types of steel and polypropylene across cracks pre-formed at 24 hours. He concluded that fibres may be used in industrial ground floor slabs to improve such properties of fresh concrete as bleeding or shrinkage cracking. They are also effective in controlling the crack width at induced joints where the crack is caused by restrained contraction forces (Hannant, 1994). Hardmeier (1997) studied the effect of AR glass fibres on floor screeds and concrete and concluded that the properties of concrete with respect to early crack formation and strength development are markedly improved. Hardmeier (1997) noted that in contrast to synthetic or steel fibres they exhibit better workability characteristics. Cian & Della Bella (2001) demonstrated that GFRC precast floor slabs can withstand similar design loads to conventional concrete slabs, and have the added advantage of low weight (less than half that of standard floors).

12.15 Overview

It is evident, from the literature review presented in this chapter, that there are several areas which require further investigation. Although wear and wear mechanisms have been extensively researched; the work has predominantly involved the study of metals. The examination of wear in brittle materials has been less extensive, especially the aspects of fatigue and cyclic loading. In particular the microscopic effects of rolling contact and fatigue in concrete are little understood. Section 2.14 highlighted the need to explore the several types of available fibre reinforcement and to establish their effects on the properties of concrete floors. A thorough examination of the applications of these materials is required before performance specifications can be proposed.

Chapter 3: Scope of investigation

3.1 Project goals and objectives

As previously identified in Section 1.2 of Chapter 1, the general goals and objectives of the work presented in this report may be summarised as follows:

- To carry out comparative tests of the three abrasion testers (i.e Aston abrasion tester – AT; Commercial abrasion tester – CT; and Original British Cement Association abrasion tester – BCAT) and to select the one that will produce the most reliable and repeatable results for use in this project.
- To determine the effect of steel, polypropylene and glass fibres on the abrasion resistance of concrete floors and to assess their role in the wear process. This is to include observations on both the macroscopic and microscopic scales.
- To simulate site practices whenever possible so that the information obtained is representative of the materials used by the industry.
- To determine the influence of several curing regimes on the abrasion resistance of fibre reinforced concrete floors, again with observations at the macroscopic and microscopic scales.
- To investigate the possibility of assessing abrasion resistance through alternative indirect and non-destructive methods.
- To study the effect of the presence of curing compound on the abrasion resistance of fibre reinforced concrete floors.
- To develop a new testing head for the effective assessment of the abrasion resistance of newly build/heavy-duty concrete floors.

3.2 Concrete mix design

During the comparative investigations of the three accelerated abrasion test apparatus three concrete mixes were used, namely B4, B5, and B6, with free water-cement ratios 0.44, 0.52 and 0.65 respectively. The main reason for using three different water-cement ratios

in this part of the programme was to asses the sensitivity of the different abrasion testers to variations in the mix design. These mixes were adopted from a previous study (Sadegzadeh, 1985) so that the results obtained, especially with reference to the AT, could be compared to the results achieved during this previous investigation (Sadegzadeh, 1985).

In the main laboratory programme, which investigated the influence of steel, polypropylene and glass fibres on the abrasion resistance of concrete, three additional mixes were used – A1, A2, and A3, again with free water-cement ratios of 0.44, 0.52 and 0.65 respectively. These water-cement ratios were used so that the investigation would include the influence of water-cement ratio on the other variables under investigation. These were considered to represent the range of water-cement ratios associated with the construction of concrete floors. The main difference of these latter three mixes, compared to the former ones, was the inclusion of fibre reinforcement.

Note that the composition of all six mixes is presented in Appendix A. These are based on trial mixes in which particular emphasis was placed on the measurement of their slump and compressive strength values. A summary of these results is presented in Table A.1 of Appendix A.

3.3 Comparative investigations of three accelerated abrasion test apparatus

At the start of the investigation the School of Engineering and Applied Science possessed two abrasion testers:

- Aston abrasion tester – AT, (the portable equipment, which was developed by Sadegzadeh, 1985 for measuring the abrasion resistance of concrete. It was based on the original design developed at the then Cement and Concrete Association (1980). This has routinely been used for both laboratory work and in situ testing) and
- Commercial abrasion tester – CT (A commercially fabricated tester purchased from Wexham Developments Ltd).

A third tester was loaned from Wexham Developments Ltd and this is based on the original design developed at the Cement & Concrete Association, now known as the British Cement Association – BCAT. It was deemed important to investigate these existing apparatus to determine whether they produced reliable and repeatable results and hence to establish whether they should be used for the main investigations of this study.

In this programme a total of 94 slabs, 1.0 x 0.5 x 0.1 m, were tested using the three abrasion testers.

3.4 Macro-study of abrasion resistance of fibre reinforced concrete

In this study the influence on abrasion resistance of three major factors was investigated. These were:

- Fibre type – steel, polypropylene and glass.
- Fibre shape and length – steel fibres only.
- Curing regimes – Air curing (AR), Plastic Sheet (PS) and Curing Compound (CC).

In this study a total of 210 slabs, of 1.0 x 0.5 x 0.1 m in size were tested using the AT.

3.5 Micro-structural study of abrasion resistance of fibre reinforced concrete

Whilst the macro-study would provide evidence of changes in the abrasion resistance of concrete, it would not provide information on the microstructure of concrete. This is considered important in developing an explanation of the behaviour on the macro-scale. The main purpose of the micro-structural study was, therefore, to examine the microstructure of the various concretes to seek supporting evidence for developing explanations of the behaviour observed in the macro-study. The investigation of microstructure of concrete was primarily performed using three techniques: microhardness, mercury intrusion porosimetry and petrographic examination.

3.6 Indirect and non-destructive methods for predicting abrasion resistance of fibre reinforced concrete

In reality, the accelerated abrasion test is perceived to be a destructive test, because a circular groove is formed on the concrete surface, and so non-destructive techniques were considered as alternatives for assessing the abrasion resistance of concrete, by their nature such assessments would be indirect. Five methods, which have been used for assessing the quality of in-situ concrete, were investigated: the Initial Surface Absorption Test, BRE

Screed Test, Ball Cratering, Scratch Test and Base Hardness Test. This study was carried out on the slabs used in the macro-study. Measurements made with these non-destructive methods were related to the abrasion values determined in the macro-study.

3.7 Abrasion resistance of heavy-duty industrial concrete floors

The accelerated abrasion tester was initially developed to assess the abrasion resistance of floors in medium industrial environments (Sadegzadeh, 1985). In this part of the study testing heads deemed to be more aggressive than the standard one (rolling wheels) were developed and subsequent testing was undertaken to assess their suitability for assessing the abrasion resistance of heavy duty industrial floors. Three testing heads were investigated namely dressing wheels, flat spot wheels and diamond electroplated wheels. These tests were carried out on slabs constructed in the laboratory using typical industrial concrete mixes. The experimental study was extended to investigate the effect of the presence of curing compound on the abrasion resistance of such concrete floors and limited tests were carried out on both laboratory samples and in situ floors.

Chapter 4: Engineering properties of the test materials

4.1 Introduction

This chapter presents the details of the materials used to manufacture the test specimens used in this study. The methods adopted for material and specimen preparation and/or fabrication are not described in this section but are collectively and individually outlined in Chapters 5 and 6.

4.2 Cement

Ordinary Portland Cement supplied by Blue Circle was used throughout the test programme. All the cement was from a single batch acquired at the beginning of the project. The detailed chemical analysis of the cement is given in Table B1 of Appendix B.

4.3 Aggregate

4.3.1 Coarse Aggregate

The coarse aggregate was Bunter quartzite and was supplied by the Weeford Quarry, at Sutton Coldfield. This was used throughout the test programme. The 20 – 10 mm fraction was natural and the 10 – 5 mm fraction had been crushed.

4.3.2 Fine Aggregate

The fine aggregate was also supplied from Weeford Quarry and was used throughout the test programme. The deposit is nominally Sherwood Sandstone and the material's petrological type is defined as Quartz / Quartzite. The entire fine aggregate came from a single batch acquired at the beginning of the project. The chemical analysis of Weeford sand is given in Appendix B, Table B.2. Further the fine aggregate was blended to conform

to the grading limits for an M sand (See Table B.3 in Appendix B) as given in BS 882 (1992). The overall limits and the limits for coarse, medium and fine sands are given in Appendix B, Table B.4. Both the coarse and fine aggregates were washed at the source and dried at the laboratory before use.

4.4 Reinforcement

4.4.1 Steel bars

Mild steel reinforcing bars of 10 mm diameter were used to reinforce the plain concrete slab specimens to minimise handling stresses. A more detailed description is given in Chapter 5.

4.4.2 Steel fibres

Four different shapes of steel fibres were used and these may be described as crimped, longitudinally twisted (triangular cross-section), flattened ends (round shaft) and straight stainless-steel. These are as presented in Plates 4.1, 4.2, 4.3, and 4.4 respectively and their properties are listed in Table B.5 of Appendix B.

Plate 4. 1 *Crimped steel fibre*

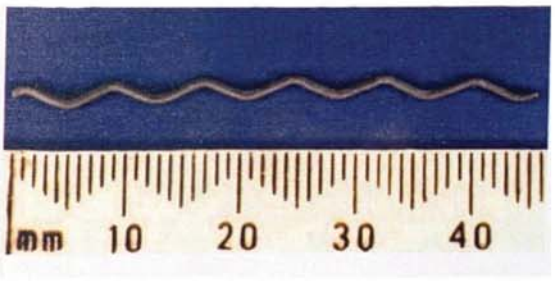


Plate 4. 2 *Twisted steel fibre*

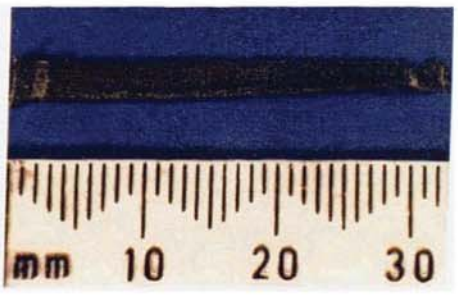


Plate 4. 3 *Flattened ends steel fibre*

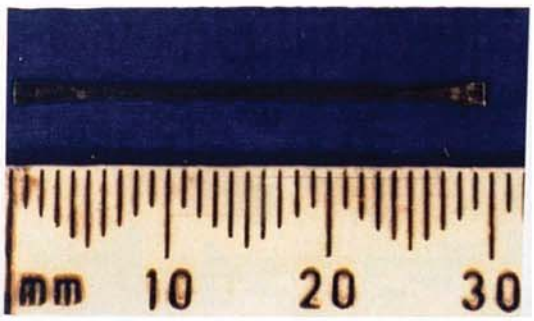
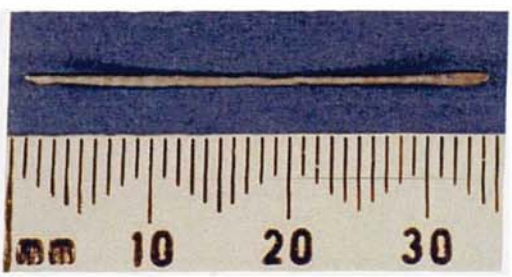


Plate 4. 4 *Straight stainless steel fibre*



4.4.3 Polypropylene fibres

In addition to the steel fibres it was deemed important to include polypropylene fibres in this investigation. Two types were used as shown in Plates 4.5 and 4.6 and their properties are given in Table B.6 of Appendix B.

Plate 4. 5 *Polypropylene fibres*

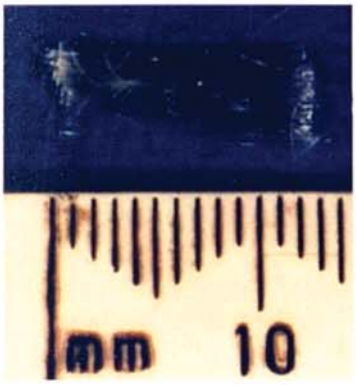
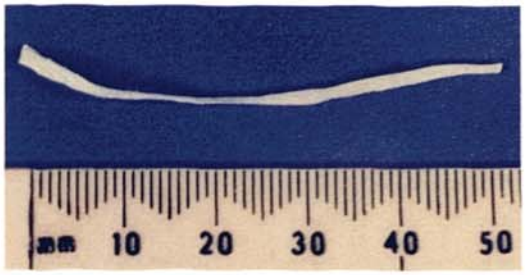


Plate 4. 6 *Polypropylene – polyethylene fibre*



4.4.4 Glass Fibres

Two types of glass fibres were also used and may be described as high performance and high dispersion alkali resistant glass fibres. These are as shown in Plates 4.7 and 4.8 respectively and their properties fibres are given in Table B.7 of Appendix B.

Plate 4. 7 *High performance glass fibres*

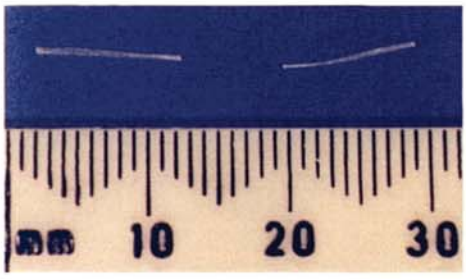
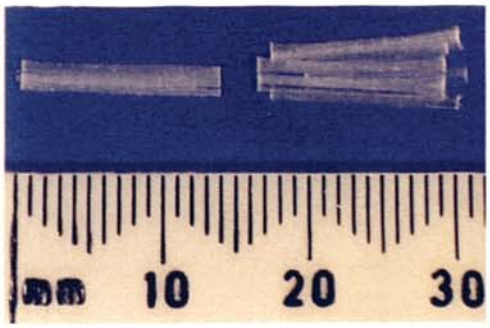


Plate 4. 8 *High dispersion glass fibres*



4.4.5 Hybrid fibres

The blend of steel and polypropylene fibres was a proprietary and is shown in Plate 4.9, it was a Dramix Duo 100 supplied by Tinsley Wire Ltd. Its properties are given in Table B.8 of Appendix B.

Plate 4. 9 Blend of steel and polypropylene fibres

4.5 Water

All concrete specimens were prepared using tap water.

4.6 Superplasticizing admixture

Glenium 51, a superplasticizing admixture, was added to a limited number of the concrete mixes containing low and high of fibre volumes in order to study its effect on the abrasion resistance of concrete. Glenium 51 is an admixture based on modified polycarboxylic ether, and is free from chloride and low alkali (Feb MBT, 1997). The technical data and typical properties of this product are as given in Appendix B, Table B.9.

4.7 Curing compound

One of the most widely used curing compounds employed to cure concrete floors was adopted and used to cure selected concrete slab specimens. It is commercially known as "Concure WB" and is a water based concrete curing compound based on a low viscosity wax emulsion. It is supplied as a white emulsion, which forms a clear film on drying. When first applied to a fresh cementitious surface the emulsion breaks to form a continuous, non-penetrating white-coating. This dries to form a continuous clear film, which provides a barrier to moisture loss, ensuring more efficient cement hydration

(Fosroc Ltd, 1998). Fosroc Ltd provided this product and a data sheet is presented in Table B.10 of Appendix B.

Chapter 5: Comparative investigations using three accelerated abrasion testers

5.1 Introduction

Aston University and the Cement and Concrete Association (C & CA, now the British Cement Association, BCA) have carried out research work on the abrasion resistance of concrete floors for many years (Kettle, Vassou & Sedegzadeh, 2000). Through their individual and co-current work, the two organisations developed a standard method for testing concrete floors for abrasion resistance (Vassou, Kettle & Sadegzadeh, 2001). The original design of the testing apparatus and method have been adopted by the industry. Subsequently a commercially developed apparatus has become available and this has been incorporated in the latest edition of the BS 8204: Part 2: 1999.

It was deemed important to investigate the three existing abrasion apparatuses to determine whether they produce reliable and repeatable results. Even though the development of the commercial abrasion apparatus was based on the design of the original abrasion machines, it has essential operational differences and so it was important to establish whether it produced results compatible with those from the other two machines which had been used in many previous studies. This chapter provides detailed experimental data from this investigation and discusses whether the results from the commercial abrasion tester are fully compatible with those obtained from the original machines that were used to establish the performance criteria in the BS 8204: Part 2: 1999.

5.2 The initial investigation

The main purpose of this initial investigation was to study the performance of three existing abrasion testers and to select the most appropriate one to be used for the main investigations of this project, in terms of reliability and compatibility with the results from previous studies. There are two means by which this objective may be achieved, namely: (i) experimental testing of sample slabs for direct numerical comparisons of the three

testers and (ii) statistical analysis of these data for further comparison. It must be noted that modification of any of the existing apparatus was outside the scope of this project.

The three existing accelerated abrasion testers considered were:

- Aston abrasion tester – AT, (the portable equipment, which has been developed by Sadegzadeh (1985), for measuring the abrasion resistance of concrete. This was an exact replica of the original C & CA design (1980) and is currently the property of Aston University)
- Commercial abrasion tester – CT (A commercially manufactured tester purchased from Wexham Developments Ltd, currently the property of Aston University).
- British Cement Association abrasion tester – BCAT (The original C & CA tester (1980) loaned by its current owners, Wexham Developments Ltd)

In this programme a total of 94 sample slabs, measuring 1.0 x 0.5 x 0.1 m, were tested using the three abrasion testers. These tests were performed on each slab, giving a total of 282 tests.

5.3 Description of basic apparatus

In this section each one of the three abrasion testers is collectively and individually described. This is to clarify both the differences and similarities of the physical parameters of the three testers.

5.3.1 Aston abrasion tester

Sadegzadeh (1985) using specifications that were provided by the BCA constructed the Aston abrasion tester (Plate 5.1). This tester was a replica of the prototype built originally at the C & CA, now BCA (See section 5.3.3). The Aston abrasion tester produces accelerated wear by means of its three especially hardened steel wheels (KEA 180) attached to a rotating circular steel plate and which are free to rotate on their individual axles. The plate is connected to a shaft, driven by an electric motor (0.09 kW, 178 rpm), so that the wheels abrade a circular path over the concrete surface (Plate 5.8). The circular path is 20 mm wide, and the depth is measured to determine the extent of abrasion. While the test is running the abrasion tester is held in position by means of two bolts inserted into

the concrete slab through holes in the feet of the tester legs. These prevent any lateral movement of the tester, but do not restrict vertical movement as the wheels pass over the concrete surface.

Plate 5. 1 *Aston abrasion tester*

Plate 5. 2 *Commercial abrasion tester*

5.3.2 Commercial abrasion tester

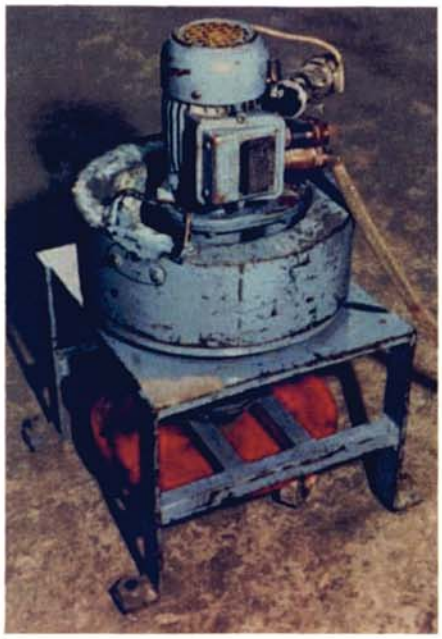
The Commercial abrasion tester (Plate 5.2) is commercially manufactured and was purchased from Wexham Developments. Overall it is very similar to the other two testers and again consists of three 75mm diameter by 20mm wide hardened steel wheels mounted tangentially on a circular steel carrier plate. The wheels are fitted such that they are free to rotate. The carrier plate is connected to a single-phase electric motor, which is calibrated to run at approximately 190 rpm mounted in a steel frame (Wexham Developments, 1998).

5.3.3 BCA abrasion tester

The Aston Abrasion tester is identical to the BCA abrasion tester (Plate 5.3). However whilst both collars were the same weight (40 kg), their dimensions were different with the diameter of the Aston tester collar being greater than that of the BCA collar (see Section 5.3.4). A previous study by Sadegzadeh (1985) revealed that there was no significant difference in the depth of abrasion obtained due to this different test format. As a result it

was suggested that there was no significant difference between the two abrasion testers and that the shape of the collars was not a significant factor.

Plate 5. 3 Original British Cement Association abrasion tester



5.3.4 Comparison of physical parameters of the three abrasion testers

Even thought the three existing abrasion apparatuses (Plates 5.1, 5.2 and 5.3) are theoretically identical it was found that in terms of their physical parameters they manifest both differences as well as similarities (Table 5.1). To clarify these differences and similarities, their physical parameters where divided into three groups, (a) general frame features, (b) wheels and (c) electric motor.

With regards to the general frame features, it was found that the height of the AT and the BCAT is the same at 570 mm whereas CT is 10 mm higher at 580 mm. In addition, the net weight of the AT and the BCAT is the same at 80 kg whereas the CT is lighter at 77.2 kg. Thus even though the weights of the machine frames are identical at approximately 40 kg each, the weight of the collar differs. That is, the collar weight for AT and BCAT is the same at 40 kg, the CT collar weighs only 37.6 kg. Further, the external and internal diameters of the collar for the AT are 380 and 280 mm respectively, whereas the external and internal diameters of the collar for the BCAT and the CT are the same at 300 and 200 mm respectively (Vassou, Kettle & Sadegzadeh, 2001).

Table 5. 1 Comparison of the three accelerated abrasion testers: Physical parameters (Kettle, Vassou & Sedegzadeh, 2000)

Parameter	Aston abrasion tester	Commercial abrasion tester	BCA Abrasion Tester
General frame features:			
Height of machine	570 mm	580 mm	570 mm
External diameter of abrasion path	225 mm	225 mm	225 mm
Internal diameter of abrasion path	205 mm	205 mm	205 mm
Thickness of abrasion path	20 mm	20 mm	20 mm
Net Weight of machine	80 kg	77.2 kg	80 kg
Weight of machine body without the collar	40 kg	39.6 kg	40 kg
Weight of collar	40 kg	37.6 kg	40 kg
External diameter of collar	380 mm	300 mm	300 mm
Internal diameter of collar	280 mm	200 mm	200 mm
No. of revolutions in 15 min	2850 rev.	2850 rev.	2850 rev.
Wheels:			
Material	KEA 180 Steel	N/A	BD2 Steel
Diameter	75 mm	75 mm	75 mm
Thickness	20 mm	20 mm	20 mm
Hardening:			
Pre heat	750° – 800° C	N/A	750 – 800°C
Harden from	980° into oil	N/A	980 – 1030°C (air / oil)
Double temper from	500° – 520° C	N/A	500 – 520°C
Hardness	720 HV Min	710 HV Min	735 HV Min
Electric motor:			
Motor brand	Bauer (GB) Ltd.	Bauer (GB) Ltd.	Bauer (GB) Ltd.
Motor No.	GB 64747, 1990	GB 1043079/001, 1998	M4723242E, 1979
Type	G072AN-20ECK-143L	G072AN-20ECK-163L	ECK 54071143L
P_2	0.09 kW	0.18 kW	0.09 kW
n_2	190 rpm	190 rpm	190 rpm
n_1	1330 rpm	1330 rpm	1330 rpm
	50Hz	50Hz	50 Hz
cosϕ	0.56, 0.7 A	0.98, 3.4 A	0.56, 0.8 A
Grease	QTY 0.30kg		
Insul. C1	B	B	B
IP	65	65	65
IM	B5/1/A	B5/1/A	V1
Output	240 V	110 V	220 V

All three testers produce an abrasion path with external and internal diameters of 225 and 205 mm respectively, so the width of the abrasion path is 20 mm. It was also found that it takes all three a 15 minute period to perform 2850 revolutions. Even though it is believed that the wheels of all three machines were hardened under identical conditions, their harness varies slightly. The hardness for the AT wheels was measured as 720 HV Min, for the BCAT as 735 HV Min and for the CT as 710 HV Min. The AT and the BCAT have a similar 0.09 kW motor whereas the CT has a 0.18 kW motor, the input voltage for the AT and the BCAT was 240 V whereas it was 110 V for the CT.

One of the most important differences between the three apparatuses is the way in which the load is applied. The collars of the AT and the BCAT simply rest on the frame of the machines whereas the collar of the CT is actually fixed on the frame of the machine and so the vertical movement of this load is restricted. Overall the structure of the CT is more rigid than that of the other two apparatuses (Vassou, Kettle & Sadegzadeh, 2001).

5.4 Specimen fabrication

5.4.1 Mix Design

Three different concrete mixes were used and were selected to cover a range of water-cement ratios – 0.44 (Mix B4), 0.52 (Mix B5) and 0.65 (Mix B6). Full details of these mixes are presented in Appendix A. These mixes were adopted from a previous study (Sadegzadeh, 1985) so that the results obtained, especially with reference to the AT, could be compared to those earlier data. All mixing and sampling was carried out in accordance to the procedures given in BS: 1881: Part 125: 1986.

5.4.2 Fabrication of test slabs and cubes

The standard procedure adopted for the fabrication of the test slabs is similar to that used in previous studies (Sadegzadeh, 1985; Phitides; 1991 and Webb; 1996) and is summarised below:

Dimensions of test slab: The slabs were cast in a wooden mould, 2.05 x 1.60 x 0.1 m. The mould was internally subdivided to produce six test sections 1.0 x 0.5 x 0.1 m. The layout is illustrated in Figure 5.1 and is presented in Plate 5.4. The size of this mould enabled full use to be made of conventional powered plant. Prior to mixing the mould was coated with release oil to ease subsequent specimen removal.

Reinforcing Bars: In order to prevent breakage and to assist the handling, it was necessary to place reinforcing bars in the slabs. Three bars of 10 mm diameter and 950 mm length were used. The three 10 mm diameter bars were placed parallel to each other and separated by 125 mm as shown in Figure 5.1. All three bars were placed at mid-depth, i.e. 50 mm below the surface, in the test slabs.

Figure 5. 1 *Mould design*

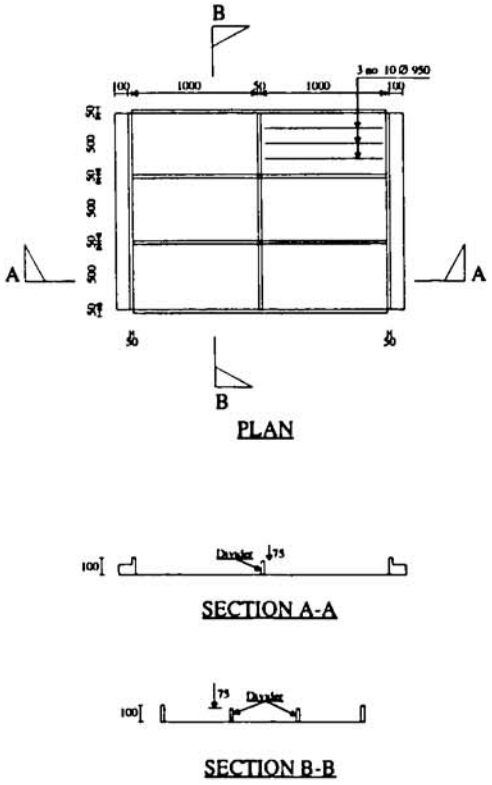


Plate 5. 4 *Empty mould internally subdivided into six sections*

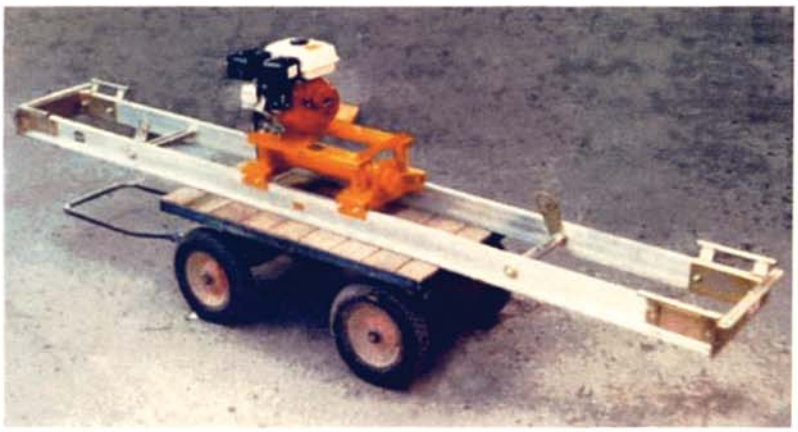
Mixing of concrete: This was carried out in a 200 kg capacity drum mixer following the practice recommended in BS: 1881: Part 125: 1986. For each large slab four identical mixes were batched. Each mix was dry mixed for 30 seconds before the required water was added, and this was followed by wet mixing for a further two minutes. For quality control purposes, three 0.1 x 0.1 x 0.1m cubes were taken from the fourth mix, which formed the surface layer in the completed slabs.

Placing and spreading: The first mix was transported to the mould and a short-handled, square-ended shovel was used to deposit and spread the concrete into the mould, while avoiding segregation. The fist mix was placed to fill the bottom 25 mm layer of the mould, and the second mix was placed on top of the first to fill the bottom 50 mm of the mould. The appropriate reinforcing bars were placed on top of this layer and the third and fourth mixes were used to fill the mould following a similar procedure.

Compaction: A vibrating poker was used for compaction. The tip of the vibrator was quickly inserted into the concrete and was slowly removed so as not to leave any voids. A constant pattern of 5 vibrator strokes was used for each layer of each small slab.

Screeding: Two different methods were used for this operation in order to establish their effect on abrasion resistance. In the first method, the screeding operation was carried out with the aid of the double beam screeder (SBS) operated by two individuals and is shown in Plate 5.5. This was twice passed over the concrete surface to ensure that the top layer of the slab had been smoothly levelled and vibrated. In the second method the screeding was carried out using a wooden hand-tamping beam (WF) operated by two individuals. The beam was dropped uniformly onto the concrete surface each contact with the concrete overlapped the previous one. This procedure was carried out twice over the slab. In a final run a sawing action was applied to the beam as it traversed the slab.

Plate 5. 5 Double beam screeder



Waiting time: After the screeding operation was completed, the concrete slabs were not disturbed until the following conditions were met: (i) all the bleeding water and excess moisture had evaporated, and (ii) the concrete had stiffened sufficiently for finishing. The methods used to gauge when these conditions were satisfied were: (i) visual inspection and (ii) foot impression. To minimise error, as these methods are subjective, one person's assessment and weight were used throughout the investigation, namely the author's.

Finishing technique: The concrete slabs were power finished. Two different power trowels were used for this operation in order to establish their effect on abrasion resistance. They were (i) A Fyne Model RT 9002 power float (OPF) driven by a 3.7 kW motor. This equipment was fitted with a steel float of 920 mm diameter and a stabilising bar (Plate 5.6) and (ii) An Errut Model 600 power float (NPF) driven by a 20 kW motor (Plate 5.7). This equipment was fitted with a steel float of 600 mm diameter. A standard floating operation was adopted with both power trowels and it started once the concrete slabs were assessed to be ready. It was performed for a period of 10 minutes, with the disk being evenly passed

over the concrete surface. This operation produced some moisture on the concrete surface and so a further waiting period was necessary before trowelling could be undertaken. This was performed for a period of 12 minutes, with the rotating blades being evenly passed over the concrete surface. Both the floating and trowelling operations were carried out only once, i.e. commercial finish. Upon completion the specimens were covered with heavy-duty polythene for 24 hours.

Plate 5. 6 *Fyne Model RT 9002 power Float (OPF)*

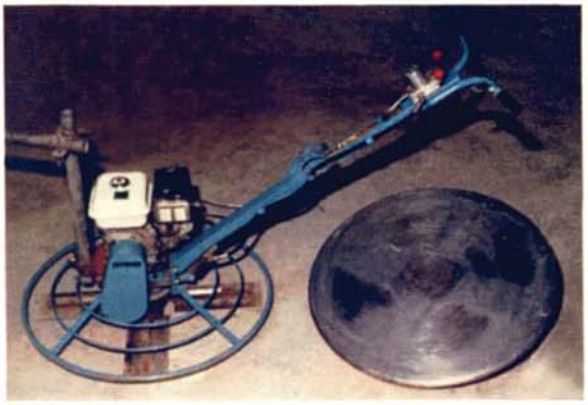
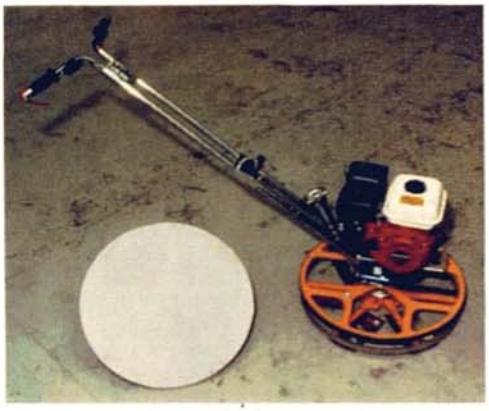


Plate 5. 7 *Errut Model 600 power float (NPF)*



Curing regime: The slabs were removed from the mould the following day and completely wrapped and sealed in heavy-duty polythene sheets. The specimens were stored in the laboratory and left undisturbed for 21 days when they were unwrapped so that they would acclimatise to laboratory conditions before testing at 28 days.

5.5 Specimen testing

5.5.1 Cube strength tests

The three 100 mm cubes, taken from each cast were cured for 7 days in the laboratory curing tank. Following a further storage of 21 days, adjacent to the test slabs, they were tested at 28 days. Note that the concrete cubes were cast, cured and tested in accordance with the following British standards:-

- BS 1881: Part 108: 1983: Testing concrete – Method for making test cubes from fresh concrete.

- BS 1881: Part 111: 1983: Testing concrete – Method of normal curing of test specimens (20°C method).
- BS 1881: Part 116: 1983: Testing concrete – Method for determination of compressive strength of concrete cubes.

5.5.2 Abrasion resistance slab tests

This test method followed the procedure adopted for previous studies (Sadegzadeh, 1985; Phitides, 1991 and Webb, 1996) and is summarised below.

The abrasion tester wheels abrade a circular groove (Plate 5.8) 20 mm wide and its depth was measured by means of the battery operated electronic LCD depth gauge, shown in Plate 5.9, to determine the extent of the abrasion.

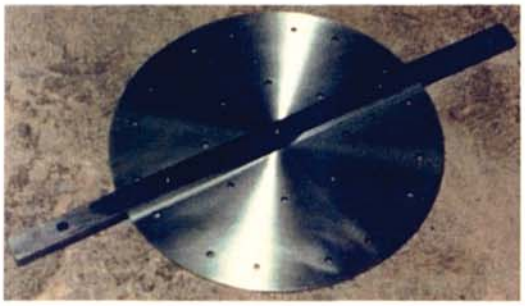
Plate 5. 8 Example of abrasion path

Plate 5. 9 Depth gauge

While the test was running lateral movement of the abrasion tester was prevented by two bolts inserted through the tester legs into the concrete slab, but this did not restrict the vertical movement as the wheels passed over the concrete surface.

The test surface was exposed for a 15 minutes period of abrasion with the rolling wheels. The extent of the abrasion damage was determined by measuring the depth of wear at a series of eight locations around the abrasion path as indicated in Plate 5.8. A circular metallic template (Plate 5.10) was used to mark these locations on the abrasion path before the test. The points of measurement were numbered around the circumference so that the readings could be taken at the same location before and after the test.

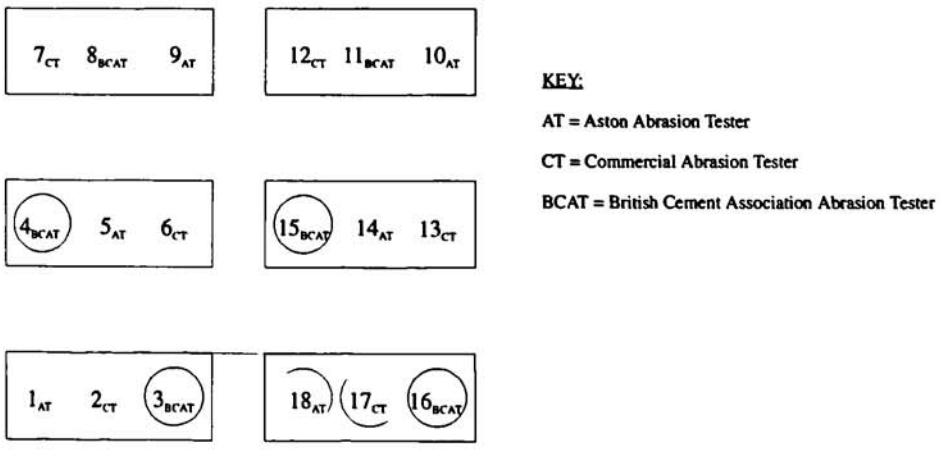
Plate 5. 10 Circular metallic template



These measurements were made with the battery operated electronic LCD depth gauge (Plate 5.9) which was set to measure in mm (to 0.01 mm). The tripod gauge has a slider, which moves in a vertical plane, the position of the slider being accurately measured by the LCD display. To use the gauge with the abrasion tester, it had to be placed on a flat surface and initially zeroed. Then, using the marking out template, the initial measurements were taken at all eight measurement points to obtain the datum readings before testing. After the test, the measurements were repeated and the two sets of readings were subtracted to obtain the depth of wear (Wexham Developments, 1998).

All the specimen slabs were tested for abrasion resistance at 28 days using the three different abrasion testers. These tests followed the procedure described above. The abrasion testers were placed one at each slab as shown in Figure 5.2. in this way it was possible for each mix to use all three machines regularly to test each large slab (2.05 x 1.60 x 0.1 m) with six tests being performed with each machine on the six sub-slabs. It was deemed important to place the abrasion testers in this manner to avoid edge effects.

Figure 5. 2 Layout of abrasion testers on the tests slabs



5.6 Presentation, analysis and interpretation of experimental findings

5.6.1 Compressive strength results

The three 100 mm cubes, taken from each cast were cured for seven days in the curing water tank of the main laboratory. Following further storage of 21 days, adjacent to the test slabs, they were tested at 28 days. A total of 48 cubes were crushed. A summary of the results of the cube crushing strength is provided in Table C.1 of Appendix C. It is clear that the mean cube strength values are very similar for each of the given mixes produced at different stages during the comparative work and are also comparable with the values previously reported (Sadegzadeh, 1985). It is clear that concrete of reliable and uniform quality has been produced and that any subsequent changes in the abrasion performance of each mix could not be attributed to poor quality control in the production of the mixes.

5.6.2 Abrasion resistance results

An abbreviated format of the results obtained from the three accelerated abrasion testers, as well as a summary of the coefficients of variation for each of the testers, are presented in Table 5.2. These values have been obtained from more detailed data that are presented in Tables C.2 and C.3 of Appendix C. Note that the results in Table C.2 are an extract of the individual data collected to form Table C.3.

Collectively, 282 tests were carried out using the three abrasion testers and, with the performance of the surface layer being very dependent on local mix variability, there was scatter in the individual results. This is recognised in the TR-34 (Concrete Society, 1994) which requires that the abrasion resistance is reported as the mean of three tests. Nevertheless, it was decided for comparative purposes to initially consider the individual test results shown in Table C.3 of Appendix C and to make comparisons between the three machines:- AT – CT, AT – BCAT and CT – BCAT. On the basis of a visual inspection of the data and using a 0.05 mm difference as the arbiter, it was found the 32 % of the results were comparable. There was a 45 % agreement between the AT – CT, 23 % agreement between AT – BCAT and 32 % agreement between CT – BCAT. However, when considering the overall averages produced for each one of the abrasion testers, it was found that out of the population of 46 values presented in Table 5.2, 59 % were comparable. From that 59 % of comparable values, there was a 22 % agreement between the AT – CT, 74 % agreement between AT – BCAT and 4 % agreement between CT – BCAT.

Sadegzadeh (1985) reported a similar high degree of agreement between the results of AT – BCAT machines when he undertook a similar comparative study.

Table 5. 2 Abrasion resistance comparative test results and coefficients of variation

Specimen ID	Finishing technique	Abrasion depth (mm)				Coefficient of variation (%)		
		Sadegzadeh (1985)	AT	CT	BCAT	V_{AT}	V_{CT}	V_{BCAT}
2 – B4	NPF – SBS	0.30	0.28	0.18	NA	18	27	NA
8 – B4	NPF – SBS		0.37	0.19	0.34	35	55	48
12 – B4	NPF – SBS		0.30	0.44	0.25	6	45	30
15 – B4	OPF – SBS		0.40	0.35	0.35	20	35	15
1 – B5	NPF – SBS	0.48	0.46	0.30	NA	13	27	NA
3 – B5	NPF – SBS		0.36	0.14	0.22	29	43	21
6 – B5	NPF – SBS		0.37	0.38	0.21	26	67	44
9 – B5	NPF – WF		0.51	0.78	0.53	14	30	46
10 – B5	NPF – SBS		0.43	0.28	0.48	25	34	38
11 – B5	OPF – SBS		0.60	0.99	0.68	24	36	40
4 – B6	NPF – SBS	0.66	0.59	0.45	0.36	16	28	16
5 – B6	NPF – SBS		0.53	0.11	0.34	64	118	62
7 – B6	NPF – SBS		0.69	1.43	0.64	7	63	19
13 – B6	NPF – SBS		0.54	0.32	0.54	35	9	22
14 – B6	OPF – SBS		0.75	1.61	0.60	18	41	36
16 – B6	NPF – SBS		0.62	2.04	0.65	32	24	33

Key:
AT: Aston abrasion tester
CT: Commercial abrasion tester
BCAT: BCA abrasion tester
NPF: Errut Model 600 power float
OPF: Fyne Model RT 9002 power float
SBS: Steel beam screeder

When comparing the coefficients of variation of the three testers for a given slab it is apparent that generally the AT and the BCAT have the lowest and similar values whereas the CT has a tendency to produce higher values than the other two.

Statistical analysis (i.e. Student t-tests) was carried out in order to determine whether the differences between the results obtained from the three abrasion testers are significant. Table C.4 of Appendix C presents a summary of the results where $t_{critical}$ is the expected value at the 5% level of significance (Paradine & Rivet, 1970) and t_{actual} is the calculated value. It was found that of the reported 46 values, 19 were significantly different and this is equal to 41% of the data. Out of this proportion, 58% of the AT – CT values were significantly different, 26% of the BCAT – CT values were significantly different but only 16% of the AT – BCAT values were significantly different, again demonstrating the strong compatibility between the results obtained with these two machines. When a manual inspection is undertaken taking for example Mix 7 – B6 with the average depths of

abrasion for the AT (= 0.69 mm) and the CT (= 1.43 mm), the Student-t tests suggested that the two values are not significantly different. Nevertheless, in terms of abrasion performance it would be accepted that they are very different, although both would simply be considered unsatisfactory when judged against the performance criteria given in BS 8204: Part 2: 1999. If Table C.4 is carefully examined it is obvious that this occurs more than just once.

Though further statistical analysis (Table C.5 of Appendix C) suggests that only the AT can distinguish differences between mixes and especially the different water cement/ratios, it may be argued that all three testers are able to do so. This is not supported by the statistical analysis, although it is evident that all three testers produced increasing abrasion depths with the increasing water/cement ratio.

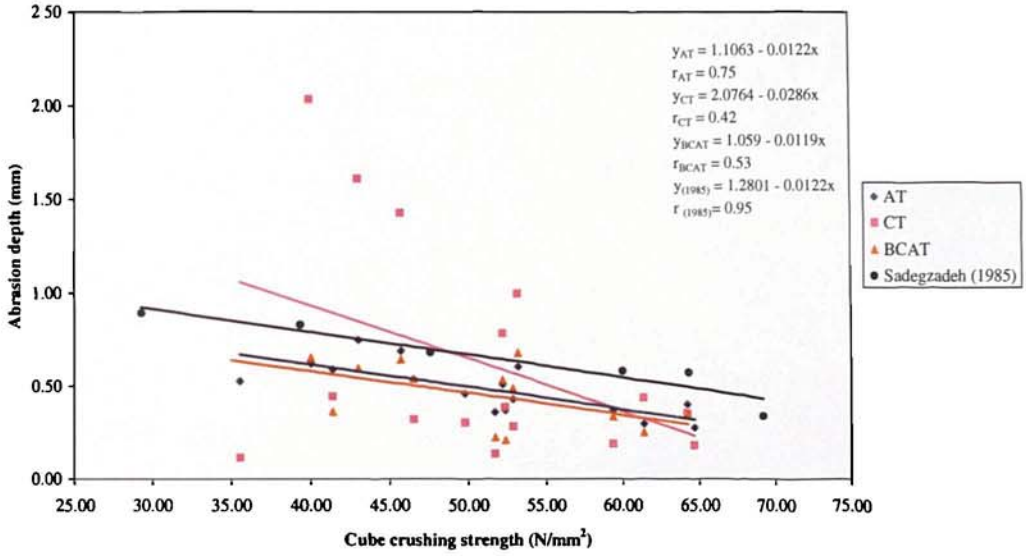
In practice the testers are primarily used to examine in-situ floors where the main outcome is to rank the abrasion resistance in terms of the four classifications given in BS 8204: Part 2: 1999. When this analysis is undertaken on the data in Table 5.2, it is clear that some 50 % of the common data from the AT – BCAT produced the same classification for the floor, the corresponding figures for the AT – CT and CT – BCAT data are 29 % and 26 %.

With regards to the different finishing techniques employed, it was found that the highest abrasion resistance was obtained from the samples finished with the double beam screeder and the Errut Model 600 power float. Similarly the lowest values of abrasion resistance were obtained from the samples finished with the double beam screeder and the Fyne Model RT 9002 power float (See Table 5.2, Mixes 11 – B5, 14 – B6 and 15 – B4). This was confirmed by all three tests using the AT, two tests using the BCAT and for one test using the CT. Examination of the third finishing technique (i.e. using a wooden hand-tamping beam and the Errut Model 600 power float) suggested intermediate values when all three abrasion testers were used (See Table 5.2, Mix 9 – B5). Due to the limited number of tests regarding the finishing methods it was not possible to carry out a statistical analysis.

The abrasion resistance versus the cube crushing strength is plotted in Figure 5.3 for specimens tested by all three abrasion testers. It generally suggests that the compressive strength and the depth of abrasion are inversely proportional and so the abrasion resistance and the compressive strength are in direct proportion. It must be noted, however, that all

points do not fall on the trend lines. It would therefore appear that the compressive strength should not be taken as a direct measure of wear, but rather as an indication. These findings confirm the conclusions of previous investigators (Sadegzadeh, 1985; Sawyer, 1957; Smith, 1958; Witte & Backstorm, 1951).

Figure 5. 3 Abrasion depth vs. Cube crushing strength of the three abrasion testers

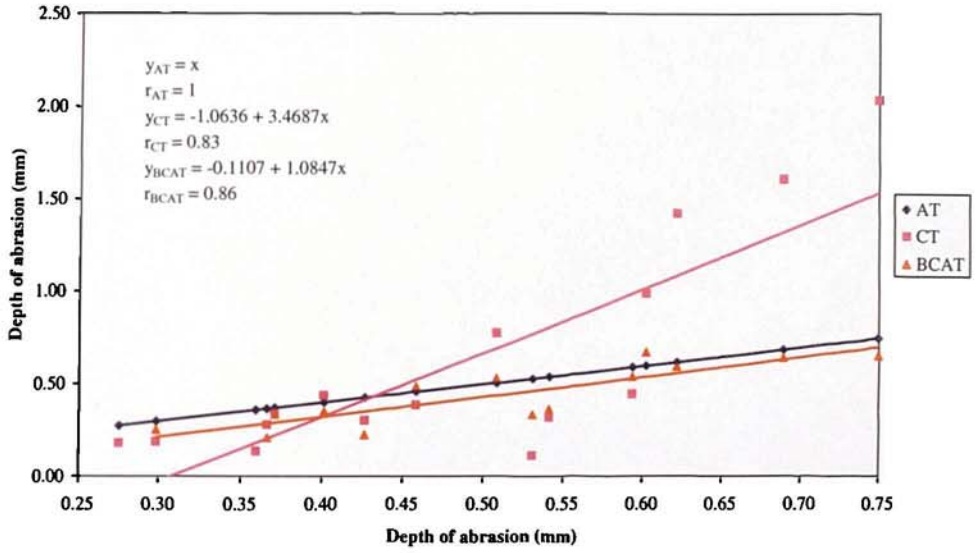


The findings of Sadegzadeh (1985) have also been plotted on Figure 5.3 for comparative purposes. It was observed that the AT, the BCAT and Sadegzadeh (1985) produce very similar trend lines especially in terms of their gradients, whereas the CT trend line is steeper than the other three. The slight differences in the trend line produced by Sadegzadeh (1985) are attributed to the fact that he used 6 different mixes rather than the 3 used for this study. In addition he produced only one specimen for each mix as opposed to the several produced for each mix tested during the current work.

Figure 5.4 shows the correlation of the abrasion depth obtained from the CT and the BCAT machines to the equality line obtained from the AT. It is again apparent that the AT and the BCAT produce very similar trend lines especially in terms of their gradients, whereas the CT trend line is again much steeper than the other two. Again, for the BCAT and the CT machines, all points do not fall on the trend line and so the graph only gives an indication of the inefficiency of the CT. Finally, when comparing the average depth of abrasion with

the average depth of abrasion established by Sadegzadeh (1985) on similar mixes (Table 5.2), it is apparent that the AT and the BCAT generally produced results compatible with the data from this previous study.

Figure 5. 4 *Correlation of abrasion depth obtained from CT & BCAT to equality line obtained from AT*



5.7 Development of performance criteria

Following an extensive laboratory programme, an in-situ comparative investigation was undertaken (Kettle & Sadegzadeh, 1987) to establish abrasion assessment criteria. The classifications developed from this work were primarily based on the results for many floor slabs subjected to medium industrial traffic. From this and related laboratory results (Sadegzadeh, 1985), limits for the accelerated abrasion depth of concrete slabs in a medium industrial environment were proposed (Table 5.3), in terms of Good, Normal, and Poor performance classifications.

Table 5. 3 *Classification of concrete floor slabs in a medium industrial environment (Sadegzadeh, 1985)*

Quality of slab	Abrasion depth
Good	< 0.20 mm
Normal	0.20 – 0.40 mm
Poor	> 0.40 mm

Table 5.3 formed the first official attempt to present the performance criteria for assessing the abrasion resistance performance of concrete floors. These were included in the 1988 edition of the Concrete Society Technical Report 34.

Chaplin (1991), using the BCAT, further refined these criteria, particularly for floor performance in the most demanding circumstances, and produced the criteria based on the four classes of abrasion resistance in Table 5.4. These were included in the 1994 edition of TR 34 but not in BS 8204: Part 2: 1987.

Table 5. 4 Classification of abrasion resistance and limiting depths of wear for the accelerated abrasion test (BS 8204: Part 2: 1999)

BS 8204 Class	Duty	Type of concrete	Concrete grade (N/mm^2)	Minimum cement content (kg/m^3)	Maximum wear depth (mm)
Special	Severe abrasion	Special mixes and resins	Special mixes and dry-shake or sprinkle finishes, resins etc.		0.05
AR1	Very high abrasion	High – strength toppings			0.1
AR2	High Abrasion	Direct finished concrete	C50	400	0.2
AR3	Moderate abrasion	Direct finished concrete	C40	325	0.4

5.8 Incorporation in BS 8204: Part 2: 1999

This extended system has now been included in the latest edition of BS 8204: Part 2: 1999 together with the specification for the commercial apparatus (CT) and test procedure. Although this is a significant development, the classification has been used by Sadegzadeh (1985), Chaplin (1991) and others for a number of years to analyse abrasion test data from site testing in order to rate the abrasion resistance of individual floors.

However, these investigators have used the AT and/or the BCAT rather than the CT machine. In the light of the new data obtained from the current work it is apparent that the CT produces results which are significantly different to those obtained from similar tests performed with both the AT and the BCAT. Therefore the incorporation of the CT into the BS 8204: Part 2: 1999 should be re-evaluated.

5.9 Conclusions

After careful consideration of the results obtained it was concluded that the AT and the BCAT produce compatible and repeatable results. It is suggested that for any future study, the CT should be calibrated against the AT and the BCAT. This future work should also look into the design of the CT and amendments should be made to allow unrestricted vertical movement as the wheels pass over the concrete surface. It is thought that the more rigid design of the CT is one of the main factors affecting the actual abrasion results it produces but it was outside the scope of this work to modify any of the existing apparatus. The incorporation of the CT into the BS 8204: Part 2: 1999 is considered to be inappropriate at this stage, because the performance of the apparatus is not satisfactory when compared with that of both the AT and the BCAT machines that were used to develop the performance criteria in Table 5.4. As a consequence it was decided to use the AT for the main part of this project since not only it produces reliable and repeatable results but it also ensures continuity of the on-going research at Aston University and compatibility with the criteria in Table 5.4.

Further, it was shown that the compressive strength and the depth of abrasion are inversely proportional and so the abrasion resistance and the compressive strength are related. Nevertheless it is suggested that the compressive strength should not be taken as a direct measure of wear, but rather as an indication, primarily as the strength does not reflect the benefits that the choice of finishing technique and curing can have on the subsequent abrasion performance.

Chapter 6: Macro-study of abrasion resistance of fibre reinforced concrete

6.1 Introduction

This chapter describes the laboratory programme designed to study the abrasion resistance of concrete surfaces at the macro level. The major aim of this element of the programme was to investigate the influence on the abrasion resistance of such variables as fibre type, shape, content and length as well as the mix constituents and curing regime. Even though the experimental project was carried out in the laboratory, the construction practices that are currently used by the industry for concrete floors were adopted wherever possible.

6.2 Assessment of current methods and practices

An important feature of this study was to design a laboratory programme which reflected the practices currently being used by the industry particularly with respect to fibre type and shape, finishing techniques, curing regimes and the concrete mix. To achieve this task it was necessary to conduct an assessment of the current practices, and this assessment was carried out in two phases, namely (i) mail survey and (ii) individual contacts as explained in sections 6.2.1 and 6.2.2.

6.2.1 Mail survey

By making use of the "Concrete Year Book" for 1997, it was possible to compile a list of 16 companies, which manufacture or sell different types of fibres. Initially a standard letter was sent to all 16 companies (Appendix D, Letter A) seeking information about the different kinds of fibres that are presently used for concrete floor construction.

The responses of this survey were as follows:

- 4 of the companies did not reply

- 4 of the companies who replied provided information which was not relevant to the present work
- 6 of the companies who replied provided information which was important to this work and were willing to provide samples for testing
- 2 of the companies who replied provided information which was important to this work but were not willing to provide samples for testing

6.2.2 Individual contacts

The second stage was to contact the 8 most relevant companies initially by sending a second standard letter (Appendix D, Letter B). This sought detailed information about current industrial practices in terms of the fibres most commonly used for the construction of concrete floors; the most popular fibres both metallic and non-metallic; the most popular mix design(s); the effect of the addition of fibres on workability and the methods used for adding fibres into the concrete mix. In addition, some companies were also contacted through telephone. The 8 companies were:

♦ Cem-FIL International Ltd	Mr Brian Marten – Sales & Technical Support Manager
♦ Fibermesh Europe	Mr Andy Gibbs – Technical Manager
♦ Fibre Technology Ltd	Ms Maria Di Vincezo – Sales Co-ordinator
♦ Fibrin (Humberside) Ltd	Mr Mark Mitchel – Technical & Quality Assurance Manager
♦ Grace Construction Products Ltd	Mr Richard Young – National Precast & Business Development Manager
♦ Philip Jones Construction Materials Ltd	Mr Philip Jones – Director
♦ Tinsley Wire Ltd	Mr Steve Gavigan – Sales & Technical Support Manager
♦ Trefil ARBED Ltd	Mr Philip Little – former Sales & Technical Support Manager and Mr Philip Ash – Sales & Technical Support Manager

These companies provided information with regards to the inclusion of fibres and the relevant methods used for placing, finishing and curing industrial floor slabs. Similar information may also be found in a publication by Knapton, (1999):

Types of fibres: With reference to steel fibres several different shapes have been used. These are classified as follows: (i) straight, (ii) hooked, (iii) crimped / wavy, (iv) double douform, (v) ordinary douform, (vi) paddled, (vii) enlarged ends, (viii) irregular and (ix) indented. Further there are several classifications in terms of the cross-section of the steel fibre, namely: (i) round wire, (ii) rectangular sheet, (iii) irregular melt extract and (iv) twisted. The various types of steel fibres are illustrated in Figure 2.6. Breaking or premature deformation of fibres is prevented by the very high tensile strength of the drawn wire (usually greater than 1100 N/mm^2). The aspect ratio, which is the ratio of fibre length to fibre diameter, is also an important factor in the fibre specification with common values between 60 and 75. Another fibre type is polypropylene, which is divided into two categories: (i) monofilament and (ii) fibrillated. Monofilament fibres are manufactured from extruded sheet/film material, which is subject to molecular alignment, coated and cut to the appropriate length. This type of fibre is usually much finer that the fibrillated fibre. A smoother surface finish may be achieved from the use of monofilament fibre as opposed to the fibrillated type. Fibrillated fibres are manufactured from extruded sheet/film material, which is subject to molecular alignment, fibrillated, coated and cut to the appropriate length. Alkali resistant glass fibres are also used and although they are not as popular as steel and polypropylene fibres, the experimental programme was expanded to cover this type. The properties of all three and other types of fibres have been discussed in more detail in Section 2.11.

Addition and mixing: The recommended dosage rate for steel fibres for concrete floor construction is between 20 and 40 kg /m^3. Fibres may be added at the mixing plant directly into the mixer at the same time as the aggregates. Superplasticizers may be added to modify workability. Similarly the addition of polypropylene fibres is at a recommended dosage of 0.90 kg/m^3 (0.1 % by volume) and they may also be added at the mixing plant. The recommended dosage rate of AR glass fibres varies, depending on the fibre type, and may be as low as 0.6 kg/m^3 or as high as 5 – 10 kg/m^3. Glass fibres may be added to the concrete mix at the mixing plant directly into the mixer.

Placing curing and finishing: When placing a floor slab, steel fibre reinforced concrete should be compacted as effectively as possible and conventional tamping or vibration is used. The usual techniques for floating and trowelling can be used for finishing. Immediately after finishing a curing compound should be applied, to combat rapid drying, forming an unbroken film on the surface of the concrete. Alternatively the concrete may be kept moist by wet spraying or by an overlay of plastic sheeting. Plastic sheeting however should not be applied if there is a risk that the temperature will become too high and result in the concrete setting too quickly. Concretes containing polypropylene and glass fibres need no special precautions and, when placing, the concrete will flow around an obstruction in the same manner as a conventional concrete mix of similar proportions. Conventional means of tamping or vibration can be used to provide the necessary compaction. Polypropylene and glass fibre concretes may be floated and trowelled using all normal hand or power tools. Curing procedures similar to those specified for conventional concrete should be strictly undertaken.

Concrete mix: In order to produce steel fibre reinforced concrete that is workable and of good quality, a manufacturer of steel fibres (Bekaert, 1990) provided the following guidelines:

- Cement content (OPC) should be between 320 and 350 kg/m^3.
- 750 to 850 kg/m^3 good quality 0 to 4 mm well graded sharp sand should be used.
- A continuous aggregate grading with a maximum size of 28 mm for rounded gravel and 32 mm for crushed should be used. The fraction larger than 14 mm should be limited to 15-20%.
- Characteristic compressive strength of at least 25 N/mm^2 should be targeted.
- Water/cement ratio should be about 0.50, and not exceed 0.55.
- The use of a superplasticizer is permitted if necessary to obtain the necessary workability.
- Admixtures of chloride or chloride containing concrete additives are not permitted.

Polypropylene and glass fibres are compatible with all cementitious products and admixtures and generally require no change to the mix design and/or water–cement ratio.

6.3 Laboratory programme

The laboratory programme was designed to enable the study of the effect of fibre type, shape, content and length, curing regime and concrete mix variation (water/cement ratio) on the abrasion resistance of concrete slabs. To simulate site practices, the 2.05 x 1.60 x 0.1 m wooden mould, described in detail in Section 5.4.2, was used. The layout is illustrated in Figure 5.1 and can be seen in Plate 5.4.

6.3.1 Fibre types, shapes and lengths

Overall three different types of fibres were used in terms of metallic and non-metallic i.e. steel, polypropylene and glass fibres. Further, four different shapes of steel, two different shapes of polypropylene and two different shapes of glass fibres were examined. A blend of steel and polypropylene fibres was also considered. All the fibres used are shown in Plates 4.1 – 4.9. A brief description of each type / shape of fibre is given below and a summary of their properties is given in Tables B.5, B.6, B.7 and B.8 of Appendix B.

Crimped steel fibres: These are undulated fibres manufactured from cold drawn steelwire. During the drawing process, the tensile strength of steel is increased significantly and, together with the undulated form, the aim is to achieve an efficient anchorage of the fibre in the concrete matrix. The undulations are designed in a way to maximise composite action between steel and concrete. The fibre diameter is 1mm in lengths of 45, 50 and 60 mm, the wave depth is 0.65 mm and the wave length is 8 mm. The tensile strength of wire is 1000 N/mm^2. The commercial name of these fibres is "Tabix 1/45", "Tabix 1/50" and "Tabix 1/60" and they were provided by Trefil ARBED Ltd.

Twisted steel fibres: These are manufactured from steel ingots, grade ST 52-3, and have a triangular cross section, longitudinal twisting and end hooks. Their surface is rough and their length is 32 mm. They have a tensile strength ≥ 800 N/mm^2. Their commercial name is "HAREX SF 01 – 32" and they were purchased from Philip Jones Construction Materials Ltd.

Flattened ends steel fibres: These fibres are crafted from high quality, low carbon, cold drawn steel wire. The fibre length is 30 mm with a diameter of 0.7 mm, so the fibre aspect ratio is 43. The tensile strength is 1150 N/mm^2. In terms of appearance, the fibres are

formed from a bright and clean wire with flattened ends and a round shaft. Their commercial name is "Novotex 0730" and they were provided by Fibermesh Europe.

Straight stainless steel fibres: These are melt extract fibres spun directly from the melt and rapidly cooled during manufacture, resulting in high temperature corrosion resistance. They are made from a range high quality alloys. The rough cast texture and irregular profile of these fibres guarantees good mechanical interlock. The unique kidney-shaped cross-section provides a higher specific surface area for bonding. The fibre length is 35 mm with a diameter of 0.7 mm so the aspect ratio is 50. The tensile strength is 47000 N/mm^2. Their commercial name is "Fibrex SS 35" and they were purchased from Fibre Technology Ltd.

Polypropylene fibres: These monofilament fibres measuring 12 mm by 18 μm diameter, are coated to improve wetting and dispersibility with the cement paste and so increase the extent of the contact between the fibres and concrete matrix in the hardened state. They are manufactured in a continuous process by the extrusion of polypropylene granules. The extruded material is heated, stretched to improve tensile strength (557 N/mm^2), coated, cut to 12 mm nominal length and crimped. Their commercial name is "Fibrin 23" and they were provided by Fibrin (Humberside) Ltd.

Polypropylene – polyethylene fibres: These are monofilament, synthetic fibres, 50 mm in length and manufactured from a unique polymer blend. This blend and the manufacturing process, enable the monofilament fibres to partially fibrillate during mixing, thereby increasing the bond between the fibre and the concrete matrix. They have a tensile strength of 550 N/mm^2 and a melt point of 160 °C. Their commercial name is "Grace Structural Fibres" and they were provided by Grace Construction Products Ltd.

High performance glass fibres: This high integrity AR (Alkali Resistant) glass fibre chopped strands are 12 mm long by 14 μm diameter. One hundred filaments are bonded together to form a multi-fibre strand. They have a similar density to concrete and so have no tendency to float. They have a specific gravity of 2.68 and an elastic modulus of 72 GPa. The commercial name of these fibres is "Anti-crak HP" and they were provided by Cem-FIL International.

High dispersion glass fibres: The only difference between these fibres and the high performance glass fibres is that they are produced in bundles of 800 filaments, which disperse on contact with moisture. They do not protrude from the surface and require no further finishing. Their commercial name is "Anti-crak HD" and they were provided by Cem-FIL International.

6.3.2 Concrete mix design

It was not possible to recover any British or indeed any other world-wide standard that specifies the production of fibre reinforced concrete and so it was important to carry out some trial mixes to select the most appropriate mixes for use during this investigation. This included performing slump tests (according to BS 1881: Part 102: 1983) as well as cube strength tests. Six 100 mm concrete cubes were cast for each trial mix, three of which where tested at 7 days and three at 28 according to the relevant British standards (see section 5.5.1). As presented in Table A.1 of Appendix A, the slump of the fibre reinforced mixes at a 0.51 % by volume of steel crimped fibres varied between 70 – 125 mm. According to fibre manufactures these are expected and acceptable values for fibre reinforced concrete. The cube strength results for the same mixes varied between 17 – 46 N/mm^2 at 7 days and 45 – 61 N/mm^2 at 28 days. The density of the concrete was found to be consistent for each mix which suggests that the fibre dispersion was uniform.

On the basis of the above preparatory work, the six basic concrete mixes presented in Appendix A were selected. Initially, one single fibre (steel crimped fibre, Plate 4.1) was considered with mixes A1, A2 and A3 (Appendix A), to study the influence of fibre inclusion on the abrasion resistance of different concrete mixes. To investigate the effects of fibre type, shape, content and length on the abrasion resistance of concrete, mix A2 was selected for extensive use throughout this project. This ensured that the variable in any given cast was the particular fibre characteristics rather than the concrete mix itself. The types of fibre and their nomenclature are summarised in Table 6.1 and the fibre contents are given in terms of the fibre volumes by percentage. The selected values were based on those commonly used in practice for floor slabs although with the steel fibre concrete a range of higher values was also investigated. The following volume contents of steel fibres were used: 0.51, 1.0, 1.5, 2.0 and 3.0 %. Two volume contents were used for the polypropylene fibres, 0.1 and 0.51 %. Volume fibre contents 0.02, 0.04, 0.21, 0.41 and 0.83 % were used for glass fibre mixes. In addition a blend of hooked-end steel and

monofilament polypropylene fibres was used, the respective fibre contents for this blend were 0.1 and 0.51 %.

Table 6. 1 Types and percentages of fibres used with mix A2

Fibre code	Fibre description	Fibre length (mm)	Fibre dosage (%)
s/c	Steel crimped	45	0.51, 1.0, 1.5, 2.0, 3.0
s/c	Steel crimped	50	0.26, 0.51
s/c	Steel crimped	60	0.26, 0.51, 0.64
s/t	Steel longitudinally twisted	32	0.51, 1.0, 1.5, 2.0
s/fe	Steel flattened ends	30	0.51, 1.0, 1.5, 2.0
s/s	Straight stainless steel	35	0.51, 2.0
p	Monofilament polypropylene	12	0.1, 0.51
GSF	Polypropylene – polyethylene	55	0.54
sp	Blend of steel hooked-end and monofilament polypropylene	60, 12.5	0.1, 0.51
HP	High performance glass	12	0.04, 0.21, 0.41, 0.83
HD	High dispersion glass	12	0.02

To assess the influence of various steel fibre characteristics, a single fibre content of 0.51 % was adopted – this being the typical dosage used for the construction of concrete floor slabs. The influence of various lengths of steel fibre was investigated – 30, 45, 50, 55 and 60 mm. For the polypropylene fibres, lengths of 12 or 55 mm were investigated. The glass fibres used had a standard length of 12 mm. In the blended fibre mix, the hooked-end steel fibres and monofilament polypropylene fibres had standard lengths of 60 and 12.5 mm respectively.

Restricted experimental work was also carried out on mixes containing superplasticizing agents. Mix A2 was used for this part of the investigation and contained both a low and high dose of steel crimped fibres (0.51 % and 2.0 % by volume). The dose of the superplasticizing agent varied covering a range of values: 0.0, 0.1, 0.2, 0.5, 0.75 and 1.0 % of the cement content.

6.3.3 Curing regimes

Three curing regimes were considered during this programme. These are described in Section 6.4 below and were:

- Air curing (AC)
- Polythene sheet (PS)

- Curing compound (CC)

6.4 Specimen fabrication

The fabrication procedure for the test slabs of fibre reinforced concrete was very similar to that described in section 5.4.2 apart from the following differences.

Fibre addition: To prevent segregation or balling of the fibres it was important that they were dispersed uniformly throughout the fibre reinforced concrete mixes. In order to achieve this, the fibres were passed through a wire mesh basket and were added at the dry stage. That is the cement, fine and coarse aggregates and the fibres were mixed thoroughly for 1 minute. Finally the water was added and mixing continued for 2 further minutes.

Screeding: The screeding operation was carried out with the aid of the double beam screeder shown in Plate 5.5 operated by two individuals. This was passed twice over the concrete surface ensuring that the top layer of the concrete slab has been smoothly levelled and vibrated.

Finishing technique: The concrete slabs were power finished using the Errut Model 600 power float (Plate 5.7) using the same procedure as Section 5.4.2.

Curing regimes: Three different curing regimes were used. Each big slab was designed so that each small slab could be subjected to different methods of curing. These were as follows:

Air Curing (AC): Immediately after demoulding and separating the slab specimens on the day after they were cast, the selected section of the slab was subjected to air curing and left exposed in the laboratory until due for testing.

Polythene sheet (PS): Immediately after the finishing operation, the selected section of the slab was covered with a heavy-duty polythene sheet. The following day after demoulding this section was wrapped in polythene sheeting for 21 days when they were unwrapped and exposed in the laboratory until they were due for testing.

Curing compounds (CC): The curing compound was sprayed onto the exposed surface of the required section immediately after the last finishing operation, according to the instruction from the manufacturer. A shield was used to avoid contamination of the adjacent sections of the slab. The following day the slabs were demoulded and the bottom part was covered in polythene sheet in order to prevent moisture loss from these surfaces, while the top surface was left exposed to the laboratory conditions.

6.5 Specimen testing

6.5.1 Cube strength tests

Three 100 mm cubes were taken from each cast. The concrete cubes were cast, cured and tested according to the relevant British standards as discussed Section 5.5.1.

6.5.2 Abrasion resistance slab tests

This is identical to the procedure described in Section 5.5.2 but only the Aston abrasion tester (Plate 5.1) was used for this part of the study.

6.6 Experimental findings and discussion

6.6.1 Compressive strength results

A total of 123 concrete cubes were tested and it was found that good quality concrete was produced as demonstrated by the 28 day strength variation, 54.25 ± 5.00 for mix A2 with 0.51% fibres (Table E.1 of Appendix E). Therefore any subsequent changes in the abrasion performance of each mix cannot be attributed to poor quality control in the production of the mixes. There is some concern at the lower cube strengths obtained from the steel fibre concretes with high fibre contents. In practice, such mixes usually also contain an additional ingredient, a superplasticizer to aid their uniform inclusion in the mix without significantly reducing its workability or mobility. In this initial phase, it was decided not to use this extra ingredient but relevant results are presented in Table 6.6 of section 6.6.2.3.

6.6.2 Abrasion resistance results

Collectively, 882 abrasion resistance tests were carried out using the 49 large slabs (2.05 x 1.60 x 0.1 m) that were subsequently subdivided into 294 small slabs (1.0 x 0.5 x 0.1 m) on each of which three abrasion tests were performed. With the performance of the surface layer being very dependent on the local mix variability, there was a scatter in the individual results. This is recognised in the TR – 34 (Concrete Society, 1994) which requires that the abrasion resistance is reported as the mean of three tests undertaken on each test slab.

6.6.2.1 Influence of fibre inclusion, mix variation and curing regime

The plain concrete control mixes B4, B5, B6 and the steel fibre reinforced concrete mixes at a constant fibre percentage of 0.51% by volume, A1, A2 and A3, were initially produced in order to establish the degree to which inclusion of fibres modified the abrasion resistance. Table 6.2 and Tables E.2, E.3 and E.4 (of Appendix E) suggest that there is a significant improvement in the abrasion resistance of concrete due to this fibre inclusion.

Table 6.2 also presents the percentage improvement achieved by steel fibre reinforced concrete when compared to the equivalent plain concrete, this ranges from 8 to 79 % and it is influenced by both the individual mix variations (Tables E.2, E.3 and E.4 of Appendix E) and the curing regime (Table E.5 of Appendix E). During this initial stage it was found that the most significant improvement was achieved by mix A2 (s/c, 0.51%) and so it was selected to study the effects on abrasion resistance of fibre shape, type and length.

Table 6. 2 Abrasion resistance and compressive strength of plain and fibre reinforced concrete

Sample ID *	Mean compressive Strength (N/mm^2)	Depth of wear for curing regime (mm)		
		PS	AC	CC
A1, s/c, 0.51 % - 45 mm	64.5	0.22 (AR3)	0.32 (AR3)	0.17 (AR2)
B4	60.0	0.29 (AR3)	0.73 (OFS)	0.32 (AR3)
Improvement due to fibre inclusion (%)		**24**	**56**	**46**
A2, s/c, 0.51% - 45 mm	55.5	0.11 (AR2)	0.17 (AR2)	0.15 (AR2)
B5	53.5	0.44 (OSF)	0.79 (OSF)	0.46 (OSF)
Improvement due to fibre inclusion (%)		**75**	**79**	**66**
A3, s/c, 0.51 % - 45 mm	45.5	0.50 (OSF)	0.78 (OSF)	0.59 (OSF)
B6	42.0	0.61 (OSF)	0.95 (OSF)	0.64 (OSF)
Improvement due to fibre inclusion (%)		**18**	**18**	**8**

Key:
* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume
In brackets: Classification of abrasion resistance in accordance with BS8204: Part 2: 1999
OSF: Out of specification/failed

The abrasion depths obtained from specimens cured with a curing compound are very similar to those obtained from the specimens cured in polythene sheeting (Table 6.2). It must be noted that the thin film created by the application of the curing compound was removed with white spirit prior to the abrasion testing in case its presence should interfere with the abrasion assessment. As a consequence, for practical reasons it was decided to abandon the curing compound method at this stage.

6.6.2.2 Influence of fibre type, shape, content and length

From the results in Table 6.3 it is apparent that by increasing the fibre dosage in the concrete mix, the depth of abrasion increases. For instance when using the steel crimped fibres, of 45 mm in length, in mix A2 at dosages of 0.51, 1.0, 1.5, 2.0 and 3.0 %, the corresponding depth of abrasion (for polythene cured specimens) are 0.11, 0.29, 0.35, 0.39 and 0.44 mm respectively. This is graphically illustrated in Figure 6.1 for samples cured in polythene sheeting and Figure 6.2 for samples cured in air. Further, with the increase of the fibre dosage in the concrete mix, the compressive strength increases up to a certain point after which it also starts to drop. Therefore for the same mixes mentioned above, the corresponding cube strengths were 55.5, 60.0, 55.0, 51.5 and 49.5 N/mm^2. The reduction of the compressive strength is attributed to incomplete compaction due to the lower workability of the high fibre content mixes. It should be noted that superplasticizers were not included in these mixes as it was considered to be an additional variable, which was outside the scope of this phase of the work. Nevertheless, a limited investigation of superplasticized fibre reinforced concrete mixes was undertaken and this is presented in Section 6.6.2.3. At this stage the crucial finding is that a relatively low dose, 0.51 %, of steel fibres significantly improved the abrasion resistance compared to that of the corresponding plain mixes, this also being the dosage rate typically used in concrete floors construction.

A similar pattern was also apparent with the other shapes of steel fibre as shown in Figures 6.1 and 6.2. The corresponding abrasion depths are presented in Table 6.3 for these concrete mixes containing longitudinally twisted, flattened ends and straight stainless steel fibres. Generally, the results suggest that the shape of the steel fibres is not a major factor influencing the abrasion resistance. For instance when any shape of steel fibre is introduced in mix A2 – at a standard dosage of 0.51% by volume – the depth of abrasion varies between 0.11 and 0.12 mm, which equates to 73 to 75 % improvement when compared to the 0.44 mm abrasion depth of the equivalent plain concrete. These findings

were further confirmed by the statistical analysis that was undertaken, a summary of which is presented in Tables E.6 and E.7 of Appendix E.

Table 6. 3 *Influence of steel fibre shape and volume on the abrasion resistance and compressive strength of concrete*

No	Sample ID *	Mean compressive strength (N/mm^2)	Depth of wear for curing regime (mm)	
			PS	AC
1	A2, s/c, 0.51% - 45 mm	55.5	0.11 (AR2)	0.17 (AR2)
2	A2, s/c, 1.0 % - 45 mm	60.0	0.29 (AR3)	0.48 (OSF)
3	A2, s/c, 1.5 % - 45 mm	55.0	0.35 (AR3)	0.50 (OSF)
4	A2, s/c, 2.0 % - 45 mm	51.5	0.39 (AR3)	0.70 (OSF)
5	A2, s/c, 3.0 % - 45 mm	50.0	0.44 (OSF)	0.94 (OSF)
6	A2, s/t, 0.51 % - 32 mm	55.5	0.12 (AR2)	0.25 (AR3)
7	A2, s/t, 1.0 % - 32 mm	60.0	0.20 (AR2)	0.36 (AR3)
8	A2, s/t, 1.5 % - 32 mm	56.5	0.25 (AR3)	0.70 (OSF)
9	A2, s/t, 2.0 % - 32 mm	54.0	0.42 (OSF)	0.72 (OSF)
10	A2, s/fe, 0.51 % - 30 mm	59.0	0.12 (AR2)	0.37 (AR3)
11	A2, s/fe, 1.0 % - 30 mm	62.0	0.20 (AR2)	0.46 (OSF)
12	A2, s/fe, 1.5 % - 30 mm	61.5	0.25 (AR3)	0.48 (OSF)
13	A2, s/fe, 2.0 % - 30 mm	59.0	0.31 (AR3)	0.58 (OSF)
14	A2, s/s, 0.51 % - 35 mm	58.5	0.12 (AR2)	0.47 (OSF)
15	A2, s/s, 2.0 % - 35 mm	59.5	0.36 (AR3)	0.49 (OSF)

Key:
* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume
In brackets: Classification of abrasion resistance in accordance with BS8204: Part 2: 1999
OSF: Out of specification/failed

Figure 6. 1 *Abrasion depth vs. fibre volume for steel fibre reinforced concrete mixes cured in polythene sheeting*

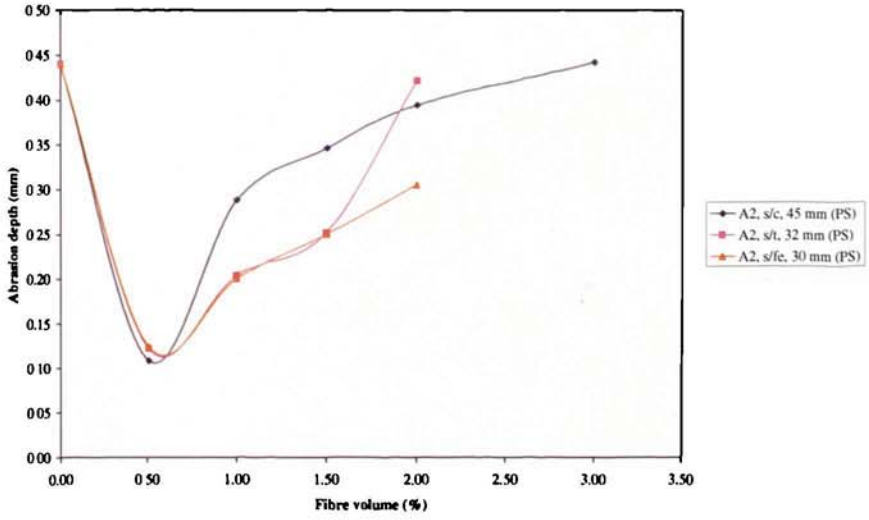
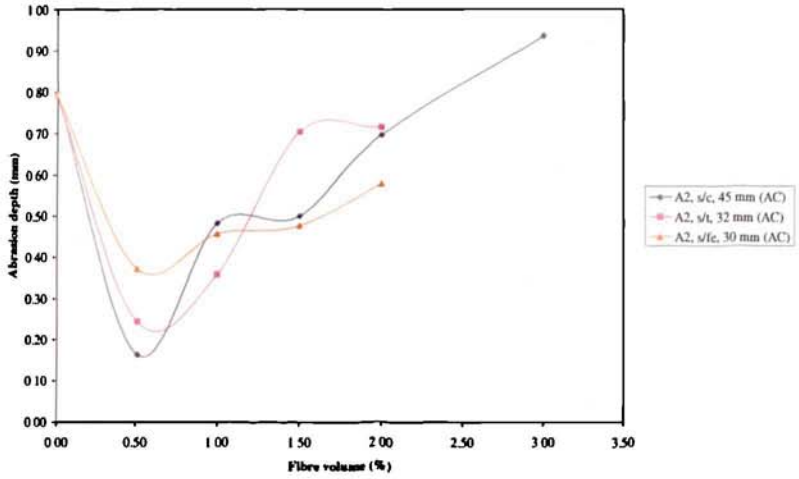


Figure 6. 2 Abrasion depth vs. fibre volume for steel fibre reinforced concrete mixes cured in air



The results obtained using different types of fibres in the concrete mix are summarised in Table 6.4 and include polypropylene, glass and a blend of hooked-end steel and monofilament polypropylene fibres. The best performance was achieved by the inclusion of polypropylene fibres in mix A2 at a volume dosage of 0.1 %. The resulting abrasion depth was only 0.06 mm compared to 0.44 mm for the equivalent plain concrete, effectively producing a reduction in wear of 86 %. Mix A2, sp, 0.1 % produced an abrasion depth of 12 mm, indicating that the inclusion of the blend of steel and polypropylene fibres into the concrete mix reduced the abrasion wear by 73 % when compared to the equivalent plain concrete. Glass fibres also improved the abrasion resistance but to a less marked extent, the best improvement was achieved with mix A2, HP, 0.04 % which produced an abrasion depth of 0.25 mm which equates to a 43 % reduction in wear. A graphical illustration of the relationship between abrasion depth and glass fibre volume is presented in Figure 6.3. Although this pattern is similar to those in Figures 6.1 and 6.2, the glass fibres produced much higher abrasion depths for smaller fibre volumes, compared to that produced by the steel fibres.

Both the visual examination of the data obtained and the statistical analysis (Tables E.6, E.7 and E.8 of Appendix E) suggest that fibre type is a more significant factor affecting abrasion resistance than the shape of the steel fibre.

The data summarised in Table 6.5 indicate that the length of the crimped steel fibres significantly (Table E.9 of Appendix E) influences abrasion resistance, with the longer

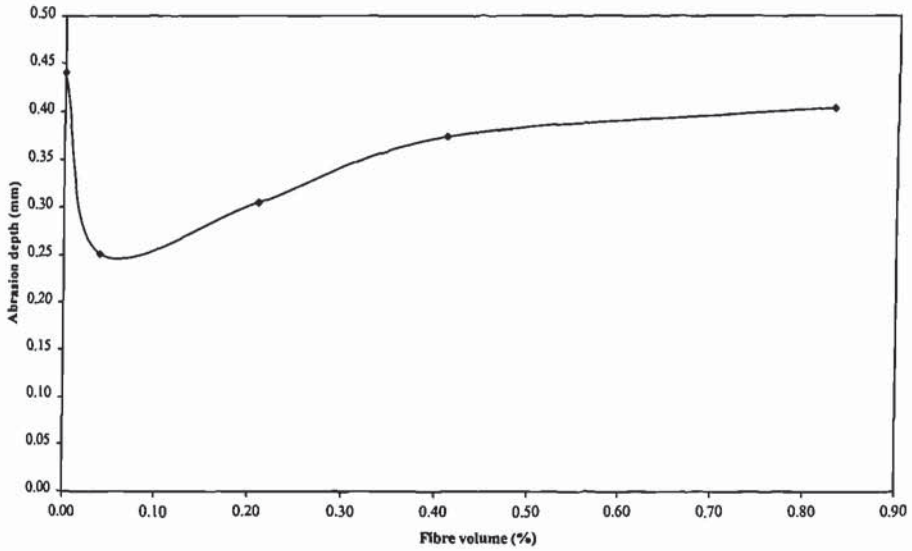
fibres leading to higher abrasion depths. For example, Mix A2, s/c, 0.51 % - 60 mm (with 60 mm long fibres) produced abrasion depths of 0.45 and 0.44 mm. The same depth was also produced by the equivalent plain concrete (B5), whereas mix A2, s/c, 0.51 % (with 45 mm long fibres) resulted in abrasion depths of 0.11 and 0.18 mm. The manufacturer's recommendation for the 60 mm long fibres was actually an inclusion of 0.64 % by volume. And so mix A2, s/c, 0.64 % - 60 mm was produced and tests resulted in an abrasion depth of 0.36 mm, a slight improvement but still inferior to that of A2, s/c, 0.51 % with 45 mm long fibres.

Table 6. 4 *Influence of fibre type and volume on the abrasion resistance and compressive strength of concrete*

No	Sample ID *	Mean compressive Strength (N/mm^2)	Depth of wear for curing regime (mm)	
			PS	AC
1	A2, p, 0.1 % - 12 mm	58.0	0.06 (AR1)	0.25 (AR3)
2	A2, p, 0.51 % - 12 mm	55.0	0.16 (AR2)	0.26 (AR3)
3	A2, sp, 0.1 % - 12.5, 60 mm	55.0	0.12 (AR2)	0.28 (AR3)
4	A2, sp, 0.5 % - 12.5, 60 mm	51.5	0.37 (AR3)	0.58 (OSF)
5	A2, HP, 0.04 % - 12 mm	56.5	0.25 (AR3)	-
6	A2, HP, 0.21 % - 12 mm	49.5	0.30 (AR3)	-
7	A2, HP, 0.41 % - 12 mm	48.5	0.37 (AR3)	-
8	A2, HP, 0.83 % - 12 mm	47.5	0.40 (AR3)	-
9	A2, HD, 0.02 % - 12 mm	48.5	0.45 (OSF)	-
10	A2, GSF, 0.54 % - 50 mm	47.0	0.41 (OSF)	-

Key:
* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume
In brackets: Classification of abrasion resistance in accordance with BS8204: Part 2: 1999
OSF: Out of specification/failed

Figure 6. 3 *Abrasion depth vs. fibre volume for glass fibre reinforced concrete mixes cured in polythene sheeting*



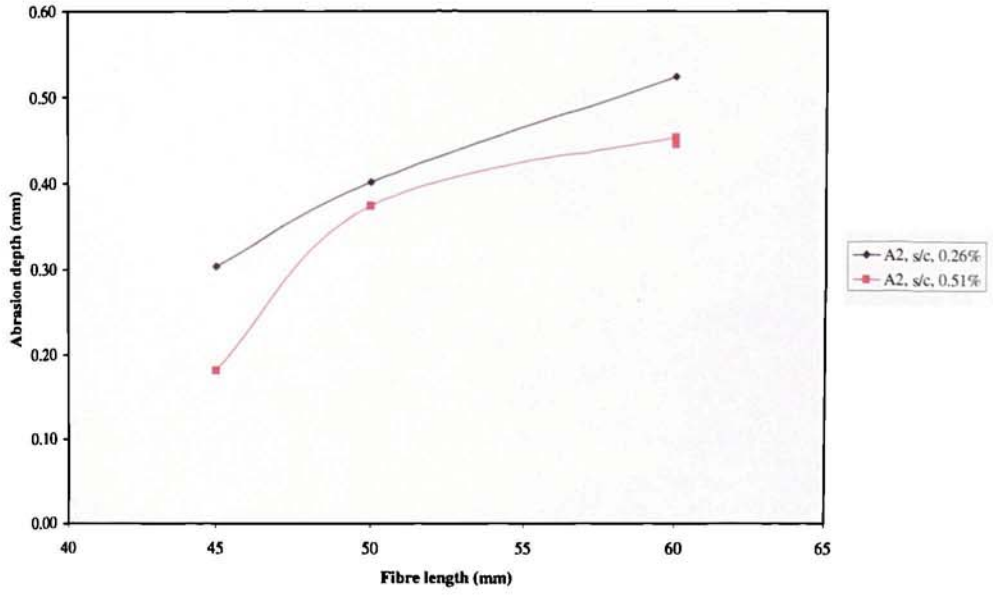
Although the relationship between abrasion resistance and fibre length is not linear, Figure 6.4 shows an increase in abrasion depth with increase in fibre length. The relationship shows a steep increase in abrasion depth between 45 and 50 mm length followed by a shallower increase from 50 to 60 mm. Identical patterns were produced by both concrete mixes containing two different volumes of fibres, 0.26 % and 0.51 %.

Table 6. 5 *Influence of steel fibre length and volume on the abrasion resistance and compressive strength of concrete*

No	Sample ID *	Mean compressive Strength (N/mm^2)	Depth of wear for curing regime (mm)	
			PS	AC
1	A2, s/c, 0.26% - 45 mm	52.0	0.30 (AR3)	-
2	A2, s/c, 0.51% - 45 mm	55.5	0.11 (AR2)	0.17 (AR2)
3	A2, s/c, 0.51% - 45 mm	56.0	0.18 (AR2)	-
4	A2, s/c, 0.26% - 50 mm	50.5	0.40 (AR3)	-
5	A2, s/c, 0.51% - 50 mm	50.5	0.37 (AR3)	-
6	A2, s/c, 0.26% - 60 mm	46.0	0.52 (OSF)	-
7	A2, s/c, 0.51% - 60 mm	56.0	0.45 (OSF)	-
8	A2, s/c, 0.51% - 60 mm	46.0	0.44 (OSF)	0.66 (OSF)
9	A2, s/c, 0.64% - 60 mm	55.5	0.36 (AR3)	0.65 (OSF)

Key:
* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume
In brackets: Classification of abrasion resistance in accordance with BS8204: Part 2: 1999
OSF: Out of specification/failed

Figure 6. 4 *Abrasion depth vs. fibre length for steel fibre reinforced concrete mixes cured in polythene sheeting*



It was observed during the abrasion testing that as the rolling wheels removed the concrete surface, some of the steel fibres were left exposed. Due to the brittle nature of the aggregate surrounding each of them, the contact of the fibres with the mortar was sometimes broken and subsequently removed by the circular motion of the abrasion machine leaving a large – relative to the depth readings – cavity which would therefore result in a higher abrasion depth reading. With an increased fibre length these cavities were longer and hence the average abrasion depth for the specimen would be expected to be higher.

Even though a range of steel fibre contents was used during this work (Tables 6.2 – 6.5) varying from 0.26 % to 3.0 %, it was observed that the optimum percentage appears to be 0.51 % by volume. It is possible that the performance of mixes with high fibre contents may have been impaired by their low workabilities, as superplasticizers were not used in this phase of the study.

6.6.2.3 Influence of superplasticizing agents

Due to time restrictions, only limited experimental work was carried out on superplasticized samples containing both a low and high dose of steel fibres (0.51 and 2.0 % by volume). The results obtained from this part of the study are presented in Table 6.6 and graphically illustrated in Figure 6.5. The amount of superplasticizing agent was varied, covering a range of values: 0.00, 0.10, 0.20, 0.50, 0.75 and 1.00 % of the cement content according to the manufacturer's instructions.

For the high steel fibre volume mixes, cured in polythene sheeting, it is apparent that initially increases in the volume of the superplasticizers produce decreases in the depth of abrasion. However, with further increases in this volume, the depth of the wear also increases so that there is an optimum volume, of around 0.75 %, at which the depth of wear is minimised for this particular mix. In contrast the introduction of the superplasticizing agent at 0.00 – 0.75 % of the cement content, to the low steel fibre volume mixes cured in polythene sheeting had little effect. However, at the highest 1.0 % dosage value, these mixes produced virtually the same (poor) performance as the high steel fibre volume mix. Overall, it was observed that the mixes containing a superplasticizing agent had improved workabilities when compared to the same mixes without this agent. It seems, therefore, that the improved abrasion resistance characteristics are attributed to the enhanced workability which, in turn led to better surface finishing. It has been found that curing becomes critical

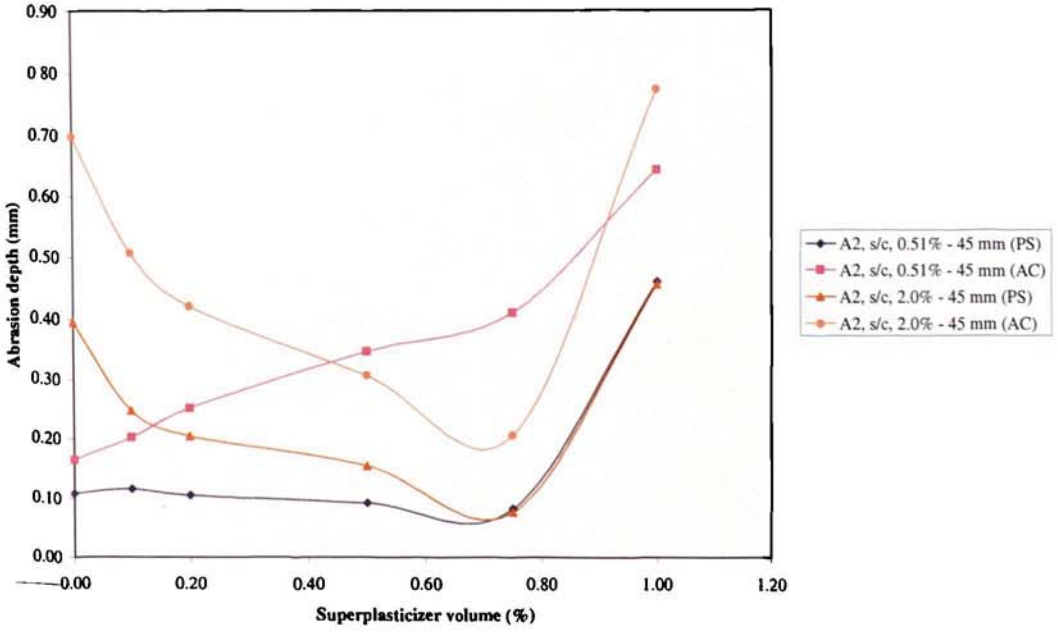
for both the low and high fibre volume mixes containing superplasticizing agents. These findings are further confirmed by the statistical analysis presented in Tables E.10 – E.12 of Appendix E.

Table 6. 6 *Influence of superplasticizing agents on the abrasion resistance and compressive strength of concrete*

No	Sample ID *	Compressive strength (N/mm^2)	Abrasion depth for curing regime (mm)	
			PS	AC
1	B5	53.5	0.44 (OSF)	0.79 (OSF)
2	A2, s/c, 0.51 % - 45 mm - SP 0.0 %	55.5	0.11 (AR2)	0.17 (AR2)
3	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	54.0	0.12 (AR2)	0.20 (AR2)
4	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	53.0	0.10 (AR2)	0.25 (AR3)
5	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	59.0	0.09 (AR2)	0.34 (AR3)
6	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	59.5	0.08 (AR2)	0.40 (AR3)
7	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	43.5	0.45 (OSF)	0.64 (OSF)
8	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	51.5	0.39 (AR3)	0.70 (OSF)
9	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	52.0	0.25 (AR3)	0.51 (OSF)
10	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	52.5	0.20 (AR2)	0.42 (OSF)
11	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	60.5	0.15 (AR2)	0.30 (AR3)
12	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	63.0	0.07 (AR2)	0.20 (AR2)
13	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	45.0	0.45 (OSF)	0.77 (OSF)

Key:
* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume
In brackets: Classification of abrasion resistance in accordance with BS8204: Part 2: 1999
OSF: Out of specification/failed

Figure 6. 5 *Abrasion depth vs. superplasticizer volume for low and high volume steel fibre reinforced concrete mixes cured in polythene sheeting and air*



From the results obtained during this part of the investigation, it is suggested that, it is possible should a high dose of fibres is required due to structural reasons, to enhance the abrasion performance and other properties of the concrete mix by inclusion of superplasticizing agents.

6.6.3 General discussion

The performance criteria, given in BS 8204: Part 2: 1999 have been used to classify the abrasion depths presented in Tables 6.2 – 6.6, and individual classifications are shown in brackets next to each result in these tables. In the majority of cases, and particularly for the mixes cured in polythene sheeting, the inclusion of fibres results in an improved abrasion resistance of the concrete floor with the performance classification generally moving from moderate to very high abrasion resistance. The criteria in Tables 5.3 and 5.4 are based on field performance, and so this comparison indicates that these fibre reinforced concretes should provide a very high level of in-service abrasion resistance.

As previously discussed (Chapter 2, Sections 2.12.4 and 2.13.2.3), while the addition of fibres into the concrete mix has little effect on the compressive and tensile strengths, significant improvements are achieved for impact resistance, flexural strength and toughness. Further, the ability of fibre reinforced concrete composites to absorb energy, even after initial crack propagation, has long been recognised as one of the most important benefits of their incorporation into plain concrete (Robins et al., 2001; Balendran & Zhou, 2001; Gopalaratnam & Gettu, 1995; Maidl, 1995; Keer, 1984; Johnston, 1974). Among the mechanisms mobilised by the abrasion test, a combination of impact and flexural stresses are developed throughout the concrete surface as the wheel passes over the surface. It has been built to simulate the action of forklift trafficking onto a concrete floor surface and abrasion performance has been linked to the surface hardness or toughness (Sadegzadeh, 1985). From the results presented in Tables 6.3 – 6.5 (for non-superplasticized samples) it is clear that the compressive strength decreases with increasing fibre volume while the samples are still able to maintain an abrasion resistance both within the limits of BS 8204: Part 2: 1999 and higher than that of the control plain concrete mix. This is attributed to reduced workability, which consequently results in incomplete compaction and affects the compressive strengths. It should be noted however that the cube samples and the slab specimens where subjected to different compaction methods. It is suggested that a combination of the enhanced compaction and finishing techniques applied only to the test

slabs would have increased their flexural strength and impact resistance resulting in improved abrasion resistance.

It has long been established that curing remains one of the most important factors affecting the abrasion resistance of concrete floors produced from plain concrete (Sadegzadeh, 1985; Chaplin, 1972). From the results summarised in Table 6.2 it is clear that the abrasion performance of specimens cured with the curing compound is very close to that of specimens cured by the use of polythene sheets, with both yielding much lower abrasion depths than the air cured samples. However, the inclusion of fibres into the concrete mix particularly improved the abrasion resistance of air cured specimens. For example, air cured mix A2, s/c, 0.51% produced a wear abrasion depth of 0.17 mm as opposed to 0.79 mm produced by the equivalent plain concrete mix, B5. Similar trends are also apparent from the data in Table 6.3 for other fibre quantities and shapes suggesting that the use of fibres would be particularly beneficial for site concrete that may not be as effectively cured as the laboratory specimens.

There exists a general antiquated perception that abrasion resistance is controlled by a single important factor: compressive strength. Thus the abrasion depths are plotted against cube strength in Figure 6.6 and there is a trend that the depth of wear is inversely related to the cube strength, this being apparent with all three curing regimes, so abrasion resistance and the cube strength are related. However, slab specimens that were cured in all three curing regimes and have identical cube strengths produced very different abrasion depths. It must also be noted that, on Figure 6.6, all points do not fall on the trend line as indicated by the various coefficients of correlation – $r_{PS} = 0.7096$, $r_{AC} = 0.5879$ and $r_{CC} = 0.8801$. It would therefore appear that cube strength should not be taken as a direct measure of wear, but rather as an indication. These findings support the conclusions of other investigators (Sadegzadeh, 1985; Smith, 1958; Sawyer, 1957; Witte & Backstrom, 1951), but direct comparison is not possible as the previous workers have only investigated plain concrete. Figure 6.6 once more confirms the significance of curing on the abrasion resistance.

Using the results in Table 6.2, Figure 6.7 was drawn and it again illustrates that the abrasion resistance of concrete floors improves considerably with the inclusion of steel crimped fibres at 0.51% by volume. This figure also shows that, for both plain and fibre reinforced concrete, the curing method and water-cement ratio are factors that influence abrasion resistance. This confirms the findings of previous research programmes

(Sadegzadeh, 1985; Dhir et al., 1991). Figure 6.7 also illustrates the previous observations that: (1) both the curing compound and polythene curing resulted in similar abrasion depths, and (2) the influence of the fibres is critical in the air cured specimens and those with the highest w/c ratios.

Figure 6. 6 Abrasion depth vs. Cube crushing strength for different curing regimes

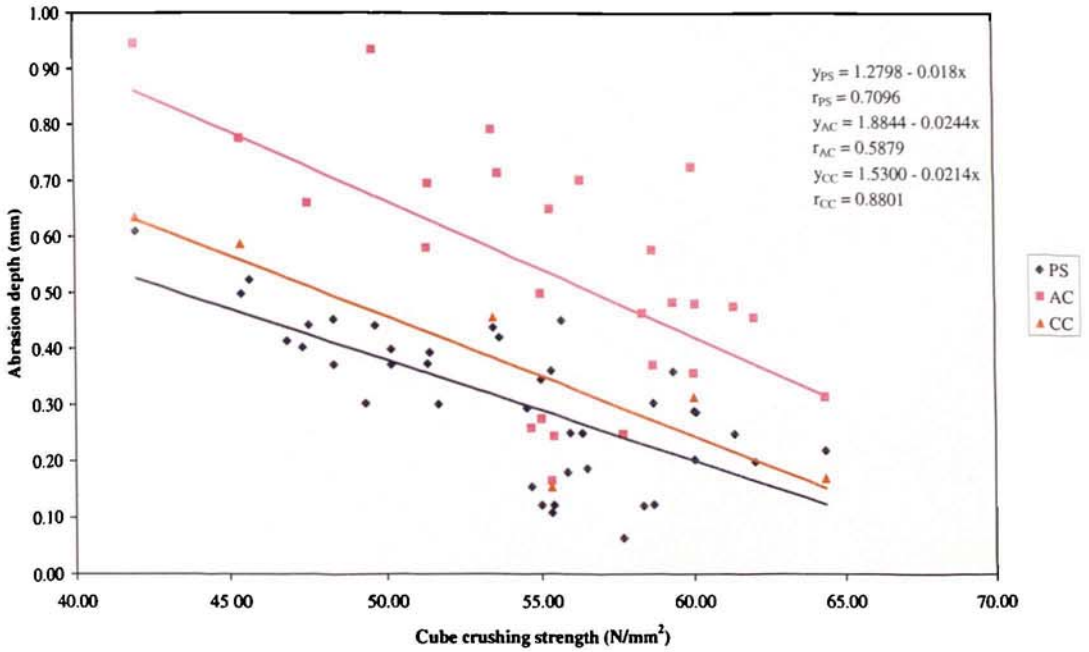
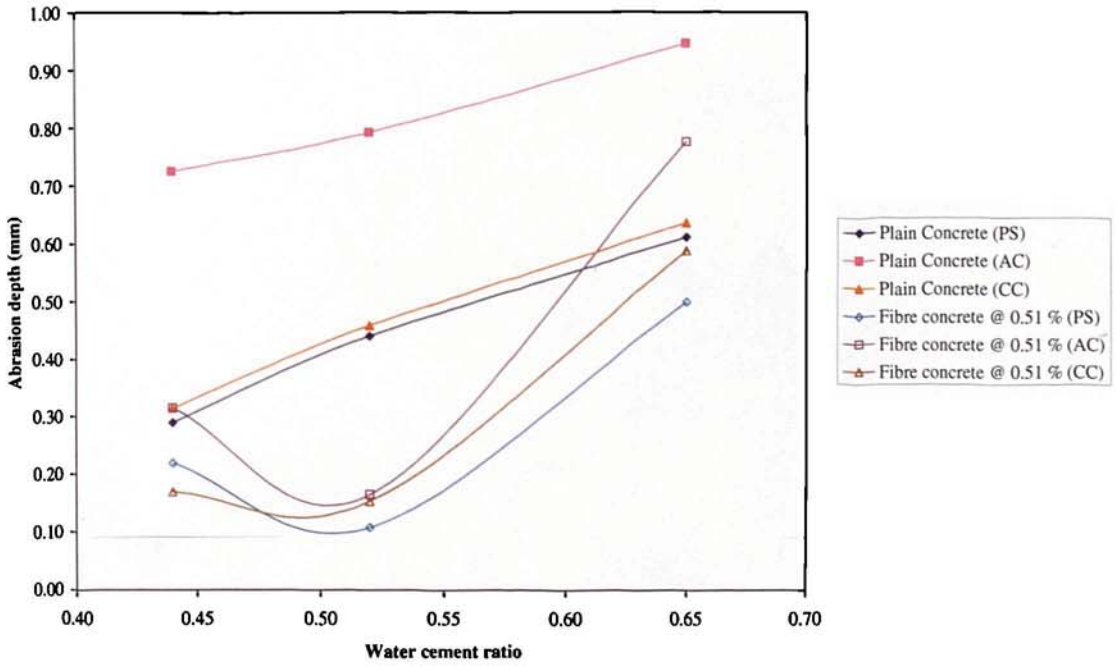


Figure 6. 7 Abrasion depth vs. Water cement ratio for different curing regimes



In an investigation by Jefferis (1988) – on the bleed and settlement problems with offshore grouting – it was suggested that in wet concretes or grouts, the bleed water may not move uniformly through the material but instead force channels. These channels may originate at some local imperfection in the formwork or an intrusion adjacent to the reinforcement. Once formed, a channel will represent a preferred drainage path. Based on this hypothesis of the movement of bleed water, it is suggested that fibre reinforcement, particularly fibres close to the power finished surface, also act as drainage channels aiding any excess water present rise to the surface. Subsequently, this bleed water evaporates before the panning (initial power finishing operation) takes place when the slab is assessed to be ready (see Section 5.4.2). This operation not only compacts the surface of the sample concrete slab, it also re-vibrates the drainage channels and causes further water to be released. This water evaporates before the second and final power trowelling operation occurs. Consequently, the w/c ratio at the surface is much lower than that of the rest of the slab but also the surface is much denser due to the compaction effect from the power finishing operations. This mechanism adds to the explanation of the abrasion depths of fibre reinforced concrete mixes being lower than those of plain concrete with the same w/c ratios.

6.7 Conclusions

Generally speaking, the inclusion of fibres produced an improvement in the abrasion resistance of the concrete. In this study, it was found that the most significant improvement was achieved with the optimum inclusion of steel fibre content at 0.51 % by volume. The results also suggest that the shape of the steel fibres was not a significant factor influencing the abrasion resistance. However, the type of fibre is significant, with the largest improvement of 86 % in abrasion resistance being obtained when polypropylene fibres were included in the concrete, compared to the equivalent plain concrete. When steel fibres were used the improvement was 75 % while the inclusion of a blend of steel and polypropylene fibres improved the abrasion resistance by 73 % and glass fibres achieved a maximum improvement of 43 %. It was demonstrated that the length of the steel fibres significantly affects abrasion resistance, with the shorter fibre being most effective.

The curing regime was also a major influence on the abrasion resistance. The experimental results indicate that specimens cured with a curing compound produced an abrasion resistance very similar to that of specimens cured by the use of a polythene sheets, both having significantly superior abrasion resistance to that of the equivalent air cured

specimens. The experimental data also clearly show that the abrasion resistance and the compressive strength are related. Further, the water cement ratio and inclusion of superplasticizing agents into the concrete mix are both factors that significantly influence abrasion resistance.

Chapter 7: Micro-structural study of abrasion resistance of fibre reinforced concrete

7.1 Introduction

The pervious chapter demonstrated that fibre content, type and length all influence the abrasion resistance of concrete floor slabs. Other factors such as curing regime and the inclusion of superplasticizing agents were also found to effect the abrasion characteristics of fibre reinforced concrete. Various mechanisms have been proposed by previous researchers (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985) to explain the influence of several variables on the abrasion resistance of plain concrete and these mechanisms were directly related to the microstructure of the concrete at the surface (Sadegzadeh, 1985). It is therefore necessary to examine the microstructure of the concretes tested in this study. Unlike previous researchers (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985), who adopted a range of techniques including mercury intrusion porosimetry, microhardness examination, scanning electron microscopy, petrographic examination, differential thermal analysis, and microscopic examination, the current research was limited to using the following methods and techniques:

- Microhardness examination
- Mercury intrusion porosimetry
- Petrographic examination

These particular techniques were shown in these previous studies to provide the most useful information with respect to abrasion performance.

7.2 Microindentation hardness examination technique

The plethora of information that may be derived by microindentation testing has made it a very useful tool in characterising and evaluating the properties of many materials, in particular metals (Boyer & Gall, 1985; Mott, 1956; Tabor, 1951) ceramics (McColllin, 1990; Sargent & Page, 1978), cement pastes (Igarashi at al., 1996a; Mehta & Monteiro, 1988; Wang, 1988; Wei et al., 1986; Saito & Kawamura; 1986) but also concrete (Webb, 1996; Kholmyansky et al., 1994; Malhotra & Carino, 1991; Phitides, 1991; Sadegzadeh, 1985). Previous researchers have generally used microhardness as a non-destructive test to determine the properties of the bulk material by relating it to various physical and/or mechanical properties of the cementitious material under investigation. Specifically, it has been shown that the compressive strength, modulus of elasticity and porosity of cement paste can be related to its microhardness (Feldman & Huang, 1985; Beaudoin, 1982; Sereda, 1972; Soroka & Sereda, 1968 a & b). Other investigators (Webb, 1996; Stiffler, 1969) have been able to correlate microhardness to the wear resistance of aggregates. In more recent years, microhardness testing has been used (Cross et al., 2000; Igarashi et al., 1996a; Igarashi & Kawamura, 1994; Sergi & Page, 1992; Mehta & Monteiro, 1988; Wang, 1988; Saito & Kawamura, 1986; Wei et al., 1986) as a means of characterising the microstructural gradients in cementitious systems, in particular at the interfacial transition zone (ITZ) around inclusions such as aggregates and fibres.

It is well established that the cement paste microstructure in the vicinity of the surface of an inclusion is quite different to that of the bulk (Igarashi et al., 1996b). This zone is characterised by greater porosity and more heterogeneous microstructure. Microhardness testing has been used by several investigators (Cross et al., 2000; Igarashi & Kawamura, 1994; Wang, 1988; Wei et al., 1986) as a means of characterising the properties of this zone relative to the bulk and as a means of estimating its width. Based on the simple description of the ITZ as a zone of higher porosity, the microhardness in this zone should be lower than that of the bulk. In some test results (Cross et al., 2000; Igarashi & Kawamura, 1994; Sergi & Page, 1992; Wang, 1988; Wei et al., 1986), this reduction was observed and the zone was reported to extend to distances of about 50 μm from the surface of the particular inclusion. In view of these findings, and the implication that microhardness could be used to compare the microstructure of different concrete specimens, this technique was considered to be relevant and was included in the experimental programme.

Hardness, conventionally expressed in kg/mm^2, is defined as the average pressure acting over the area of contact of a diamond indenter and is found by dividing the load by the surface area of the impression (Brace, 1960; Mott, 1956). In the microhardness indentation test a diamond pyramid indenter is pressed under a known load into a flat polished surface of the material under investigation. After the load is removed the size of the indentation is measured and the microhardness expressed as discussed previously. The two most common microindentation tests are the Vickers and Knoop tests and have been described in detail elsewhere (Vander Voort & Lucas, 1998; ASTM E 384 – 89, 1998; Mott, 1956; Tabor, 1951). For the current work, the particular equipment employed, was a Buehler Micromet hardness tester, which was fitted with a rhombohedral – shaped diamond indenter known as Knoop indenter (Figure 7.1). This is an elongated pyramid such that the angles between the long and short edges are 172°30' and 130° respectively. The shape of the perfect impression is a parallelogram for which the long diagonal is about seven times (7.114 actually) the length of the short diagonal.

Figure 7. 1 (a) Knoop indenter and (b) the indentation formed (Mott, 1956; Tabor, 1951).

Since the hardness, $H = \frac{Load}{Area}$

Then the Knoop hardness may be calculated from

$$HK = \frac{14229P}{l^2} \qquad (7.1)$$

Where P = the load in g

l = the long diagonal in μm

thus, only the long diagonal needs to be measured and this is undertaken using an optical system within the microhardness instrument and the same equipment electronically determined the hardness.

7.2.1 Specimens under investigation

7.2.1.1 Steel fibre inclusion and mix variation

This study was confined to selected plain and fibre reinforced concrete specimens cured in polythene sheeting. It was considered that microhardness profiles, from the surface matrix into the core of the concrete specimens, would provide further insight into the mechanisms by which the inclusion of fibres into the concrete mix increased abrasion resistance. A detailed study was therefore undertaken of the microhardness profiles produced by testing and comparing the following concrete mixes:

- A1, s/c, 0.51 % - 45 mm
- A2, s/c, 0.51 % - 45 mm
- A3, s/c, 0.51 % - 45 mm
- B4
- B5 and
- B6

One core was taken from each slab to produce a total of 6 samples to be investigated. In order to determine the microhardness profiles, indentation readings were recorded at the following locations below the surface of the samples: 0.00, 0.25, 0.50, 0.75, 1.00, 1.50, 2.00, 3.00, 5.00, 8.00, 12.00 and 16.00 mm.

7.2.1.2 Steel fibre content

In this series of tests, the influence of steel fibre content was more closely investigated. A concrete mix containing polypropylene fibres was also considered. Overall, the following concrete mixes were investigated:

- A2, s/c, 0.51 % - 45 mm
- A2, s/c, 1.0 % - 45 mm
- A2, s/c, 1.5 % - 45 mm
- A2, s/c, 2.0 % - 45 mm
- A2, s/c, 3.0 % - 45 mm
- A2, p, 0.1 % - 12 mm

One core was taken from each slab to produce a total of 6 samples to be investigated and the microhardness profiles, were recorded at the same locations as explained in section 7.2.1.1 above.

7.2.1.3 Interfacial transition zone

As with the previous sections, this was limited to studying the microstructural gradients of a concrete mix (A2, s/c, 0.51 % - 45 mm) at the ITZ around both a fibre near the surface and a fibre in the main body of a sample. The surface fibre was positioned at 0.055 mm (or 5.5 μm) from the surface while the bulk body fibre was positioned at 0.725 mm from the surface.

Unlike the previous sections, in order to determine the microstructural gradients, indentation readings were recorded at the following locations into the ITZ around the fibre: 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90 and 100 μm.

7.2.2 Experimental procedure

A 100 mm diameter core was taken from each test slab. A 5 mm thick section was cut using a diamond cutting wheel, from each core. One sample was selected from each core, on the basis of a minimum exposed aggregate area. The sample was cut parallel to the core axis from the top 30 mm. The face of each sample was approximately 60 x 30 mm and they were 5 mm thick. Each sample was embedded in Polyester repair paste (ISOPON 38, W David). Before embedment, the samples had been ground flat using a 9 μm aluminium oxide. The upper face of the sample was ground to 1 mm using diamond cutting pastes on a lapping plate.

Like all cementitious materials, concrete is characterised by a porous and heterogeneous microstructure and as such contains a wide range of particle and pore sizes. Therefore, it

was necessary that a significant number of particles and pores were included in the test area so that the microhardness data would be representative. Earlier studies (Henrikes, 1957) suggested that the error in microhardness values reduces considerably as the number of indentations increases. It has been reported (Sadegzadeh, 1985) that for non-porous materials, the optimum number of impressions is ten. All the samples were subjected to microhardness testing approximately 200 days after casting, using a Buehler Micromet 4 (See Figures F.1 and F.2 and Table F.1 of Appendix F) and following the procedure described below.

The polished specimen was placed on the graduated movable stage, so that when the stage was moved the sample surface moved in parallel with the objective lens. Two micrometer screws, at right angles to each other, allowed a network pattern of impressions to be conducted. For each sample, thirteen readings were recorded, distributed across its width. The position of each indentation was selected on the basis that it should not be over an aggregate particle. An appropriate load of 100 grams was selected and the period of indentation was kept constant in all tests, at 15 seconds. The length of the longer diagonal of the impression was accurately measured, three times, using the optical micrometer eyepiece and the high power objective.

The readings at the surface level, 0.00 mm, were in fact 4 μm below the surface. This was to ensure that the diagonals of the impression were wholly within the sample, and any which were partly located outside the sample were rejected. The impressions were not made adjacent to any visible voids, and were kept at least 5 diagonal lengths apart to prevent mutual interference. The three highest readings were rejected, on the assumption that they are probably taken on aggregate particles which had not been detected. The mean Knoop hardness value for any particular sample, was therefore the average value obtained from the remaining ten indentations. This is similar to the procedure adopted by Sadegzadeh (1985) in his investigation.

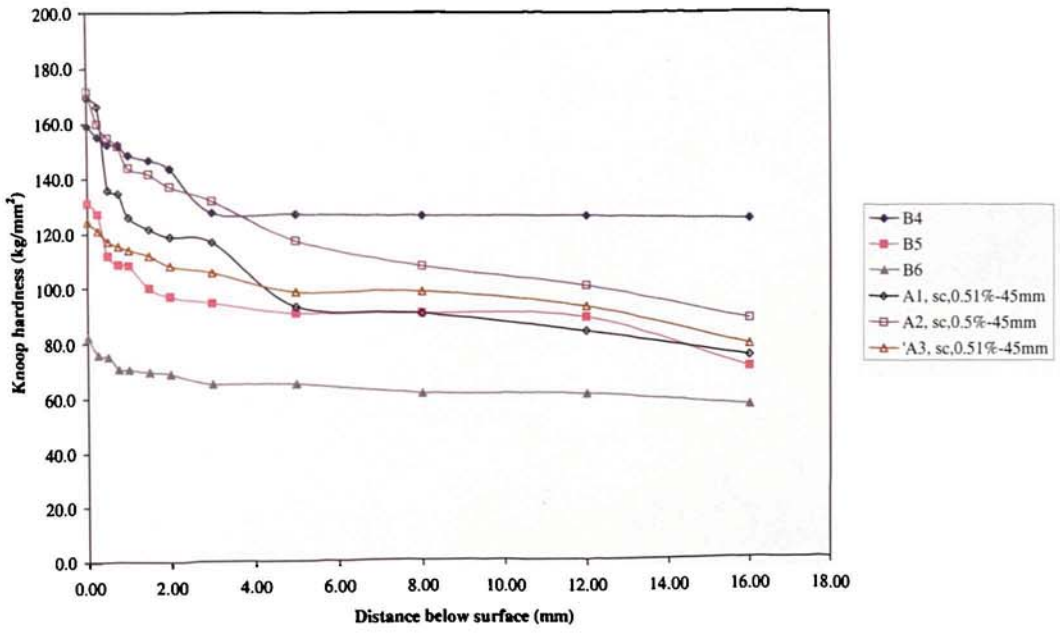
7.2.3 Results and discussion

The microhardness profiles for each of the samples investigated, together with the measurement range of Knoop hardness values, are presented in Figures F.3 to F.13 of Appendix F. The coefficient of variation for the Knoop hardness results varied between 10.17 – 15.87 %. A summary of these profiles has been plotted on Figures 7.2 and 7.3, to

permit comparisons. Of particular interest are the microhardness profiles which provide assessments of the hardness throughout the surface layer, to a depth of 16 mm, which may be used to assess the effectiveness of fibre inclusion and mix variation within the zone under investigation.

From an examination of the hardness profiles in Figures 7.2 and 7.3, several important trends are apparent. Figure 7.2 suggests that the hardness values for mix B4 are higher than those of mixes B5 and B6, which indicates that this method is sensitive to variations in the water-cement ratio. Furthermore, the same pattern was observed with the fibre reinforced concrete mixes at a standard steel fibre dose, 0.51 % by volume, i.e. the hardness values for mix A1, s/c, 0.51 % - 45 mm are higher than those of mixes A2, s/c, 0.51 % - 45 mm and A3, s/c, 0.51 % - 45 mm. These findings confirm the findings of Sadegzadeh (1985) for plain concrete, though direct comparison is not possible as the Vickers microhardness technique was used for the previous study.

Figure 7. 2 *Summary of the microhardness profiles, comparison of B4, B5 and B6 to A1, A2 and A3, s/c, 0.51 % - 45 mm*

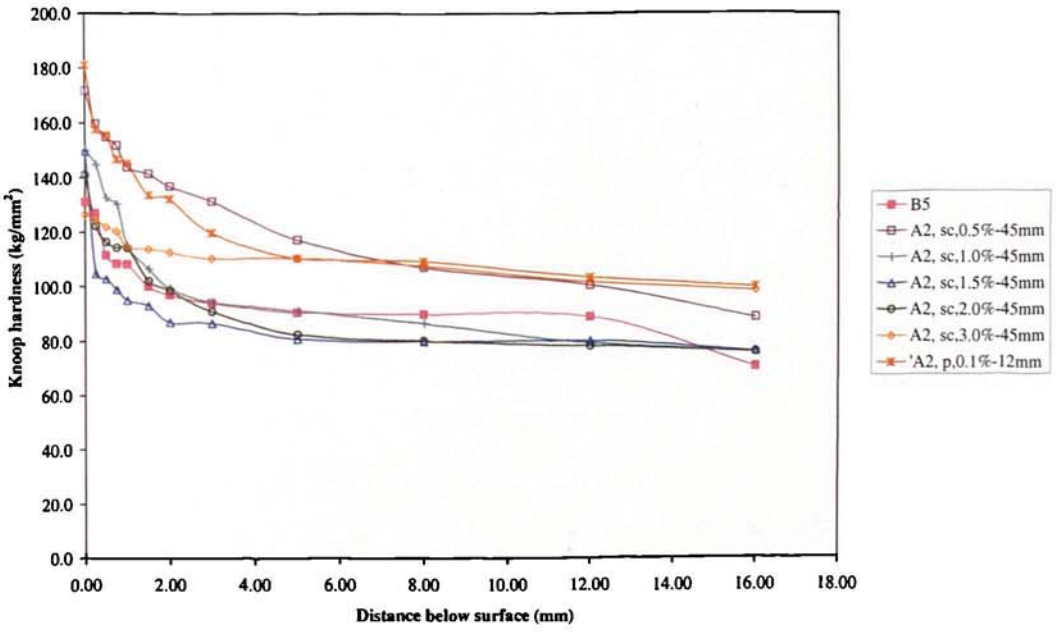


It is interesting to note that the fibre reinforced concrete mixes at a standard fibre dose of 0.51 % registered higher hardness values than the equivalent plain concrete mixes. For

example the hardness values for mix A3, s/c, 0.51 % - 45 mm are higher than those of mix B6. It appears that the top 2.00 – 2.50 mm are critical with the highest hardness values, this then becomes constant approximately 5 mm below the surface of each concrete sample. These hardness profiles demonstrate that the technique was able to detect the influence of fibre inclusion into the particular concrete mixes.

Figure 7.3 illustrates that with only one exception (mix A2, s/c, 3.0 % - 45 mm), the hardness values for the steel fibre reinforced concrete mixes are higher than those of the corresponding plain mix, B5, which suggests that this method is sensitive to variations in the steel fibre dose. The magnitude of this increase is greater at the immediate surface, with the top 2.00 mm being again critical. Furthermore, it has been found in that the highest hardness values were obtained from mix A2, p, 0.1 % - 12 mm which achieved a hardness profile higher than the corresponding plain and the steel fibre reinforced concretes.

Figure 7. 3 *Summary of the microhardness profiles, comparison of B5 to A2 mixes with various inclusions of fibres*



It is suggested that by considering the mechanisms developed in earlier studies (Wei et al., 1986; Cross et al., 2000) an explanation of this behaviour can be provided. Although Wei et al. (1986) used steel fibres and acrylic polymers when producing their samples, they

concluded that the properties of the fibre-matrix interface influenced both the tensile strength and toughness (capacity to absorb energy) of concrete. Cross et al. (2000) complimented this work and reported that polypropylene fibres also have an important role in influencing parameters such as the tensile strength of the matrix, the interfacial bond strength and the microhardness of the matrix.

In order to try and develop an explanation of the mechanism whereby the addition of acrylic polymers and reduced w/c ratio produced a material with higher tensile strength, bond strength and microhardness, Wei et al. (1986) studied the microstructure of the cementitious matrix with a scanning electron microscope. They found that for samples without acrylic polymer, there was substantial cracking at and near the fibre interface. After the fibre-matrix interface had been broken, they observed that the surface of the fibre, for samples without the acrylic polymer, was relatively clean (free of cement particles), while for the samples with acrylic polymer, the surface of the fibre had cement particles adhered to it suggesting higher bond strength and hence increased mechanical properties. This is consistent with the findings of other investigators (Alwahab & Soroushian, 1987; Barr & Liu, 1982) who used polypropylene fibres in their studies and reported that they increase flexural strength and toughness. They (Bayasi & Zeng, 1993; Ramakrishnan et al., 1987; Alwahab & Soroushian, 1987; Litvin, 1985; Zollo, 1984; Hanna, 1981) also suggested that the post cracking behaviour of PFRC is much greater due to its ability to continue absorp energy as fibres pull out. Although no scientific procedure was used to measure the bond strength between the cementitious matrix and the polypropylene fibres in mix A2, p, 0.1 % - 12 mm, it was clear when the specimen were subsequently broken up for disposal, that the hardened PFRC sample and the corresponding SFRC sample, that the polypropylene fibres behaved in a similar manner as the acrylic polymers – with the cement particles adhered to them – while no adhesion was apparent with the crimped steel fibres, confirming the findings by Wei et al. (1986).

It has been established (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985) that, with respect to abrasion resistance, once the immediate surface matrix has been penetrated the sample is considered to have failed. Therefore, the main objective in increasing abrasion resistance of concrete floors has centred on reinforcing this surface matrix. Indeed Sadegzadeh (1985) has shown that abrasion resistance is controlled by the hardness of the surface layer, some 200 – 500 μm in thickness, and so the depth of abrasion has been plotted against the microhardness values at the surface of each slab. Figures 7.4 and 7.5 suggest that the

abrasion resistance is directly related to the microhardness of the sample. It is clear that a surface matrix with high value of hardness leads to a very low abrasion depth as is demonstrated by samples with low w/c ratio and with low fibre doses. On the other hand, where the immediate surface had a low hardness value, a high abrasion depth was obtained, as was the case with high w/c ratio samples and samples with high fibre doses.

Figure 7. 4 *Abrasion depth vs. Surface microhardness for plain concrete mixes B4, B5 and B6 and fibre reinforced concrete mixes A1, A2 and A3, s/c, 0.51 % - 45 mm*

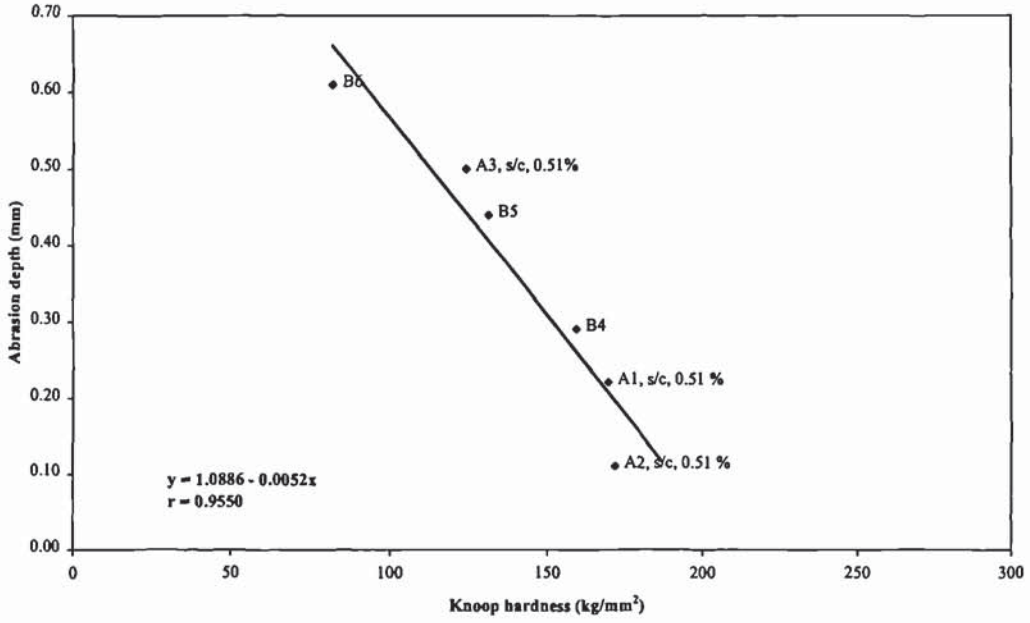
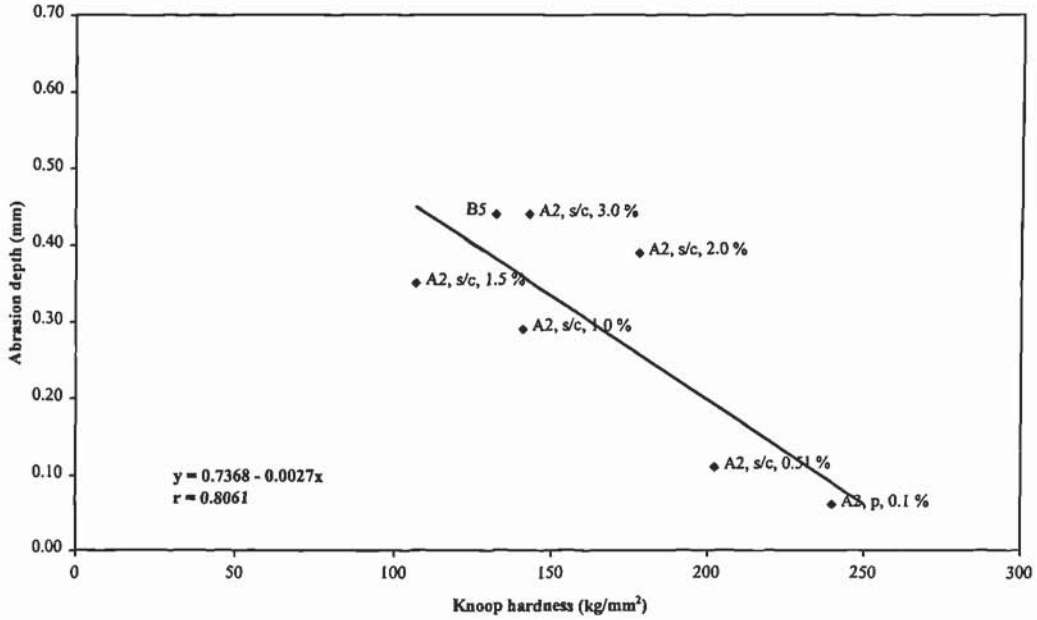
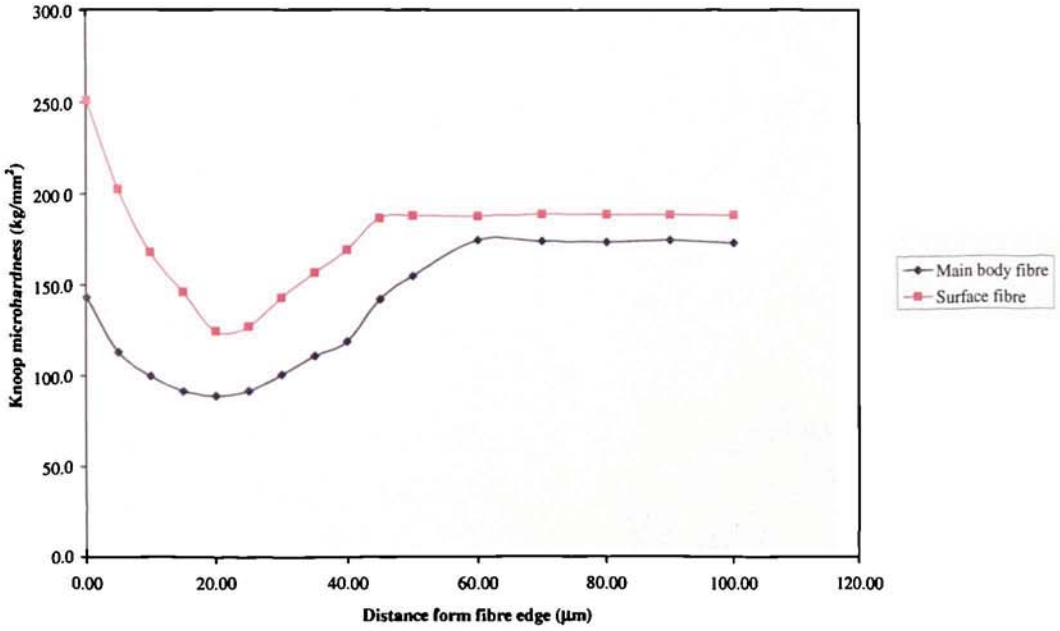


Figure 7. 5 *Abrasion depth vs. Surface microhardness for B5 and A2 mixes with various inclusions of fibres*



A limited investigation was conducted to characterise the ITZ around a steel fibre near the surface and around one within the bulk concrete. The microhardness profiles for each of these, together with the measurement range of Knoop hardness values, are presented in Figures F.14 and F.15 of Appendix F. A summary of these profiles has been plotted in Figure 7.6, for comparison. As illustrated, it was generally found that the paste around the fibre at the surface produced higher hardness values than the paste around the fibre within the bulk body of the sample. This is consistent with the findings previously discussed.

Figure 7. 6 Microhardness profile of the ITZ around steel fibre in mix A2, s/c, 0.51 % - 45 mm

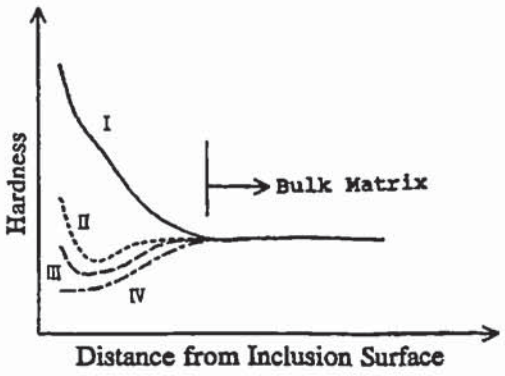


However, these profiles in Figure 7.6 also show the existence of a softer region roughly 40 to 60 µm away from the reinforcement. This region appears similar to that reported by Wei et al. (1986) for cement paste microhardness near a steel fibre and Cross et al. (2000) for cement paste microhardness near a polyolefin fibre. This indicates that the type of fibre probably does not significantly affect the structure of the ITZ. A variety of microhardness profiles have been reported (Cross et al., 2000; Igarashi et al., 1996a; Wang, 1988; Wei et al., 1986). Common to all, including the current study, is the observation that in the vicinity of the inclusion surface there is a gradient in the microhardness, but the hardness of the bulk paste is relatively constant.

The nature of the microhardness gradients previously reported (Cross et al., 2000; Igarashi et al., 1996a; Wang, 1988; Wei et al., 1986) can be quite different. Some investigators have

reported smaller microhardness values in the ITZ in the main body of the material. This reduction terminates as the inclusion surface is approached and the microhardness increases to values equal to or greater than those of the bulk paste. Rarely has a trend of consistently lower microhardness, right up to the inclusion surface, been reported (Igarashi et al., 1996b). The trends in the gradients can be classified into four types as shown in Figure 7.7.

Figure 7. 7 *Classification of microhardness profile in the ITZ around a rigid inclusion in a cement past matrix (Igarashi et al., 1996b)*



According to Igarashi et al. (1996b), Type I curve (Figure 7.7) is expected to occur in systems in which:

(a) the matrix in the vicinity of the inclusion has the same properties as the bulk and the inclusion and the matrix are well bonded at the interface or
(b) the near surface ITZ is rich in massive calcium hydroxide – $Ca(OH)_2$.

Deviations from these conditions can lead to changes in the shape of the curve and can account for shapes such as Types II, III and IV. If the structure at the ITZ is weaker than that of the bulk matrix and the bond at the actual interface is poor, the shape that will result is IV (Figure 7.7). If there is a depression in the curve as in II and III, it can be assumed that there is a weak microstructure at the ITZ. The rise in the curve as the inclusion surface is approached can be indicative of at least partial bonding at the surface that enables the inclusion to provide a restraining effect on the indenter or the presence of massive $Ca(OH)_2$ (Igarashi et al., 1996b).

The microhardness profiles in Figure 7.6 may therefore be classified as type II for the ITZ around the steel fibre near the surface and type III for the ITZ around the steel fibre within the bulk concrete. This indicates that even though the bond between the steel fibre and the matrix in general is probably quite weak, the bond of the steel fibre nearer the surface and the paste is stronger than the one between the main body fibre and the paste. It should be borne in mind, however, that such interpretations of the microhardness curves are qualitative in nature and based on indirect evidence.

7.3 Mercury intrusion porosimetry method

Mercury intrusion porosimetry (MIP) is a popular method for studying porosity and pore structure of cement based materials. Many investigators have used this technique on hydrated cement pastes and cement mortars (Robens et al., 2002; Vocka et al., 2000; Olson et al., 1997; Almudaiheem, 1992; Odler & Röβler, 1985; Röβler & Odler, 1985; Alford & Rahman, 1981; Cebeci, 1981; Goto & Roy; 1981; Bager & Sellevold, 1975; Sellevold, 1974; Auskern & Horn, 1973; Diamond, 1971; Winslow & Diamond, 1970). In more recent years it has been adopted for studying the microstructure of concrete as well (Laskar et al., 1997; Webb, 1996; Cook & Hover, 1993; Phitides, 1991; Sadegzadeh, 1985). The current study, utilised a Micrometrics Poresizer (Model: 9310, V1.05) which operated to a maximum pressure of 50 000 psi. Further details of the equipment used and the operating procedure are fully described in the instruction manual (Micrometrics Instrument Corporation, 1988). This method was used to study the effect of mix design, fibre content and fibre type on the microstructure of concrete, particularly that of the surface layer.

The underlying principle of the mercury penetration method is negative capillary. A non-wetting liquid (one forming a contact angle with a given solid greater than 90^{o}) will intrude open pores of the solid only under an applied pressure. The pressure required is a function of the contact angle, the surface energy of the liquid and the geometry of the pores. For the case of cylindrical pores the relation between applied pressure and the pore size penetrated at that pressure was reported by Washburn (1921):

$$P = \frac{-4\gamma \cos\theta}{d} \tag{7.2}$$

Where P = pressure required to intrude a pore

d = diameter of the intruded pore

γ = surface energy of the liquid

θ = contact angle between the liquid and the pore wall

The porosimeter provides the volume of mercury that is forced, under various pressures, into the pores of the material and the void spaces between particles. The material under investigation is first dried and evacuated to remove absorbed gases and vapours. Mercury will then penetrate the pores or void spaces in proportion to their size and to the applied pressure.

When using the MIP technique to investigate concrete, it must be borne in mind that the results may be affected by the method of sampling, sample conditioning, sample mass, sample dimension, rate of pressure application, assumed pore shape, value of the contact angle and the assumed surface tension of mercury. Other factors, such as the expansion of sample cell under pressure, differential mercury compression, sample compression and hydrostatic head of mercury may also affect the MIP results (Laskar et al., 1997). Some investigators have recognised the above effects and suggested relevant correction factors (Cook & Hover, 1993). Hearn & Hooton (1992) reported the effects of sample mass, sample dimensions and rate of pressure application on pore size distribution (PSD) results obtained from MIP testing of cement paste samples. Konecny & Naqvi (1993) have reported the effect of different techniques of sample conditioning on pore size distribution of cement mortar.

From the published literature it has become clear that the accuracy of the MIP technique is limited by several assumptions, the three most important are as follows:

- the pores are cylindrical,
- the wetting angle is constant throughout the microstructure and
- the surface tension of mercury is constant

It should be appreciated that the Washburn equation (7.2) assumes cylindrical pores, though in reality the pores are highly irregular. Nevertheless, it is considered to have an insignificant effect to the present study since the equation affects the calculated diameter but not the PSD curve (Sadegzadeh, 1985). In addition, as the purpose of this exercise is

comparative, it focuses on the changes in the PSD between the different concrete samples rather than the establishment of absolute values.

The choice of mercury contact angle and surface tension values both have the effect of shifting the PSD curve horizontally along the pore size axis but do not change its shape (Cook & Hover, 1993). Several factors were shown to affect the contact angle, including the material being intruded, the drying method and the purity of the mercury (Olson et al., 1997; Winslow & Diamond, 1970). For concrete porosimetry two values are commonly used: 117°, for oven-dried materials and 130°, for materials dried by any other means (Cook & Hoover, 1991; Feldman & Beaudoin, 1991; Sadegzadeh, 1985; Bager & Sellevold, 1975; Auskern & Horn, 1973; Winslow & Diamond, 1970). For comparing porous materials of the same type, it does not really matter which value is chosen, unless an exact measure of the pore openings is required (Rootare, 1970). While previous investigators (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985) used a contact angle value of 117° and oven-dried their samples, for the present programme the contact angle value of 130° was considered to be more appropriate because the samples were not oven-dried. The method used to dry the samples is described in detail in Section 7.3.2.

Commonly accepted surface tension values are 0.473, 0.480, 0.485 N/m, with 0.485 N/m being predominantly used (Cook & Hover, 1993; Sadegzadeh, 1985; Roberts, 1964). The effect of the choice of surface tension is similar to that of a contact angle, the range of accepted values, however, is much smaller. Therefore, the choice of surface tension within the range of commonly accepted values has a much smaller effect than does the choice of a contact angle (Cook & Hover, 1993) and a value of 0.485 N/m was adopted for this investigation. This is the same value used by other investigators (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985) of abrasion resistance at Aston.

Finally, while the MIP technique is not perfect (Diamond, 2000), it provides results which are consistent with those from other methods such as capillary condensation and nitrogen adsorption techniques (Almudaiheem, 1992; Diamond, 1971).

7.3.1 Specimens under investigation

7.3.1.1 Steel fibre inclusion and mix variation

This study was confined to selected plain and fibre reinforced concrete specimens cured in polythene sheeting. Specimens removed from slabs cast for abrasion testing in Chapter 6 were tested. The following concrete mixes were investigated:

- A1, s/c, 0.51 % - 45 mm
- A2, s/c, 0.51 % - 45 mm
- A3, s/c, 0.51 % - 45 mm
- B4
- B5 and
- B6

One sample was removed from the surface matrix of each of these slabs and a total of 6 MIP were carried out for this part of the work. It was decided to only test single samples as work by other researchers (Sadegzadeh, 1985; Cebeci, 1981; Winslow & Diamond, 1970) had demonstrated that the test is reproducible.

7.3.1.2 Steel fibre content

In this series of tests, the influence of increased steel fibre content was investigated. A concrete mix containing polypropylene fibres was also considered. The following concrete mixes were investigated:

- A2, s/c, 0.51 % - 45 mm
- A2, s/c, 1.0 % - 45 mm
- A2, s/c, 1.5 % - 45 mm
- A2, s/c, 2.0 % - 45 mm
- A2, s/c, 3.0 % - 45 mm
- A2, p, 0.1 % - 12 mm

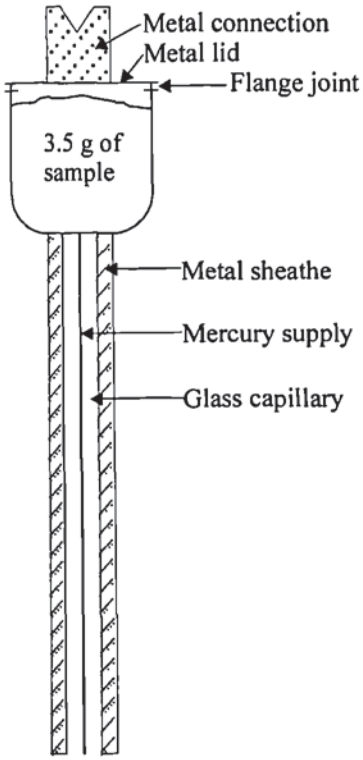
One sample was taken from each slab to produce a total of 6 samples for MIP investigation.

7.3.2 Experimental procedure

The 100 mm diameter cores taken for the microhardness investigation also provided the samples for this study. A 5 mm thick section was sliced from the surface matrix of each of these cores using a diamond cutting wheel. Each of these slices was broken using a hammer and chisel, into small pieces of approximately 5 – 7 mm in size and the large aggregate particle were discarded to leave the cement paste matrix. 5 – 6 g were placed in a tube with propan-2-ol and placed in an ultrasonic bath for 2 – 3 minutes. The original propan-2-ol was discarded and replaced with a fresh amount. It was allowed to stand for 48 hours to replace any moisture/water within the sample. The propan-2-ol was poured away and the sample was spread out on a filter paper and blown with cool air, to surface dry the sample. It was placed in a clean tube and evacuated in a vacuum desiccator for 1 day to remove the majority of the propan-2-ol from the pores.

A specimen of 3.5 grams was accurately weighed and sealed into the glass penetrometer cell (Figure 7.8). The penetrometer was inserted into the low-pressure port of the poresizer and evacuated for at least an hour at a pressure of less than 50 μm of mercury to remove any gases. The cell was then completely filled with mercury. The column of mercury in the capillary forms a coaxial capacitor with the metal sheathe surrounding the glass tube. Starting at 1 psi the pressure surrounding the glass cell was increased in stages allowing mercury to penetrate pores of suitable size. The capacitance changes, which occurred as the mercury column shrank back, were used to calculate the volume of pores filled. When atmospheric pressure was reached the penetrometer was removed from the low-pressure port and placed in the high-pressure vessel surrounded by fluid. Pressure was then applied in stages of up to 30 000 psi. Errors due to mercury compressibility were corrected by carrying out a blank run using only mercury.

Figure 7. 8 The glass penetrometer cell



7.3.3 Results and discussion

The PSD data are presented in the form of cumulative pore diameter distribution curves, shown in Figures 7.9 and 7.10. In these the pore volume (volume of penetrated mercury), expressed in cm^3 of pore per gram of dried sample, is plotted against the pore diameter, expressed in μm. The applied pressure was converted to the pore diameter by using the Washburn equation (7.2). It is usual practice to represent the pore diameter on a logarithmic scale, mainly for convenience since the diameters range from a few tens of Angstroms to several microns. Further, this representation of data enables easier comparison of the current findings to those of previous studies (Webb, 1996; Phitides, 1991; Sadegzadeh, 1985) that have also used this method from presenting their findings.

The samples were subjected to MIP tests at approximately 230 days after the slabs had been cast. During this period the slabs had been stored at laboratory conditions. This exposure to the atmosphere could have influenced the PSDs due to carbonation. Although this was not investigated, it is suggested that all the samples were affected in a similar manner. It is also recognised that the particular drying process may have caused some

modification to the pore structure but was considered that this technique is the best with respect to preserving the pores (Konecny & Naqvi, 1993; Almudaiheem, 1992).

The PSD curves obtained from the 12 samples are illustrated in Figures 7.9 and 7.10 for each concrete mix. The curves for the fibre inclusion and/or mix variation (Figure 7.9) and the curves for fibre content (Figure 7.10) are provided in one graph for ease of comparison. In each of these graphs there is one PSD curve for each of the concrete mixes previously mentioned in Section 7.3.1.

The following observations have been drawn from an examination of the general form and appearance of the PSD curves shown in Figures 7.9 and 7.10:

- There is a systematic change in the PSD curves of the samples with increasing w/c ratios with the general distribution shifting to the left at lower w/c ratios, i.e. the pores become increasingly finer. This is true for both the plain and fibre reinforced concrete mixes (Figure 7.9). A similar pattern in the PSD curves has been observed with decreasing fibre volume (Figure 7.10) with the finest pores present in the concrete mixes with 0.51 % of steel and 0.1 % of polypropylene fibres.
- The total pore volume intruded decreased with decreasing w/c ratio for both the plain and fibre reinforced concrete mixes. This confirms the findings of previous investigators (Almudaiheem, 1992; Sadegzadeh, 1985; Odler & Röβler, 1985; Röβler & Odler, 1985; Auskern & Horn, 1973; Sellevold, 1974; Diamond, 1971; Winslow & Diamond, 1970) that the PSD is a function of w/c ratio. From the information extracted from Figures 7.9 and 7.10, and summarised in Table 7.1, it is apparent that the total pore volume intruded decreased with the addition of 0.51 % steel crimped fibres into the equivalent plain concrete mixes. Table 7.1 also shows that for these particular mixes the total pore volume intruded increased as the steel fibre content was increased beyond the threshold of 0.51%. Similar trends were also obtained for the median and mode pore diameters. This suggests that, up to a certain percentage, fibre inclusion reduced the porosity of concrete. Of particular note is the observation that the mix containing polypropylene fibres produced the lowest value of intruded pore volume amongst any of the tested mixes. This reduced porosity parallels the increased penetration resistance reported by the British Board of Agrément (1995), Certificate No. 92/2830, when Initial Surface Absorption Tests were carried on a similar PFRC mix. It was suggested that polypropylene fibres reduce the initial flow rate of water

absorption and this is further concentrated upon when comparing the results on Initial Surface Absorption Tests on several types of fibres presented in Section 8.2.2 of Chapter 8.

- There is a large variation in the initial pore entry diameter values and though no clear conclusions may be drawn, there is a tendency for smaller diameters with the FRC mixes. This suggests that fibre inclusion into the concrete mix effectively reduced the size of the surface pores.
- In comparing the PSD curves, a useful parameter is the "threshold diameter" which is described as the pore diameter at which the intruded pore volume rises sharply on the PSD curve. Further details concerning the determination of the "threshold diameter" have been published elsewhere (Khatib & Mangat, 1999; Khatib & Wild, 1996) and they have been used to examine the PSD curves in Figures 7.9 and 7.10. This suggests that the "threshold diameter" decreased with decreasing w/c ratio, this is more clearly shown in Figure 7.11. It is also apparent that, compared to the values for the equivalent plain concrete mix, the "threshold diameter" decreased with the addition of 0.51 % steel crimped fibres into the corresponding plain concrete mixes (Figure 7.11). Figure 7.12 shows that when the volume content of these fibres was increased above 0.51 %, the "threshold diameter" increased, particularly at the highest fibre contents of 2 and 3 %. The lowest value for this parameter was again found to be with the mix containing polypropylene fibres. This is also comparable with the reduced porosity and increased penetration resistance as discussed above.
- In general the inclusion of steel crimped fibres at 0.51 % and polypropylene fibres at 0.1 % by volume appears to have reduced both the coarse and fine pores in the surface matrix of the concrete slab.

Figure 7. 9 *Pore size distribution curves, comparison of B4, B5 and B6 to A1, A2 and A3, s/c, 0.51 % - 45 mm concrete mixes*

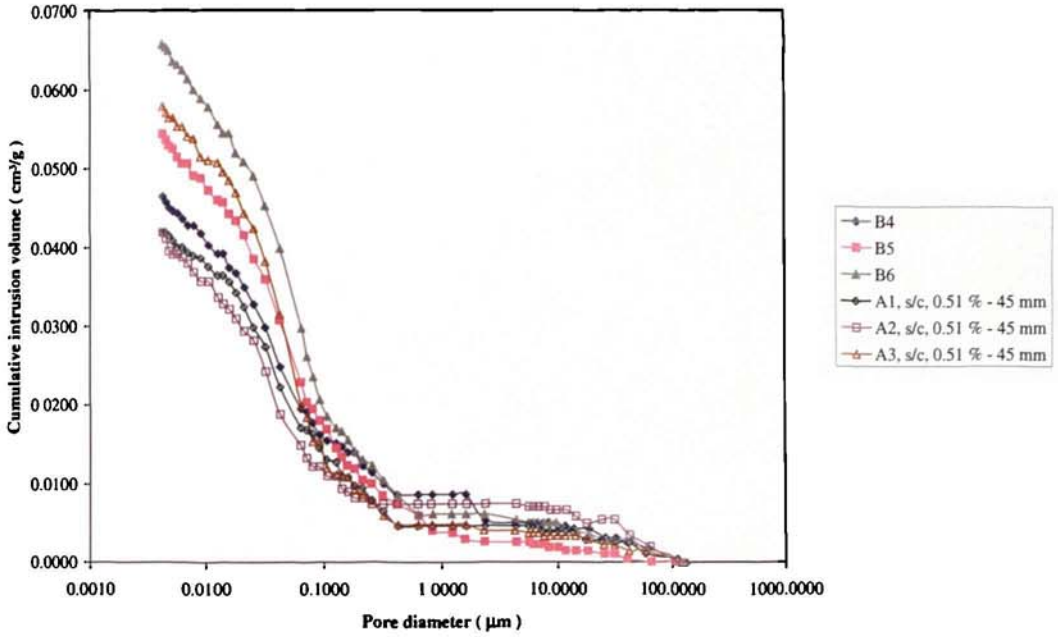


Figure 7. 10 *Pore size distribution curves, comparison of B5 to A2 mixes with various inclusions of fibres*

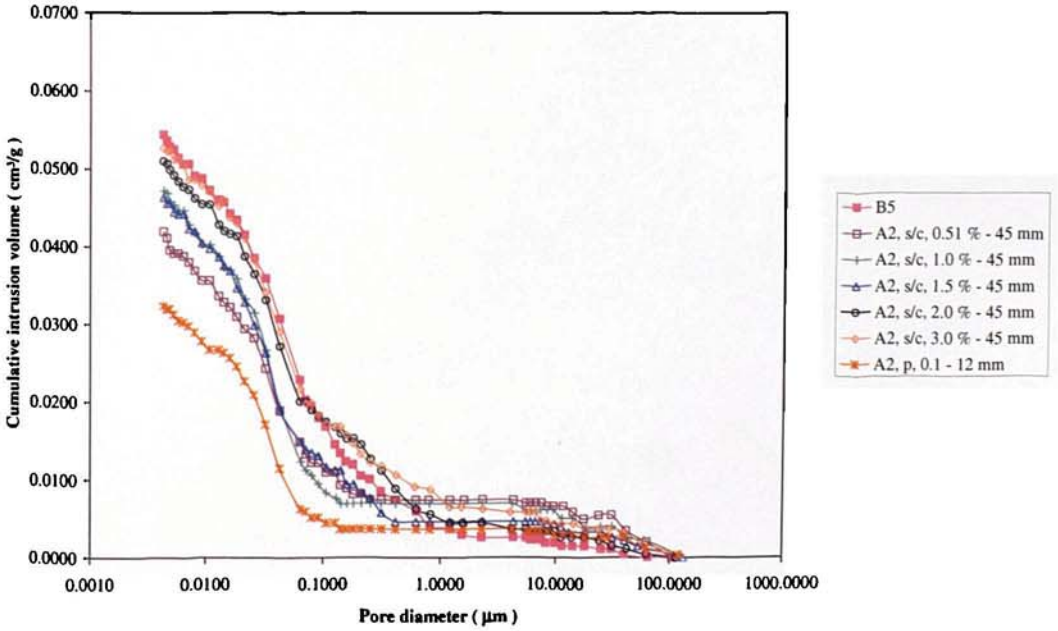


Table 7. 1 *Abrasion depth and MIP data for selected plain and fibre reinforced concrete mixes cured in plastic sheeting*

Mix No	Abrasion depth (mm)	Total pore volume (cm^3/g)	Initial pore entry diameter (μm)	Median pore diameter (μm)	Mode pore diameter (μm)
B4	0.29	0.0465	132.6482	0.0487	1.0769
B5	0.44	0.0544	106.7169	0.0519	1.1636
B6	0.61	0.0658	125.6049	0.0574	1.1018
A1, s/c, 0.51% - 45 mm	0.22	0.0419	112.6457	0.0477	1.1421
A2, s/c, 0.51% - 45 mm	0.11	0.0420	105.9205	0.0384	1.1693
A3, s/c, 0.51% - 45 mm	0.50	0.0579	121.3107	0.0473	1.1114
B5	0.44	0.0544	106.7169	0.0519	1.1636
A2, s/c, 0.51% - 45 mm	0.11	0.0420	105.9205	0.0384	1.1693
A2, s/c, 1.0% - 45 mm	0.29	0.0472	125.6049	0.0365	1.1036
A2, s/c, 1.5% - 45 mm	0.35	0.0464	133.8996	0.0365	1.0696
A2, s/c, 2.0% - 45 mm	0.39	0.0510	115.3931	0.0474	1.1341
A2, s/c. 3.0% - 45 mm	0.44	0.0527	125.6049	0.0505	1.0953
A2, p, 0.1% - 12 mm	0.06	0.0324	120.2827	0.0337	1.1160

Figure 7. 11 *Influence of fibre inclusion and mix variation on threshold diameter of concrete*

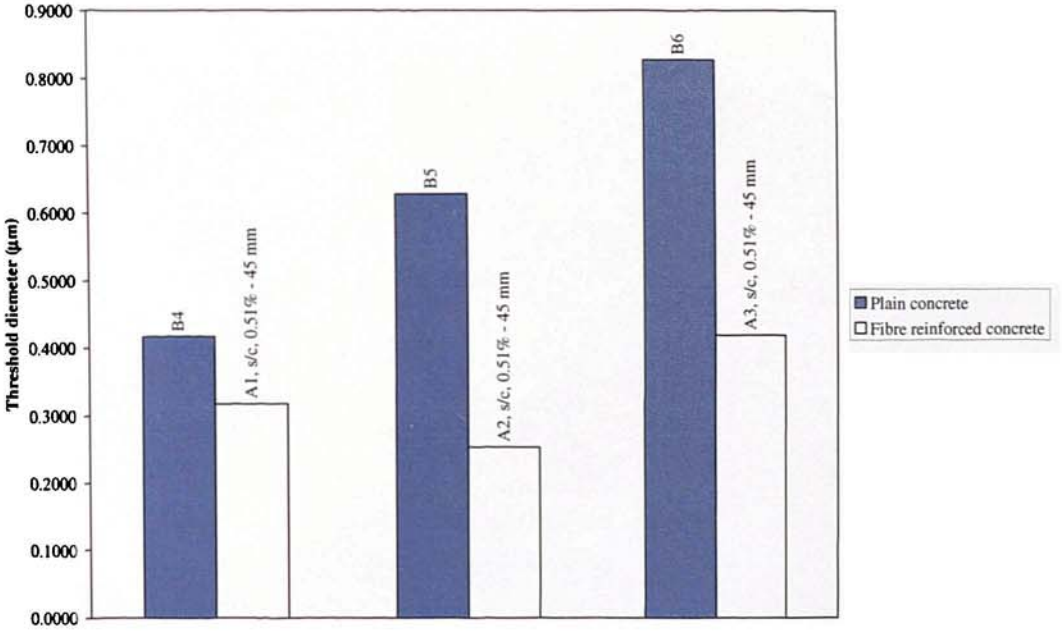
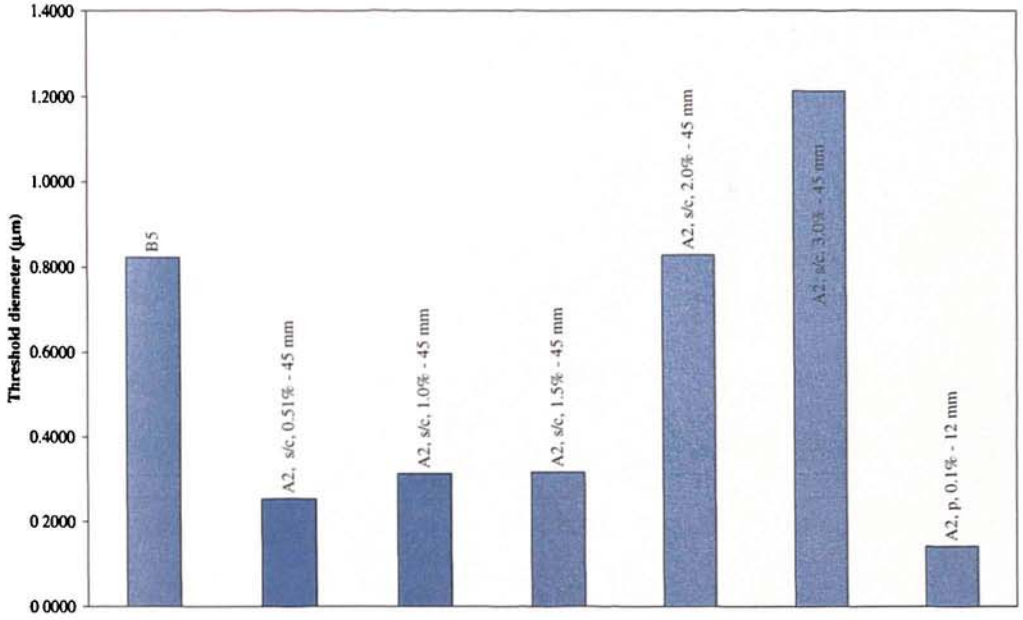


Figure 7. 12 Influence of fibre content on threshold diameter of concrete



These results have been used to prepare Figures 7.13 and 7.14, which show the relationships between total pore volume and abrasion depth for the various concrete mixes under investigation. It is clear from these graphs that the abrasion depth is directly related to the total pore volume, with the highest values of abrasion resistance, i.e. least depth of wear, being achieved by concrete with smallest volumes of pore space.

Figure 7. 13 Abrasion depth vs. Total pore volume for plain concrete mixes B4, B5 and B6 and fibre reinforced concrete mixes A1, A2 and A3, s/c, 0.51 % - 45 mm

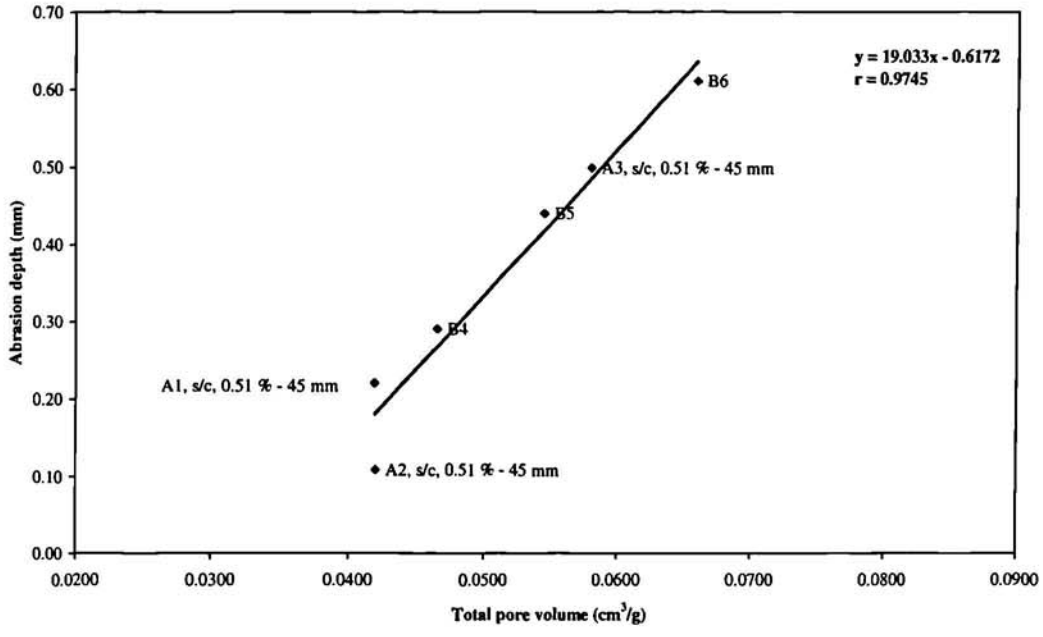
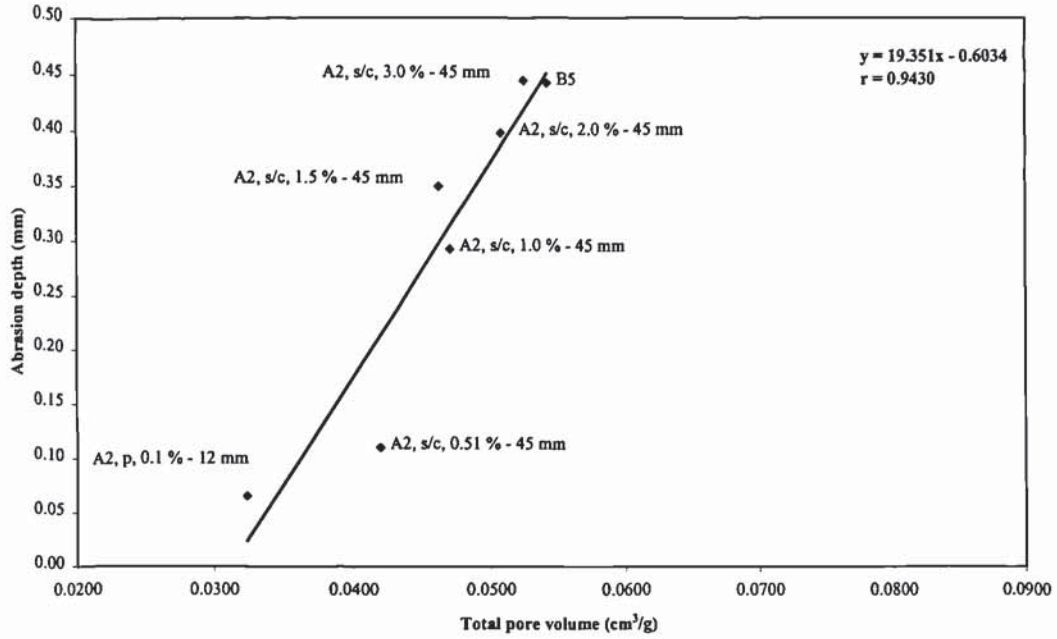


Figure 7. 14 *Abrasion depth vs. Total pore volume for B5 and A2 mixes with various fibre inclusions*



The results obtained from this part of the experimental study generally suggest that inclusion of fibres into the concrete mix influence the pore structure of surface matrix of the concrete floors. It has already been established (Sadegzadeh, 1985) that the abrasion resistance of concrete is controlled by the pore structure of its surface matrix so changes in pore structure are likely to influence the abrasion performance.

Several investigators (Belaid et al., 2001; Igarashi et al., 1996b; Sadegzadeh, 1985; Ramachandran & Feldman, 1973; Sereda, 1972; Soroka & Sereda 1968 a & b) have attempted to correlate porosity (of cement pastes) to microhardness. The current work has also demonstrated positive correlations between the hardness profiles and the MIP results, as shown by the relationships in Figures 7.15 and 7.16. These graphs show a direct relationship between porosity and microhardness. This is consistent with the findings of previous researchers, although the relationship concerning the effect of fibre content, given in Figure 7.16, is not as definitive as that given in Figure 7.15 for plain concretes and concretes containing 0.51 % by volume of the particular steel fibre. It may be that the porosity of mixes with higher fibre contents has also been influenced by their lower workability as none of these mixes contained a superplasticizer.

Figure 7. 15 *Total pore volume vs. Surface microhardness for plain concrete mixes B4, B5 and B6 and fibre reinforced concrete mixes A1, A2 and A3, s/c, 0.51 % - 45 mm*

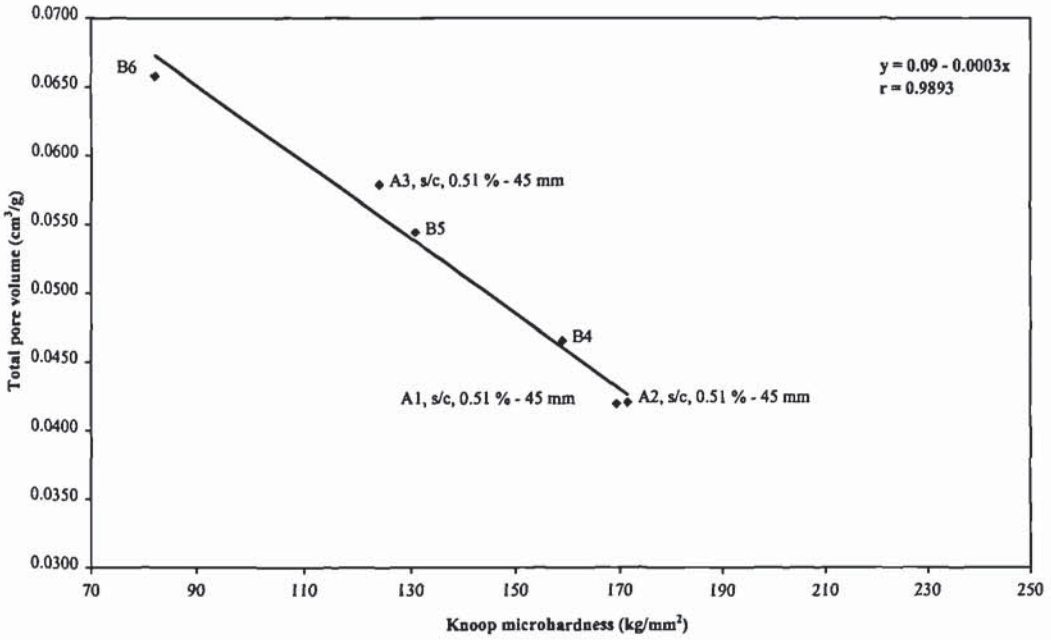
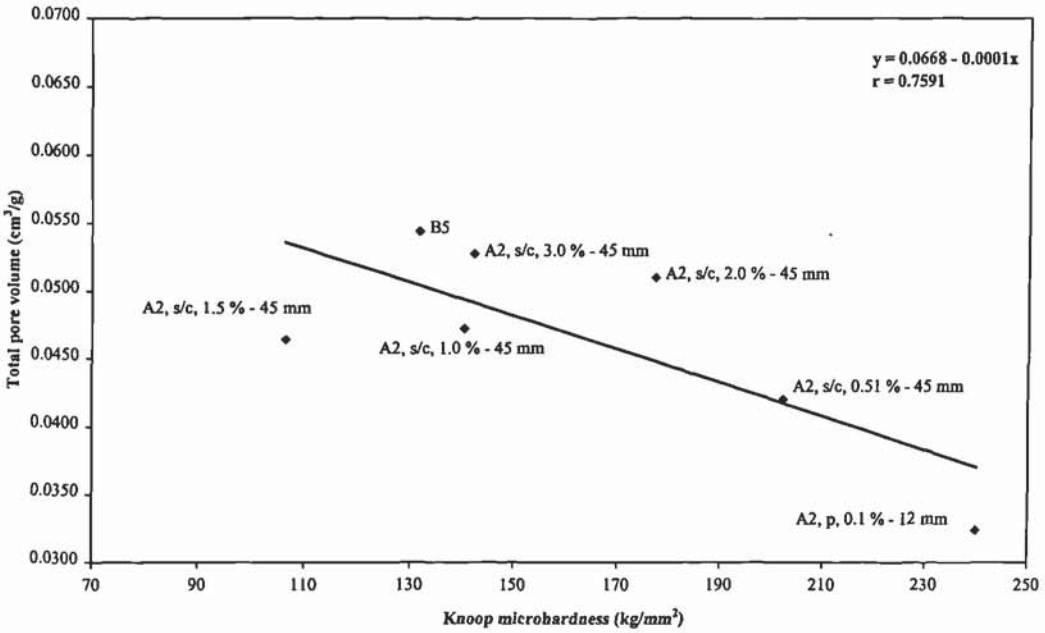


Figure 7. 16 *Total pore volume vs. Surface microhardness for B5 and A2 mixes with various fibre inclusions*



The results of the abrasion tests presented in Chapter 6 clearly showed that the inclusion of fibres into the concrete mix influenced the abrasion resistance of concrete floor slabs. Both the MIP and microhardness tests have demonstrated that fibre inclusion into the concrete mix produced significant changes in the quality of the surface matrix of the slab. The MIP

results showed that the PSDs were modified by fibre inclusion, suggesting that the w/c ratio and porosity of the surface layer had been reduced through a more effective surface bleed (i.e. the fibres acted as a bleed path). In essence this factor, in conjunction with an effective finishing operation, led to increased surface hardness which is further supported by the microhardness results. This extends the conclusions of a previous study (Sadegzadeh, 1985), which suggested that the abrasion resistance of plain concrete is primarily controlled by the porosity of the surface layer, to fibre reinforced concretes.

7.4 Petrographic examination

Petrography is the examination and evaluation of the composition and structure of rock and ceramic materials – such as bricks, natural stones, cementitious composites, concrete etc. The petrographic examination of concrete has a long history, as illustrated by several publications (St John, Poole & Sims, 1998; French, 1991; Mielenz, 1962; Mather, 1966) and it is considered to be a very useful tool in determining the underlying causes of performance problems (ASTM C856 – $95^{\varepsilon 1}$, 2001; Marfil & Maiza, 2001; Aligizaki & Cady, 1999; Livingston et al., 1999; Wigum et al., 1997).

A petrographic analysis begins with a visual examination of the material under investigation. During this phase, the petrographer also gathers information regarding the extent of the problem and the history of the project, including specific construction practices and preliminary observations of any unique characteristics in the concrete structure or test samples. Sometimes this is all that is needed to solve a particular problem. However, if the underlying cause is not self-evident, a more detailed examination using conventional or advanced techniques of microscopic analysis may be required (St John, Poole & Sims, 1998). A detailed examination may include any of the following tools applied to fractured, polished or thin sections: stereo microscopy, transmitted light microscopy, reflected light microscopy or scanning electron microscopy. In the present study, polished and thin sections were employed to conduct examinations of the specimen slabs.

7.4.1 Specimens under investigation

The same plain and fibre reinforced concrete slab specimens used for the microhardness and the MIP studies also provided the samples for this part of the work. A 100 mm diameter core was cut from each slab for this investigation.

7.4.2 Preparation of polished surfaces and thin sections

7.4.2.1 Preliminary examination

The cores were examined with a binocular microscope and their dimensions and main features were recorded. The features observed include the following:

- The presence and position of reinforcement
- The nature of the external surfaces of the concrete
- The features and distribution of macro and fine cracks
- The distribution, size range and type of the aggregate
- The type and condition of the cement paste
- Superficial evidence of any deleterious processes affecting the concrete

7.4.2.2 Polished surfaces

A plate was cut, where possible, from each core. This was typically 20 mm thick and provided as large a section of the sample as possible. The plate was polished to give a high quality surface that could be examined with a high quality binocular microscope or even with a petrological microscope if it was deemed necessary. The polished plate was used to assess the following:

- The size, shape and distribution of the coarse aggregate
- The coherence, colour and porosity of the cement paste
- The distribution, size, shape and content of voids
- The composition of the concrete in terms of the volume proportions of coarse aggregate, fine aggregate, paste and void.
- The composition of fine cracks and microcracks. The surface was stained with a penetrative dye, so that these cracks could be seen. Microcrack frequency was measured along traverses across the surface.
- The relative abundance of different rock types in the coarse aggregate.

7.4.2.3 Thin sections

A thin section was prepared for each sample as appropriate. The section was made from a plate cut at right angles to the external surfaces of the concrete, so that the outer 70 mm or so of the concrete were included in the section. The section approximately measured 50 x 70 mm.

In manufacturing the thin section, an initial sample some 10 mm thick was cut from the core. This was impregnated with a penetrative resin containing a yellow fluorescent dye. The resin penetrated into the cracks, microcracks and capillary pores in the sample. One side of the impregnated plate was then polished and the plate was mounted on to a glass slide. The surplus sample was then removed and the plate was ground and polished to give a final thickness of between 20 and 30 micrometers. At all stages the cutting and grinding was carried out using an oil based coolant in order to prevent further hydration of the cement and excessive heating of the section. The thin section was covered and then examined with a high quality petrological photomicroscope. A thin section usually supplies the following types of information:

- Details of the rock types present in the coarse and fine aggregate and, in particular, structures seen within these rocks.
- Details of the aggregate properties, such as the degree of strain in the quartz.
- The size, distribution and abundance of phases in the cement paste.
- Any products of the processes of deterioration of the cement paste and/or the aggregate.

7.4.2.4 Broken surfaces

After the specially prepared surfaces and sections were completed, the remainder of the core was examined with a binocular microscope. In particular, pieces were broken to produce fresh surfaces. These surfaces allowed the contents of voids and the nature of aggregate surfaces to be investigated.

7.4.2.5 Composition

The composition of the binder was measured using either the polished slice or the thin section, depending on the size of the sample and the details of the aggregate type and paste. The thin section is preferable, for example, where large quantities of dust are present. The volume proportions were found by the method of point counting using a mechanical stage.

The amount of coarse aggregate can also be assessed by this method if a distinction can be made between it and the fine aggregate. The results obtained usually represent the sample, reasonably, but may not represent the concrete. The amount of individual rock types present in the aggregate as a whole were assessed. From this information and the volume proportions, the weight fractions of aggregate, cement and water could be calculated.

7.4.2.6 Water/cement ratio

The hydration processes of cement paste vary significantly with the original w/c ratio. Concretes with a low w/c ratio tend to leave substantial quantities of unhydrated clinker and to develop only limited amounts of coarsely crystalline calcium hydroxide. In particular, the extent to which calcium hydroxide is separated into layers on the aggregate surfaces and occurs in voids and on voids surfaces varies with the original w/c ratio. The number and proportion of unhydrated cement clinker particles varies inversely with the original w/c ratio. Comparison with the standard concretes made with known w/c ratios, and by measurement allows the w/c ratio of the cement paste to be assessed directly. The standard error attached to the estimation of w/c ratio by this means is considered to be approximately ± 0.03 (Eden, 2001; St John et al., 1998).

7.4.2.7 Terminology in the description of the binder

A typical hydrated cement paste will contain some residual unhydrated cement grains, pseudomorphically hydrated cement grains and portlandite. Residual unhydrated cement grains occurs in nearly all cement pastes, even at w/c ratios in excess of 0.60. The term "pseudomorphically hydrated" indicates that the structure of the original cement grain remains, but the cement grain has been replaced with cement hydrates. "Portlandite" refers to calcium hydroxide crystals present in cement paste. In a normal concrete made with a w/c ratio of about 0.55 these crystals typically occupy about 30 % by volume of paste (Eden, 2001; St John et al., 1998).

7.4.3 Description of the samples

7.4.3.1 General features

(i) Introduction

The samples were all of similar concrete that contained a siliceous natural gravel coarse aggregate and a predominantly siliceous fine aggregate in a Portland cement based paste. The samples generally represented coherent and robust concrete and none of the samples

had macrocracking or obvious fine cracking. With the exception of samples B4, B5, B6, which contained no fibres, and A2, p, 0.1% - 12 mm, which contained polypropylene fibres all the other samples contained varied amounts of steel fibres. A circular swallow groove had been worn into the surface of each sample by the abrasion testing undertaken before coring. A typical sample as extracted from the concrete slab is illustrated in Plates G.1 and G.2 in Appendix G and the general features of the samples are listed in Tables G.1 (a) and (b) in Appendix G.

(ii) External surfaces

The top surfaces of all the samples were smooth, formed surfaces with a thin laitance. The surfaces of all the samples had a circular abrasion groove worn into their surfaces, these being approximately 20 mm wide. A typical groove is illustrated in Plate G.2 of Appendix G. With only two exceptions, sample A2, s/c, 0.51% - 45 mm and A2, p, 0.1% - 12 mm, the worn areas of surface exhibited coarse aggregate particles and/or fibres. Fine aggregate particles were exposed in the worn parts of the surfaces of all samples. The accompanying distribution of microcracking at the surfaces of the samples is described in detail in Section 7.4.3.5 of this report.

(iii) Cracking

None of the samples have macrocracking or obvious fine cracking. Details of microcracking extracted from the thin sections are given in Sections 7.4.3.4 and 7.4.3.5 of this report.

(iv) Carbonation

The carbonation depths have been measured using the thin sections and the results are given in Tables G.1 (a) and (b) in Appendix G. The general extent of carbonation at the external surfaces is low. However, carbonation occasionally penetrates along microcracks that intersect the external surfaces to depths of up to 10 mm from the external surface.

7.4.3.2 Coarse aggregate

(i) Size range and shape

The coarse aggregate was very similar in all the samples with a nominal maximum size between 16 and 21 mm. The particles were typically sub-rounded with low aspect ratios.

(ii) Rock types present

The coarse aggregate contained a wide range of rock types but was dominated by Metaquartzite and recrystalized sandstone and siltstone. The aggregate also contained minor amounts of chert and greywacke.

(iii) Properties of the rock types

The majority of the rock types in the coarse aggregate were dense and robust and of low porosity.

(iv) Surfaces of the coarse aggregate particles

The aggregate particles in all the samples generally made sound contact with the cement paste. However, there were sporadic patches of locally porous paste developed around the surfaces of some of the aggregate particles. In all samples coarsely crystalline portlandite was present around the surfaces of the coarse aggregate particles. Further details on the nature of the coarse aggregate are given in Tables G.2 (a) and (b) in Appendix G.

7.4.3.3 Fine aggregate

(i) Size range and shape

The fine aggregate in all the samples was a fine to medium siliceous sand composed mainly of sub-angular particles with low aspect ratios.

(ii) Rock types present

The sand was dominated by quartz and metaquartzite but also contained minor recrystalized siltstone, greywacke and chert and traces of ironstone and mica.

(iii) Properties of the rock types

The rock types in the fine aggregate were dense and robust and of low porosity.

(iv) Surfaces of the fine aggregate particles

The fine aggregate particles generally made sound contact with the cement paste. Coarsely crystalline portlandite was commonly present throughout all samples. Further details on the nature of the fine aggregate are given in Tables G.2 (a) and (b) in Appendix G.

At the worn surfaces of the samples there was evidence of sporadic microcracks developed around the surfaces of the aggregate particles exposed in the external surfaces and details of these microcracks are given in Sections 7.4.3.5 and 7.4.3.6 of this report.

7.4.3.4 Paste

(i) General features

As seen from the polished plates, the paste is very similar in appearance in all samples and has a mottled light reddish brown to medium reddish brown colour. The thin sections show that the paste in all samples is based on Portland cement and contains moderately abundant particles of unhydrated cement and coarsely crystalline portlandite. The paste has a moderate to high porosity in all samples and the distribution of the porosity is uneven on the microscopic scale. The petrographic features of the paste are listed in Tables G.3 (a) and (b) in Appendix G and details of the paste at the surfaces of the samples subjected to abrasion testing are given in Section 7.4.3.5 of this report.

(ii) Portlandite

The paste in all samples contains abundant quantities of coarsely crystalline portlandite. The amount of portlandite is slightly higher in samples "B6", "A2, s/c, 1.5% - 45 mm" and "A2, s/c, 2.0% - 45 mm" than it is in the other samples. Portlandite typically occupies between 10 and 15% by volume of the cement hydrates.

(iii) Residual cement grains

The paste in all samples contains moderately abundant particles of residual unhydrated cement. The residual unhydrated cement grains are of greatest abundance in Samples "B6", "A2, s/c, 1.5% - 45 mm" and "A3, s/c, 0.51% - 45 mm". The paste also contains pseudomorphically hydrated cement. However, the amount of pseudomorphically hydrated cement is generally lower than the amount of unhydrated cement.

(iv) Porosity

The paste has a moderate to high porosity in all samples. The distribution of the porosity is uneven with local patches of high porosity paste sometimes present around the surfaces of the aggregate particles. The areas of carbonated cement paste at the external surfaces are often of lower porosity than the paste at depth.

(v) Microcracking

Away from the external surfaces the level of microcracking is generally very low in all samples and no visible microcracking was found in the paste of samples "A1, s/c, 0.51% - 45 mm", "A2, s/c, 0.51% - 45 mm", "A2, s/c, 1.5% - 45 mm", "A2, s/c, 2.0% - 45 mm" and "A2, s/c, 3.0% - 45 mm". The microcracks in all samples are empty and are typically of the order of 0 to 1.5 μm wide. The majority of the microcracks away from the external surfaces are orientated radially around fine aggregate particles and sometimes penetrated some of the aggregate particles. Microcracks are locally abundant at the external surfaces and these are described in detail in Section 7.4.3.5.

(vi) Voids

Some of the voids throughout the plain concrete samples contain trace quantities of very fine needle-like crystals resembling ettringite. The voids throughout the fibre reinforced concrete samples are empty and no evidence was found for the presence of crystalline material such as ettringite or gel within the voids.

7.4.3.5 Microcracking at the external surfaces

The microcracking at the surfaces of the samples is illustrated in the fluorescent light photographs given in Appendix G. The petrographic observations of the microcracking below the worn external surfaces of the samples are summarised in Tables 7.2 (a) and (b).

The most commonly encountered microcracks in the external surfaces of all samples were orientated vertically. The vertically orientated cracks mostly passed through the cement paste but occasionally passed through some of the aggregate particles. The majority of these cracks were restricted to the outer 5 mm of the concrete and were generally truncated where they intersected the surfaces of coarse aggregate particles or voids. The number of vertically orientated cracks have been measured on lines of traverse across the external surfaces and the results are given in Tables 7.2 (a) and (b). It is clear that the number of cracks were reduced when introducing 0.51 % of steel crimped fibre to the equivalent plain concrete mixes. This suggests that the particular fibre is able to arrest and/or suppress crack formation and confirms the findings of other investigators (Aveston et al., 1974; Korczynskyj et al., 1981; Hannant et al., 1983) that have been discussed in detail in Section 2.12.2 of Chapter 2. From the results in Table 7.2 (b), it is apparent that the addition of the same fibre type at volumes of 1.0, 1.5, 2.0 and 3.0 % generated a higher number of cracks in these samples. Even though the reverse effect was anticipated, this

outcome is attributed to the reduced workabilities of these mixes, as they did not contain any superplasticizers. Not surprisingly mixes with reduced w/c ratios contained a larger number of cracks, whether plain or fibre reinforced and this is again attributed to reduced workability.

Table 7.2 (a) Microcracking distribution below the worn external surfaces

Sample reference	B4	B5	B6	A1, s/c, 0.51% - 45 mm	A2, s/c, 0.51% - 45 mm	A3, s/c, 0.51% - 45 mm
Maximum depth of sub-parallel cracking in the paste below worn surface (mm)	0.32	0.49	0.74	0.18*	0.19	0.33
Maximum depth of cracking along aggregate particle surfaces below the worn surfaces (mm)	Not found	0.20	0.92	0.20	0.31	0.28
Maximum depth of cracking in aggregate particles below the worn surface (mm)	0.09	0.20	0.92	0.18	0.12	0.16
Frequency of vertically orientated microcracks (cracks/40mm of surface)	26	5	9	12	5	6

*The paste has plucked from the surface of a steel wire about 0.2 mm below the general depth of the worn surface.

Table 7.2 (b) Microcracking distribution below the worn external surfaces

Sample reference	B5	A2, s/c, 0.51% - 45 mm	A2, s/c, 1.0% - 45 mm	A2, s/c, 1.5% - 45 mm	A2, s/c, 2.0% - 45 mm	A2, s/c, 3.0% - 45 mm	A2, p, 0.1% - 12 mm
Maximum depth of sub-parallel cracking in the paste below worn surface (mm)	0.49	0.19	0.30*	0.32**	0.35	0.81	0.18
Maximum depth of cracking along aggregate particle surfaces below the worn surfaces (mm)	0.20	0.31	0.14	0.25	0.75	1.00	0.34
Maximum depth of cracking in aggregate particles below the worn surface (mm)	0.20	0.12	0.22	0.22	0.50	0.64	0.13
Frequency of vertically orientated microcracks (cracks/40mm of surface)	5	5	6	11	12	12	5

*The greatest depth of cracking is seen where a particle of ironstone occurs just below the external surface
**Cracking most intense at the edges of the worn area

The second type of microcracking was orientated sub-parallel or parallel with the external surfaces. Though it has not been possible to quantify these cracks below the unworn parts of the sample surfaces, they visually appeared to be of greatest abundance below the worn parts of the surfaces. The depth of these cracks is again given in Tables 7.2 (a) and (b). Microcracks were also occasionally seen within some of the fine aggregate particles

exposed at the external surfaces and microcracks also developed around the surfaces of some of the fine aggregate particles where the fine aggregate particles were exposed at the surfaces. Overall a similar pattern was observed with the depth of these crack as with their number, discussed above. The depth of cracks reduced when introducing 0.51 % of steel crimped fibre to the equivalent plain concrete mixes. Further, the addition of the same fibre type at higher volumes generated deeper cracks in these samples. This is not only consistent with the results in the above discussion, which concentrated on the number of cracks present, but also with the abrasion depths presented in Chapter 6.

Where the steel fibres were less than about 0.5 mm from the surfaces of the samples during the abrasion tests the paste was plucked from the concrete surfaces. In sample A2, s/c, 3.0 % - 45 mm there were locally abundant microcracks in the paste surrounding a steel fibre very close to the surface of this sample. Where the steel fibres were more than about 0.5 mm from the surfaces there were no changes in microcracking levels in the paste surrounding the fibres.

Sample "A2, p, 0.1 % - 12 mm" contains polypropylene fibres, some of which were exposed in the worn parts of the surface of the sample. No evidence has been found for the development of locally abundant microcracking around the polypropylene fibres at the surfaces of sample "A2, p, 0.1 % - 12 mm". The polypropylene fibres in sample "A2, p, 0.1 % - 12mm" sometimes bridged microcracks at the external surface. This particular mix, appears to have performed better than most of the other mixes. This is consistent with the report by Hannant et al. (1983) who suggested that the inclusion of polypropylene fibres may enhance the matrix cracking strain by about 50 %.

7.4.3.6 Fibres

While sample "A2, p, 0.1 % - 12 mm" contained polypropylene fibres, the rest of the fibre reinforced concrete samples contained various proportions of steel fibres. The steel fibres were typically about 1 mm in diameter and the polypropylene fibres were about 0.02 mm in diameter. In Samples "A2, s/c, 1.5 % - 45 mm", "A2, s/c, 2.0 % - 45 mm" and "A2, s/c, 3.0 % - 45 mm" the steel fibres were sometimes concentrated into bundles of fibres. This is clear evidence of "balling" in mixes containing steel fibres in excess of 1.0 %. In the other samples the fibres appeared more or less randomly distributed. The polypropylene fibres in sample "A2, p, 0.1 % - 12 mm" occured as single fibres that appear randomly distributed throughout the cement matrix.

In all the samples that contained steel fibres there was no change in porosity of the paste around the surfaces of the fibres and no evidence for the development of microcracking in the paste surrounding the fibres. However, there were occasional voids at the surfaces of the steel fibres – particularly where the steel fibres were situated close to the external surface. No evidence has been found to suggest microcracking or porosity changes around the polypropylene fibre reinforcement in sample "A2, p, 0.1 % - 12 mm".

7.4.4 Discussion

7.4.4.1 Composition

(i) Water/cement ratio

The proportions of unhydrated cement have been used in conjunction with laboratory control concretes to make an assessment of the original water/cement ratios of the samples under investigation. The results are given in Tables G.4 (a) and (b) in Appendix G and it was observed that for plain concrete mixes the w/c ratio remained close to the expected values of 0.44, 0.52 and 0.65 for mixes B4, B5 and B6 respectively. However for at least two of the mixes containing 0.51 % of steel crimped fibres the w/c ratio was lower than these expected values. This confirms the findings presented in Chapter 6 with regards to the combined effects of fibre inclusion and surface finishing. The petrographically measured w/c ratio near the surface, for mixes containing steel fibres in excess of 1.0 %, was shown to be very close to the anticipated value of 0.52, suggesting that the w/c ratio increased with increasing fibre content. This again demonstrated the consequences of high fibre content without the use of superplasticizing aids, that mainly led to reduced workability and so with incomplete compaction the role of the steel fibre as an escape route for bleed water was much reduced. For mix A2, p, 0.1 % - 12 mm, containing polypropylene fibres the expected w/c value (= 0.52) dropped to 0.45 near the surface, due to the small dimensions of this type of fibres and therefore enhanced dispersion throughout the concrete mix.

(ii) Composition in terms of weight fractions

The volume factions have been converted into weight fractions assuming that the density of the aggregate is 2620 kg/m^3 and the density of the cement is 3140 kg/m^3. Combining the assumed densities with the measured volume proportions gives the compositions listed in Tables G.4 (a) and (b) in Appendix G. The values presented were calculated as an equivalent percentage by mass of oven-dried samples and particular attention is drawn to

the coarse aggregate content and the possibility that these compositions are not representative of the concrete as a whole. In terms of the cement content, the calculated values for the plain concrete mixes are very close to the expected ones, i.e. 365, 345 and 300 kg/m^3 for B4, B5 and B6 respectively. It is therefore assumed that the calculated cement contents for the rest of the mixes are correct. There is a tendency for those mixes that have performed poorly in terms of abrasion resistance to have a reduced cement content and vice versa. This is consistent with the findings of previous investigators (Chaplin, 1987; Sadegzadeh, 1985) who suggested that increased cement content led to improved abrasion resistance. It must be noted, however, that this content did not exceed 390 kg/m^3 compared to 400 - 475 kg/m^3 reported by others (Chaplin, 1987; Sadegzadeh, 1985).

7.4.4.2 Aggregate

The coarse and fine aggregates are very similar in all samples and are composed of generally dense and robust lithologies that show no evidence of deterioration within the concrete. Some of the rock types in the aggregate are potentially reactive with alkalies in cement paste. However, no evidence has been found to suggest alkali-aggregate reaction in these samples.

Away from the external surfaces there are few microcracks or voids present around the surfaces of the aggregate particles and the aggregate particles generally make sound contact with the cement paste. Where fine aggregate particles are exposed in the worn parts of the surfaces of the samples there are sometimes microcracks developed around the contact between the fine aggregate particles and the surrounding cement paste. This is discussed further in Section 7.4.4.5 of this report.

7.4.4.3 Paste

The paste in all samples is based on Portland cement, although in some samples it also contained either polypropylene or steel fibres. The paste is a generally coherent and robust material that has very low levels of microcracking. However, the paste in all samples has moderate to high levels of porosity with the porosity being patchy in distribution. No evidence has been found to suggest deterioration of the cement paste in these samples.

7.4.4.5 Effects of abrasion resistance testing

(i) Comparison of plain and fibre reinforced concrete samples

The surfaces of all samples have been subjected to abrasion resistance testing. The abrasion testing carried out on the plain concrete samples has worn a circular groove into the concrete surfaces, removed the surface laitance and exposed some of the aggregate particles. The thin sections show that microcracks had developed within the cement paste at the concrete surfaces of all three plain concrete samples as a result of abrasion resistance testing.

The depths of the grooves in the surfaces of the fibre reinforced concrete mixes show considerable variation. In samples "A2, s/c, 0.51% - 45 mm" and "A2, p, 0.1 % - 12 mm", which produced the lowest abrasion depths, the abrasion testing has patchily removed the surface laitance exposing a few aggregate particles. In the other fibre reinforced concrete samples the surface laitance has been completely removed in the worn areas exposing both coarse and fine aggregate particles as well as fibres. In all samples there are vertically orientated cracks at the surfaces and these show a considerable variation in frequency and are considered to reflect drying shrinkage.

Below the parts of the surfaces subjected to abrasion testing there were locally abundant sub-parallel microcracks in the paste with further microcracks occurring sporadically around the surfaces of aggregate particles exposed in the external surfaces. The depths of cracking below the worn parts of the external surfaces (given in Section 7.4.3.5 of this report) show a very wide variation. However, the distribution and form of cracking at the external surfaces is remarkably similar in all samples. The mechanism of wear at the surfaces appears to relate to microcracking in the paste and very localised weakening of the bond between aggregate particles and the surrounding paste as a result of microcracking. The greatest depth of sub-parallel and surface parallel microcracking in the paste is seen in samples B5 and B6, and in sample "A2, s/c, 3.0% - 45 mm". The cracking at the surface of sample "A2, s/c, 3.0% - 45 mm" is greatest at the edges of the worn areas of the surface.

(ii) Effect of steel fibres on abrasion resistance testing

Steel fibres occur in the paste of samples "A1, s/c, 0.51% - 45 mm", "A2, s/c, 0.51% - 45 mm", "A2, s/c, 1.0% - 45 mm", "A2, s/c, 1.5% - 45 mm", "A2, s/c, 2.0 % - 45 mm", "A2, s/c, 3.0% - 45 mm" and "A3, s/c, 0.51% - 45 mm". Where the steel fibres are greater than about 0.5 mm from the surface there is no change in microcracking levels. However, where

the fibres are closer than about 0.5 mm from the surfaces, the paste has plucked from the surfaces of the wires and in sample "A2, s/c, 3.0% - 45 mm" there is locally intense microcracking in the paste surrounding the steel wires. It is considered that this may reflect the transmission of vibration along the steel fibres situated very close to the abraded surfaces. These is also a tendency for fine, irregular voids to be present on the surfaces of the steel wires situated close to the outer surfaces.

(iii) Effect of polypropylene fibres on abrasion resistance testing

Polypropylene fibres are present in sample "A2, p, 0.1% - 12 mm". The fibres are more or less randomly distributed and no evidence has been found for the development of microcracking or for porosity changes in the paste surrounding the fibres. Some of the fibres are exposed in the worn part of the surface of sample "A2, p, 0.1% - 12 mm". However, no evidence has been found to suggest that the abrasion is more severe in the parts of the paste containing fibres at the surface of this sample. The polypropylene fibres occasionally bridge some of the microcracks in the external surface of sample "A2, p, 0.1% - 12 mm" and it seems a possibility that the fibres may have reduced the loss of the paste due to abrasion in this sample.

7.5 Conclusions

In this chapter, the investigation has been concerned with the microstructure of the concrete specimens that had been produced for the abrasion resistance study (Chapter 6). Three different techniques were used:

(i) Microindentation hardness examination technique, which revealed that:

- Variations in the water-cement ratio for both plain and fibre reinforced concrete mixes influence the microhardness of the surface matrix.
- The abrasion resistance of plain and fibre reinforced concrete was directly related to the microhardness of the surface matrix.
- The fibre dose influenced the microhardness of the surface matrix.
- The paste around a steel fibre nearer to the surface produced higher hardness values that the paste around the fibre within the bulk body of the sample, though the results showed the existence of a soft region roughly 40 to 60 μm away from the reinforcement.

(ii) Mercury intrusion porosimetry, which showed that:

- Variations in the water-cement ratio for both plain and fibre reinforced concrete mixes influenced the pore structure of the cement matrix within the specimens.
- The fibre dose influenced the pore structure of the cement matrix within the specimens.
- The abrasion resistance of plain and fibre reinforced concrete is directly related to the porosity of the surface matrix.

(iii) Petrographic examination of polished surfaces and thin sections that generally confirmed the results of the microhardness and MIP studies. In particular it revealed that:

- Variations in the water-cement ratio for both plain and fibre reinforced concrete influenced the formation and dimensions of microcracking within the specimens.
- The fibre dose influenced the formation and dimensions of microcracking within the specimens.
- The addition of 0.51 % of steel crimped fibres into the concrete mix suppressed crack formation.
- The abrasion resistance was influenced by "fibre balling" in mixes containing steel fibres in excess of 1.0 %. Improved performance was achieved with samples containing polypropylene fibres, where they occurred as single fibres and appeared randomly distributed throughout the cement matrix.
- The abrasion resistance is influenced by variations in the water-cement ratio near the surface that resulted from the combined effects of fibre inclusion and surface finishing.
- The abrasion resistance was improved with increasing cement content and vice versa, provided this amount did not exceed 390 kg/m^3.

The results obtained from the microstructural studies, generally support the findings which were presented in Chapter 6 and attempt to explain the influence of a number of factors upon the abrasion resistance of concrete in both quantitative and qualitative terms.

Chapter 8: Indirect and non-destructive testing for predicting abrasion resistance of fibre reinforced concrete

8.1 Introduction

The accelerated abrasion apparatus may be used to establish the quality of a concrete floor in terms of its abrasion resistance. Even though this type of test has gained general acceptance, an important shortcoming is that the abrasion machine will leave a circular abrasion path on the area tested which may be perceived as a lasting defect on a concrete floor. In general all abrasion testers are destructive to the concrete floor in that they permanently damage the particular test area. This incentive has prompted a number of research programmes (Dhir et al., 1991; Sadegzadeh & Kettle, 1986; Tomsett, 1974; Levitt, 1969) to investigate the use non-conventional and non-destructive methods to predict abrasion resistance. However, none of the previous researchers have used fibre reinforced concrete during their investigations, a material that nowadays is being increasingly used by the UK floor industry.

The surface zone has a vital role in determining the durability of concrete. It is well established that the structure and properties of this surface concrete are different from those of the matrix (Dhir et al., 1991; Sadegzadeh et al., 1987) and its quality and performance are influenced by such factors as the water-cement ratio, curing regime and finishing technique (Sadegzadeh et al., 1987). These factors contribute in the material's performance in terms of its surface permeability, hardness, impact and abrasion resistance. It was therefore considered important to examine any relationships between these near surface characteristics and this aspect is reported in this chapter. The particular methods that were investigated have frequently been used for assessing the quality of concrete and they are:

- Initial surface absorption

- Impact test
- Ball cratering
- Scratch test
- Base hardness test

8.2 Initial surface absorption test

The initial surface absorption has been defined as the rate of flow of water into concrete per unit area after a stated interval from the start of the test, at a constant applied head and temperature (BS 1881: Part 208: 1996). The initial surface absorption test (ISAT) has been used by many investigators (Wilson et al., 1998; Claisse et al., 1997; Price & Bamforth, 1993; Dhir et al., 1993; Dhir & Byars, 1991; Dhir et al., 1991; Dhir et al., 1987; Sadegzadeh, 1985; Powers et al., 1954; Levitt, 1969) to assess the surface quality of concrete. In fact this test has been available for over 30 years and is included in BS 1881: Part 208: 1996 for testing concrete. ISAT test results have been shown to be a sensitive indicator of concrete surface quality as influenced by the constituent materials, the w/c ratio and the curing regime (Dhir & Byars, 1991; Price & Widdows, 1991; Sadegzadeh, 1985). Although the ISAT is easy to carry out and interpret, two potential disadvantages that limit its more widespread use have been identified.

The first disadvantage concerns the effects of the moisture condition and the state of saturation of the test specimens prior to undertaking the test and the difficulties in achieving a uniform reproducible moisture content, these have been described by a number of investigators (Price & Bamforth, 1993; Dhir & Byars, 1991; Dhir et al., 1987). The non-uniaxial flow of water through the concrete surface is the second disadvantage. In practical terms, the absorption of water (and other aggressive agents) will be predominantly uniaxial in plane surfaces. However, in detailed examinations of the ISAT test, both Hall (1989) and Dhir & Byars (1991) have described the phenomenon of lateral spreading of the wetting front during the test period. This is particularly noticeable in low grade and poorly cured concretes. To remedy these shortcomings several modified tests have been proposed (Price & Bamforth, 1993; Dhir et al., 1987) but none has gained general acceptance (Neville, 1999).

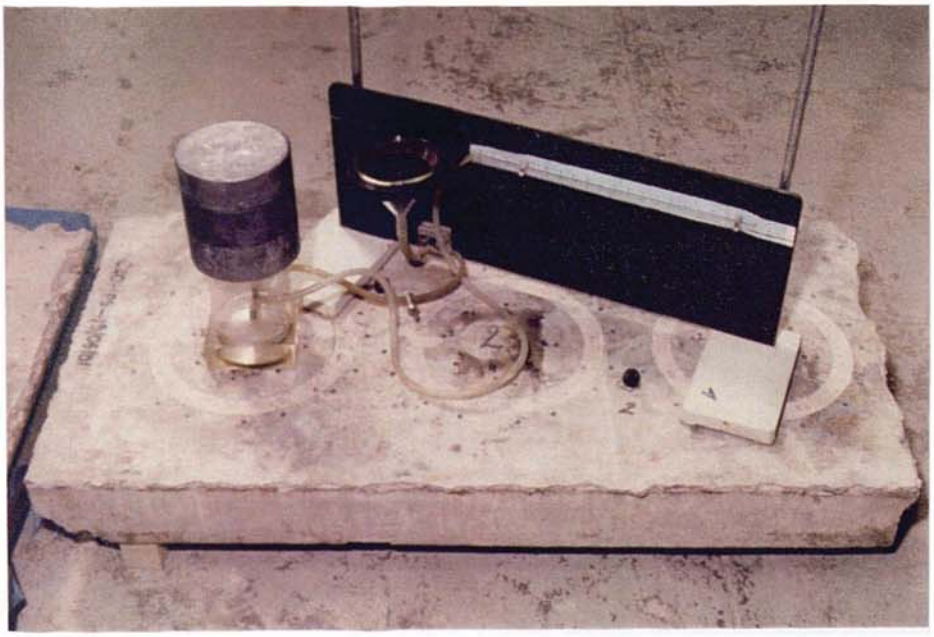
To fully assess the suitability of this technique, a range of specimen slabs was selected for the ISAT to cover several aspects of the main investigation presented in Chapter 6, namely:

- The influence of fibre inclusion and mix variation
- The influence of fibre type, shape and content.

8.2.1 Experimental Procedure

As the ISAT results are influenced by the loss of moisture from the concrete and its final moisture condition (Dhir et al., 1987), it was decided to perform these tests 56 days after casting the samples. These were carried out on the clean, dry surface of slabs that had been cured in polythene sheets, three tests being performed on each slab (1.0 x 0.5 x 0.1 m). To maintain consistency, each test was located inside the circular groove worn during the accelerated abrasion test as shown in Plate 8.1.

Plate 8. 1 Modified ISAT rig on a sample concrete slab



The test procedure is fully described in BS 1881: Part 208: 1996, and this procedure was adopted in this study. It involved fixing a sealed cap onto the surface of the test specimen, the face area of this cap was known. This fixing was achieved by coating the rubber ring sitting inside the cap with grease and applying the 19.8 kg lead weights developed for this

investigation; the general arrangement is as presented in Plate 8.1. The top of the cap was fitted with two access pipes, one connected to a filter funnel reservoir, the other to a capillary tube of known dimensions. The inlet pipe connected to the reservoir was fitted with a stop tap.

To start testing, the reservoir was fitted with water, which entered the cap via the inlet tube and could exit the apparatus via the end of the capillary. As soon as the water came into contact with the specimen a clock was started to register the beginning of the test period. When the reservoir was disconnected the rate of absorption of water was determined by timing the movement of the meniscus as it travelled back along the capillary. Measurements were taken at 10, 30 and 60 minutes.

Levitt (1984) proposed a classification for the quality of concrete based on the ISAT and this is provided in Table 8.1. This classification has subsequently been included in the Concrete Society's, TR 31 (1987).

Table 8. 1 Suggested limits for the ISAT (Levitt, 1984)

	ISAT (ml/m^2/s)		
	10 min	30 min	60 min
Good	< 0.25	< 0.17	< 0.10
Average	0.25 – 0.50	0.17 – 0.35	0.10 – 0.20
Poor	> 0.50	> 0.35	> 0.20

8.2.2 Results and discussion

The ISAT was initially developed for smaller samples, like cubes or cores (BS 1881: Part 208: 1996) and so the standard ISAT rig shown in Plate 8.2 has been widely used over the years. However, when testing larger samples, like the concrete slab specimens used during this study, it is not possible to use the clamping device shown in Plate 8.2. Instead, lead weights were placed on top of the cap in order to achieve adequate sealing. These weighed 19.8 kg in total and are shown in Plates 8.1 and 8.3.

To establish the suitability of the modified ISAT rig, a total of six "five star" repair concrete cubes were tested using each of the rigs. The results of these preliminary tests are presented in Table H.1 of Appendix H. It was found that there was no significant

difference between the results achieved with these two ISAT rigs (Table H.2, Appendix H) on these selected concretes.

Plate 8. 2 Standard ISAT rig on a concrete cube in accordance with BS 1881: Part 208: 1996

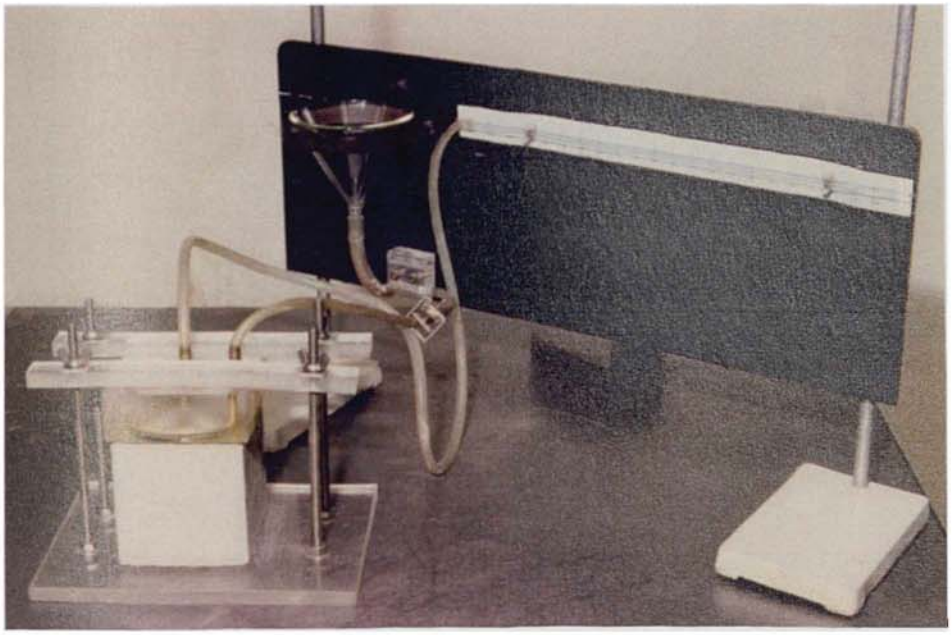
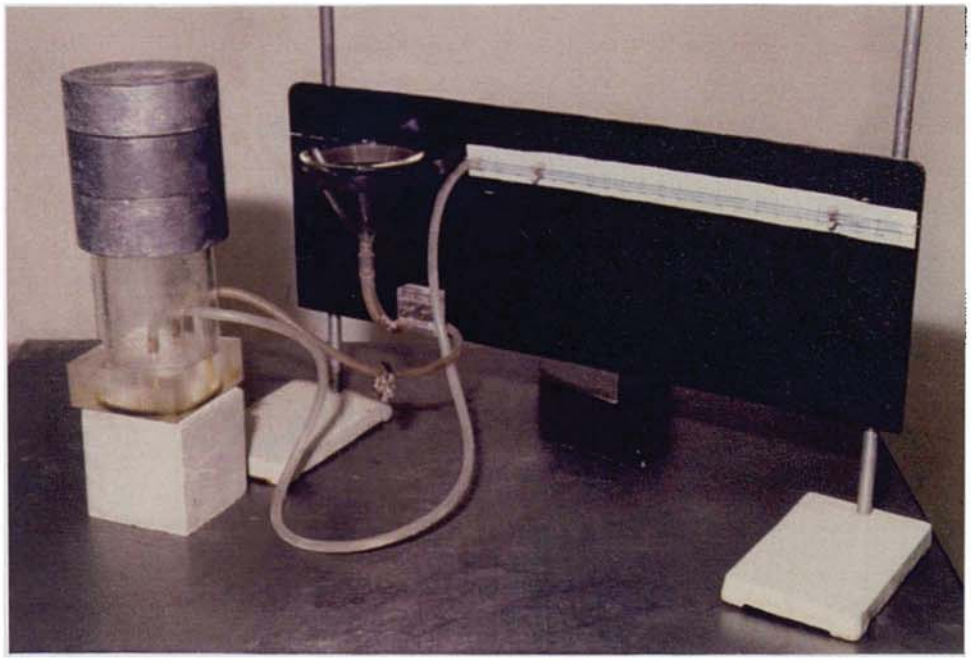


Plate 8. 3 Modified ISAT rig on a concrete cube



The results obtained by the Initial Surface Absorption technique are shown in Table 8.2 and suggest that the method is extremely sensitive to the mix design particularly the water-cement ratio. It has been found that this technique is also sensitive to fibre inclusion, type

and volume. The results of the ISAT further support the conclusion from the MIP tests that higher pore volumes are associated with higher w/c ratio mixes and that fibre inclusion and/or fibre dosage influence both the PSD and pore volume of the surface matrix of the specimen (see Section 7.3.3), these changes in porosity characteristics have clearly influenced the surface permeability. The variations in ISAT are statistically significant, as is illustrated in Tables H.3 – H.8 of Appendix H and are also consistent with the abrasion depths obtained with the accelerated abrasion test. The summarised results presented in Table 8.2 have been used to plot the abrasion depth and cube strength against the 10 minute ISAT values. These plots are shown in Figures 8.1 and 8.2, and they illustrate that abrasion depth is directly related to the ISAT values whilst the cube strength varies inversely with the ISAT values. Whilst neither relationship has a high coefficient of correlation, that for the cube strength, 0.4307, is very low suggesting a very weak or even non-existent relation. Although these plots relate only to the values determined at 10 minutes, similar relationships were observed with the 30 and 60 minute values.

Table 8. 2 Summary of ISAT results for samples cured in polythene sheeting

Specimen ID *	ISAT** ($ml/m^2/s$)			Mean compressive strength (N/mm^2)	Depth of wear (mm)
	10 min	30 min	60 min		
B4	0.0375	0.0142	0.0092	60.00	0.29
B5	0.0558	0.0258	0.0133	53.47	0.44
B6	0.0758	0.0433	0.0308	42.00	0.61
A1, s/c, 0.51 % - 45 mm	0.0433	0.0200	0.0142	64.33	0.22
A2, s/c, 0.51% - 45 mm	0.0467	0.0283	0.0142	55.33	0.11
A3, s/c, 0.51 % - 45 mm	0.0950	0.0442	0.0258	45.40	0.50
A2, s/c, 1.0 % - 45 mm	0.0550	0.0242	0.0150	60.07	0.29
A2, s/c, 1.5 % - 45 mm	0.0792	0.0350	0.0200	55.00	0.35
A2, s/c, 2.0 % - 45 mm	0.0825	0.0383	0.0225	51.40	0.39
A2, s/c, 3.0 % - 45 mm	0.0850	0.0358	0.0208	49.67	0.44
A2, s/t, 0.51 % - 32 mm	0.0592	0.0233	0.0125	55.40	0.12
A2, s/t, 1.0 % - 32 mm	0.0650	0.0283	0.0167	60.00	0.20
A2, s/t, 1.5 % - 32 mm	0.0850	0.0400	0.0267	56.33	0.25
A2, s/t, 2.0 % - 32 mm	0.1058	0.0358	0.0175	53.67	0.42
A2, s/fe, 0.51 % - 30 mm	0.0475	0.0175	0.0100	58.67	0.12
A2, s/fe, 1.0 % - 30 mm	0.0583	0.0275	0.0125	62.00	0.20
A2, s/fe, 1.5 % - 30 mm	0.0825	0.0375	0.0158	61.33	0.25
A2, s/fe, 2.0 % - 30 mm	0.0842	0.0342	0.0183	58.67	0.31
A2, s/s, 0.51 % - 35 mm	0.0383	0.0192	0.0133	58.33	0.12
A2, s/s, 2.0 % - 35 mm	0.0650	0.0408	0.0217	59.33	0.36
A2, p, 0.1 % - 12 mm	0.0425	0.0192	0.0117	57.67	0.06
A2, p, 0.51 % - 12 mm	0.0433	0.0192	0.0133	54.67	0.16
A2, sp, 0.1 % - 12.5, 60 mm	0.0458	0.0225	0.0142	55.00	0.12
A2, sp, 0.5 % - 12.5, 60 mm	0.0533	0.0300	0.0175	51.33	0.37

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

** Mean of three sets of test results

Figure 8. 1 Abrasion depth vs. ISAT at 10 min for samples cured in polythene sheeting

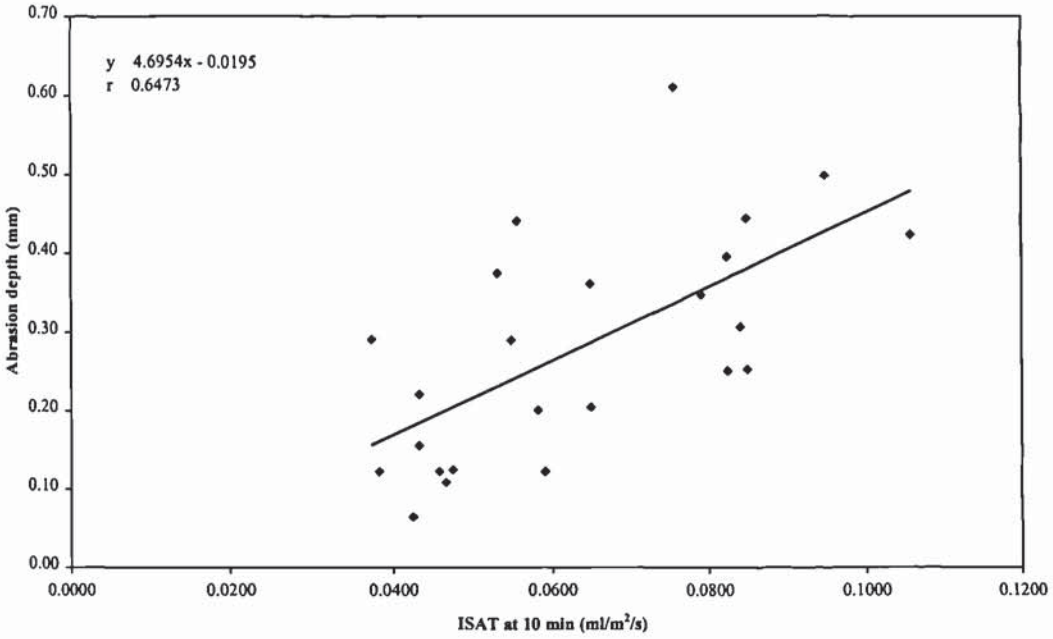
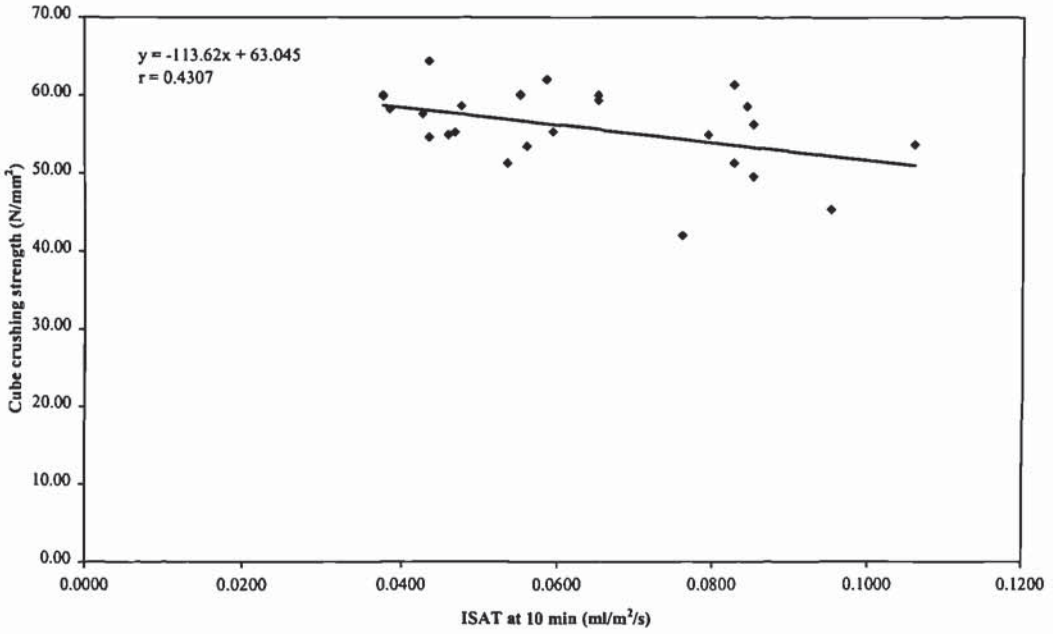


Figure 8. 2 Cube crushing strength vs. ISAT at 10 min for samples cured in polythene sheeting



It is not surprising that the relationship with cube strength is weak since the cube strength depends on the bulk properties not just of the surface assessed by the ISAT. However, Figure 8.1 illustrates a relatively close relationship between the abrasion resistance and the Initial Surface Absorption. This is primarily attributed to both tests being influenced by the

micro-surface texture and the quality of the surface matrix. This is consistent with the conclusion that porosity is a function of water-cement ratio and that permeability is related to porosity (Neville, 1999; Dhir et al., 1991; Sadegzadeh, 1985; Powers et al., 1954).

The maximum coefficient of variation calculated for the ISAT results at 10 minutes was 10.07 %, at 30 minutes it was 11.11 % and at 60 minutes it was 20.00 %. Both higher and lower values of 5.2 % (Sadegzadeh, 1985), 5.5 % (Dhir et al., 1987) 9.5% (Dhir et al., 1987), 6.7 – 65.7 % (Dhir et al., 1993) have been reported. In general, the findings of this part of the study appear to be consistent with the findings of a number of previous investigators (Dhir et al., 1991; Sadegzadeh, 1985) who reported that the ISAT is sufficiently sensitive to the factors affecting the abrasion resistance of concrete. However, due to the limited published data and different construction techniques, direct comparison of their results and those of the present study is not possible. Nevertheless, Levitt (1984) has proposed a classification for the quality of concrete, based on the ISAT, as presented in Table 8.1. It is interesting to compare the results of the present study with these limits. By considering the data in Table 8.2 it is clear that all slabs, exhibit ISAT values which fall within the "good" quality limits of the proposed classification. This may be attributed to the increased surface compaction (hence reduced porosity) due to the power finished samples, although the suitability of this classification is questionable as Dhir et al. (1991) also reported ISAT values that varied between 0.05 – 0.15 $ml/m^2/s$ for much higher abrasion depths than those presented in Table 8.2.

Overall, when performing ISAT on samples cured in polythene, it was found that the relationship between the abrasion resistance and ISAT values was close but not as highly significant ($r = 0.6473$) as had been hoped. Therefore this test may, if necessary, be used as the basis of a method which could indirectly and non-destructively rate the abrasion resistance, but it is considered to be an inadequate method for accurately predicting abrasion resistance. In the present study little difficulty was encountered in fixing the cap onto the surface of the specimen to ensure that a water-tight fit was obtained. This was made possible by the use of the modified test rig shown in Plate 8.3, which was designed for this study. However, the use of this equipment for in-situ testing may be more difficult since considerable experience is necessary to ensure a good seal between the cap and the concrete. Further the test results are temperature dependent, which may lead to several practical problems, and possibly errors, when it is performed on in-situ concrete floors.

8.3 Impact test

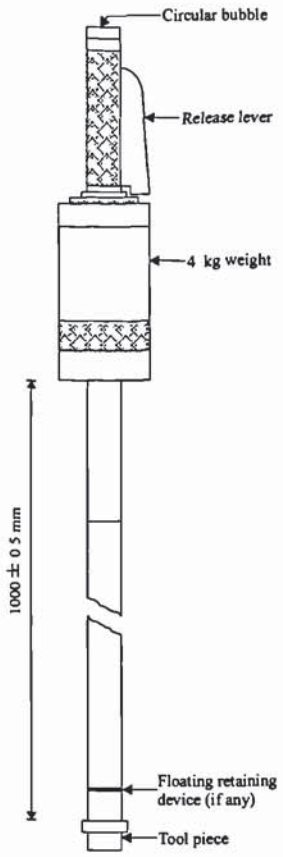
Using both dynamic and static test methods, Parameswaran et al. (1987) studied the behaviour of FRC beams with equal tension and compression reinforcement. They established that the inclusion of steel fibres delayed initial cracking and improved ductility, energy absorption and resistance to impact. In addition they concluded that the SFRC beams gave far better load dispersion for concentrated loads. For the particular range of main reinforcement (up to 2.5 %), the failure of SFRC beams was by rupture of the tensile steel. The failure ductility and rotation at the plastic hinge within SFRC beams have been found to be significantly different from the values for normal reinforced concrete beams. Ramakrishnan (1988) who also used FRC beams for his experiments found significant improvements in the following properties: ductility, toughness, impact resistance, tensile and flexural strengths, fatigue life, abrasion resistance, shrinkage, durability, and cavitation resistance.

Balasubramanian et al. (1996) used a drop-weight test method, known as Schrader, to study the impact resistance of SFRC cylinders and cubes. The FRC showed the ability to control cracking under impact loading and was found to absorb a substantially higher number of impact blows compared with the equivalent plain concrete. The addition of fibres, even in small quantities, clearly improved the impact resistance of concrete and, of the three types of steel fibres used, the impact resistance of specimens with crimped fibres was found to be consistently the highest. Banthia et al. (1998b) studied the impact resistance of concrete slabs reinforced with a fibre reinforced plastic (FRP) grid. They used a drop weight impact machine for their investigations, which had a 505 kg hammer and was dropped from a fixed height (0.5 m). They found that under impact, a concrete slab reinforced with FRP grid absorbs only a third of the energy absorbed by those reinforced with a traditional steel grid and attributed this to the brittle nature of the FRP composites. Further they concluded that although the use of a high-strength concrete does not improve the load carrying capacity of the plates, it does improve the energy absorption capability. Banthia et al. (1998b) found that the best performance in terms of impact resistance of slabs reinforced with FRP reinforcement, was achieved with the use of fibre reinforced concrete, with improvements occurring both in the ultimate load carrying capacity and the energy absorption capacity.

It was considered that there are insufficient data with respect to the impact resistance of FRC floors, especially with regard to less aggressive techniques than those used by the

above researchers, since many concrete floors are not routinely subjected to extreme impact loading. A less destructive impact device was therefore used for this study. It is shown in Figure 8.3 and is currently used to assess the quality and bonding of hardened screeds. This technique was developed at the Building Research Establishment (BRE) (Pye & Warlow, 1978) and has gained widespread acceptance. It has now been included in the latest edition of BS 8204: Part 1: 1999.

Figure 8. 3 BRE screed tester (BS 8204:Part 1: 1999)



A thorough literature survey revealed that only one investigator has previously reported experimental findings utilising this test (Beningfield, 1986) on cementitious screeds. In fact the equipment was developed (Pye, 1986; Pye & Warlow, 1978) for testing the soundness of floor screeds rather than the floor surface. Nevertheless it was thought that both the abrasion and the BRE screed testers operate in terms of assessing the hardness of a given cementitious surface.

Due to the obvious lack of data, as far as impact resistance of fibre reinforced concrete floors is concerned, it was considered important to examine this parameter. Special attention was subsequently given to examining any possible relation(s) between the results

obtained from these tests to those obtained by the abrasion resistance test, as there was no published record concerning such links.

To fully assess the suitability of this technique, a range of specimen slabs was selected for testing so as to cover several aspects of the main investigation presented in Chapter 6, namely:

- The influence of the curing regime
- The influence of fibre inclusion and mix variation
- The influence of fibre type (metallic and non-metallic), shape and content
- The influence of fibre length
- The influence of superplasticizer volume

8.3.1 Experimental Procedure

The impact tests were performed 28 days after casting the concrete slab specimens. These were carried out on the clean, dry surface of slabs that had been subjected to the three curing regimes described in Section 6.4. Three tests were performed on each slab and each test was located inside the circular groove worn during the accelerated abrasion test. The testing apparatus (BRE screed tester) is shown in Figure 8.3.

The test procedure is fully described in BS 8204: Part 1: 1999 and was adopted by this study. It involved placing the tool piece of the screed tester on the test surface in contact with the sample. The guide rod was held vertically and four successive blows of the test weight were delivered to the tool piece at the same position on the sample. The weight was dropped freely each time by releasing it from the trigger point. After completion of the fourth blow, the indentation depth in the sample was measured with a depth gauge.

A detailed classification of screeds and acceptance limits for test indentations, listing three categories of use of floor, as shown in Table 8.3, were first published by Pye (1984) and were subsequently included in the BS 8204: Part 1: 1999.

Table 8. 3 Acceptance limits for in-situ crushing resistance (BS 8204 Part 1: 1999; Pye, 1984)

Category	Type of use	Examples of use	Acceptance limits after dropping the weight four times
			Maximum depth of indentation (mm)
A	**Heavy** Areas expected to take very heavy foot traffic and/or heavy trolleys or where any breakdown of the screed would be unacceptable.	Hospital operating theatres, X-ray rooms, main hospital corridors; rooms where radioactive material is handled or requiring microbe-free environment; telecommunication rooms; shopping malls.	3
B	**Normal** Areas expected to take heavy foot traffic and/or medium weight trolleys.	Public areas, corridors, main lift and lobby areas; canteens and restaurants; public rooms in residential accommodation, classrooms, hospital wards and offices.	4
C	**Light** Other areas subjected to foot traffic and light trolleys.	Light office use, consulting rooms, domestic housing.	5

Note 1: Up to 5 % of indentations may exceed those in this table by up to 1 mm

Note 2: Tests carried out on an area of levelling screed that has been laid with a rough texture or has been roughened by wear may result in some extra compaction of the surface layer on the first impact, which may give rise to an increase in indentation of up to 1 mm.

Note 3: The method of test for in-situ crushing resistance measures the strength and integrity of a levelling screed in depth. It does not measure the surface strength of a screed. Very occasionally screeds may be encountered that pass the test but because they have a weak or dusty surface, are suitable to receive flooring.

8.3.2 Results and discussion

The results collected from the impact test are presented in Table 8.4 and an initial inspection suggests that this technique is extremely sensitive to variations of the mix design and curing method. Further detailed analysis shows that this technique was also sensitive to factors such as fibre inclusion, fibre type, length and content. These variations are statistically significant, as illustrated in Tables H.9 – H.16 of Appendix H and are consistent with the abrasion depths obtained from the corresponding accelerated abrasion tests. The results in Table 8.4 have been used to explore the relationship between both abrasion depth and compressive strength and the impact test indentation values. These are presented in Figures 8.4 and 8.5 and they show that the abrasion depth and impact indentation are directly related whilst the compressive strength varies inversely with the impact indentation.

Table 8. 4 Summary of impact test results for samples cured by three different curing regimes

Specimen ID *	Impact indentation for curing regime (mm)			Mean compressive strength (N/mm^2)	Depth of wear for Curing regime (mm)		
	PS	AC	CC		PS	AC	CC
B4	0.08	0.22	0.10	60.00	0.29	0.73	0.32
B5	0.16	0.25	0.14	53.47	0.44	0.79	0.46
B6	0.31	0.39	0.31	42.00	0.61	0.95	0.64
A1, s/c, 0.51 % - 45 mm	0.16	0.20	0.17	64.33	0.22	0.32	0.17
A2, s/c, 0.51% - 45 mm	0.09	0.18	0.11	55.33	0.11	0.17	0.15
A3, s/c, 0.51 % - 45 mm	0.33	0.35	0.20	45.40	0.50	0.78	0.59
A2, s/c, 1.0 % - 45 mm	0.15	0.22	-	60.07	0.29	0.48	-
A2, s/c, 1.5 % - 45 mm	0.16	0.21	-	55.00	0.35	0.50	-
A2, s/c, 2.0 % - 45 mm	0.19	0.27	-	51.40	0.39	0.70	-
A2, s/c, 3.0 % - 45 mm	0.20	0.35	-	49.67	0.44	0.94	-
A2, s/t, 0.51 % - 32 mm	0.08	0.17	-	55.40	0.12	0.25	-
A2, s/t, 1.0 % - 32 mm	0.10	0.18	-	60.00	0.20	0.36	-
A2, s/t, 1.5 % - 32 mm	0.10	0.20	-	56.33	0.25	0.70	-
A2, s/t, 2.0 % - 32 mm	0.21	0.23	-	53.67	0.42	0.72	-
A2, s/fe, 0.51 % - 30 mm	0.10	0.13	-	58.67	0.12	0.37	-
A2, s/fe, 1.0 % - 30 mm	0.11	0.15	-	62.00	0.20	0.46	-
A2, s/fe, 1.5 % - 30 mm	0.13	0.20	-	61.33	0.25	0.48	-
A2, s/fe, 2.0 % - 30 mm	0.13	0.29	-	58.67	0.31	0.58	-
A2, s/s, 0.51 % - 35 mm	0.12	0.22	-	58.33	0.12	0.47	-
A2, s/s, 2.0 % - 35 mm	0.16	0.24	-	59.33	0.36	0.49	-
A2, p, 0.1 % - 12 mm	0.12	0.19	-	57.67	0.06	0.25	-
A2, p, 0.51 % - 12 mm	0.14	0.23	-	54.67	0.16	0.26	-
A2, sp, 0.1 % - 12.5, 60 mm	0.11	0.17	-	55.00	0.12	0.28	-
A2, sp, 0.5 % - 12.5, 60 mm	0.15	0.28	-	51.33	0.37	0.58	-
A2, HP, 0.04 % - 12 mm	0.10	-	-	56.33	0.25	-	-
A2, HP, 0.21 % - 12 mm	0.12	-	-	49.33	0.30	-	-
A2, HP, 0.41 % - 12 mm	0.14	-	-	48.33	0.37	-	-
A2, HP, 0.83 % - 12 mm	0.15	-	-	47.33	0.40	-	-
A2, HD, 0.02 % - 12 mm	0.20	-	-	48.33	0.45	-	-
A2, GSF, 0.54 % - 50 mm	0.18	-	-	46.83	0.41	-	-
A2, s/c, 0.26% - 45 mm	0.13	-	-	51.67	0.30	-	-
A2, s/c, 0.51% - 45 mm	0.07	-	-	55.83	0.18	-	-
A2, s/c, 0.26% - 50 mm	0.19	-	-	50.17	0.40	-	-
A2, s/c, 0.51% - 50 mm	0.16	-	-	50.17	0.37	-	-
A2, s/c, 0.26% - 60 mm	0.28	-	-	45.67	0.52	-	-
A2, s/c, 0.51% - 60 mm	0.22	-	-	55.67	0.45	-	-
A2, s/c, 0.51% - 60 mm	0.26	0.28	-	47.53	0.44	0.66	-
A2, s/c, 0.64% - 60 mm	0.15	0.23	-	55.33	0.36	0.65	-
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	0.09	0.18	-	55.33	0.11	0.17	-
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.10	0.23	-	53.83	0.12	0.20	-
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.09	0.26	-	53.00	0.10	0.25	-
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.07	0.30	-	58.73	0.09	0.34	-
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.09	0.34	-	59.17	0.08	0.40	-
A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.18	0.32	-	43.50	0.45	0.64	-
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.19	0.27	-	51.40	0.39	0.70	-
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.14	0.24	-	51.83	0.25	0.51	-
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.11	0.21	-	52.50	0.20	0.42	-
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.09	0.17	-	60.33	0.15	0.30	-
A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.05	0.10	-	63.00	0.07	0.20	-
A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.14	0.30	-	44.67	0.45	0.77	-

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

** Mean of three sets of test results

Figure 8. 4 *Abrasion depth vs. impact indentation for samples cured using three different curing regimes*

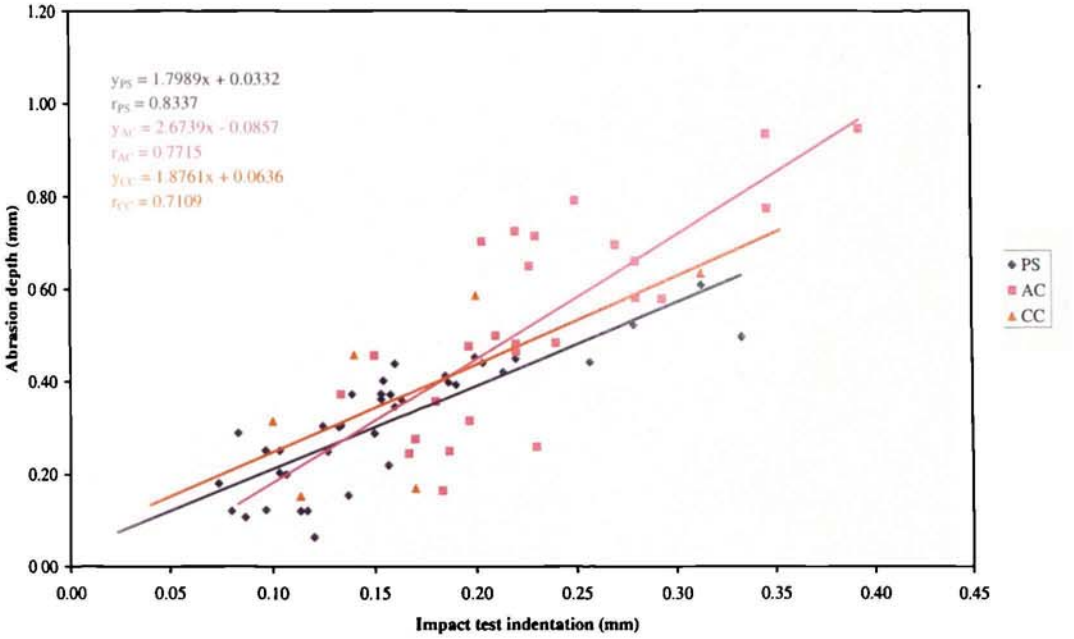


Figure 8. 5 *Cube crushing strength vs. impact indentation for samples cured using three different curing regimes*

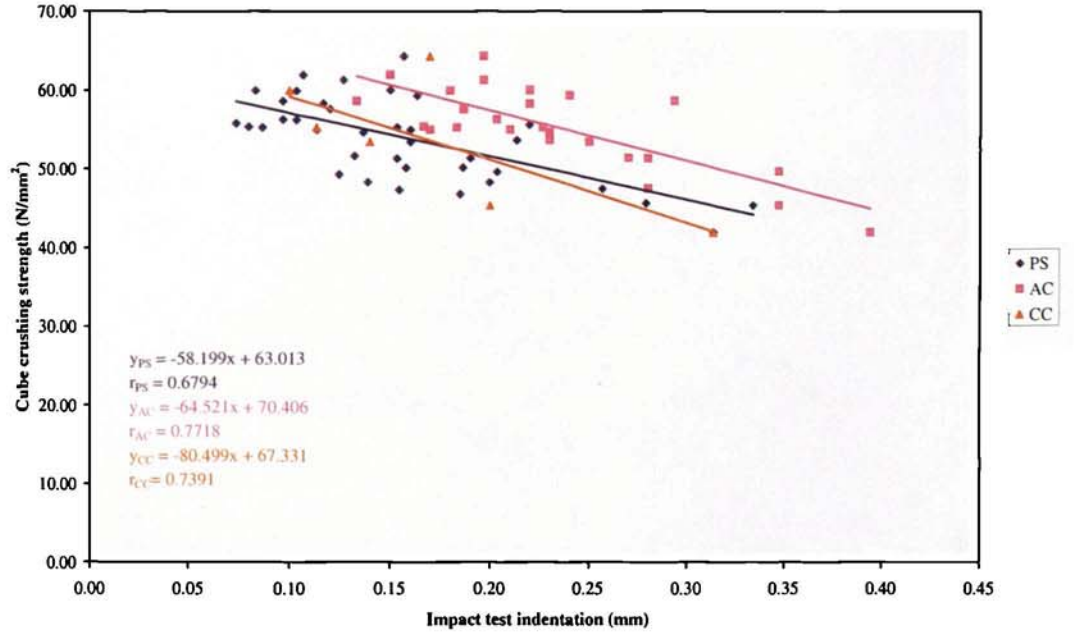


Figure 8.4 shows a close, and statistically significant, relationship between the impact resistance and the depth of abrasion of fibre reinforced concrete floors. This can be attributed to the fact that both parameters are influenced by the quality of the surface matrix. Furthermore, like the accelerated abrasion test, the impact test has also been able to pinpoint the influence of the three curing regimes employed (Figures 8.4 and 8.5). Generalised plots, irrespective of the curing regime, have also been presented in Figures H.1 and H.2 of Appendix H, and the same close statistical relationship was repeated, although there is a higher degree of scatter in the results which is attributed to the use of different curing methods. The practical implication is that the impact resistance test has the potential of being adopted to assess non-destructively the abrasion resistance of concrete slabs.

The results of the impact test further confirm the conclusions of the microindentation hardness technique, that variation in the mix design – primarily in the w/c ratio – for both plain and fibre reinforced concrete influences the hardness of the surface matrix and that fibre inclusion and content also appear to influence the hardness of the surface matrix. In addition the abrasion resistance of plain and fibre reinforced concrete is directly related to the hardness of the surface matrix (also see Section 7.2.3).

The maximum coefficient of variation for the impact test results for polythene cured samples was 14.57 %, for samples cured with a curing compound it was 10.00 % and for samples cured in air it was 10.00 %. No published results have been retrieved which can be compared directly to the results and conclusions of the present study.

This part of the study was extended to investigate the influence of superplasticizing agents. The data in Table 8.4 show that this technique was also sensitive to the superplasticizer volume especially for samples containing higher fibre dosages and those that received poor curing. These variations are statistically significant, as illustrated in Tables H.17 and H.18 of Appendix H and are consistent with the corresponding abrasion depths.

The classification proposed by Pye (1984), shown in Table 8.3 is not considered to be directly relevant to power finished concrete floors and therefore a new classification has been proposed, as shown in Table 8.5. This was produced by extending the classification of the abrasion resistance given in BS 8204: Part 2: 1999 (Table 5.4) by using the equations shown in Figure 8.4.

Table 8. 5 Classification of abrasion and impact resistance and limiting values

BS 8204 Class	Duty	Type of concrete	Concrete grade (N/mm^2)	Minimum cement content (kg/m^3)	Maximum wear depth (mm)	Maximum impact indentation (mm)
Special	Severe Abrasion	Special mixes and resins	Special mixes and dry-shake or sprinkle finishes, resins etc.		0.05	0.02
AR1	Very high abrasion	High – strength toppings			0.1	0.05
AR2	High Abrasion	Direct finished concrete	C50	400	0.2	0.1
AR3	Moderate abrasion	Direct finished concrete	C40	325	0.4	0.2

After careful consideration of all the results generated from this investigation the impact resistance method has been shown to be an appropriate method for predicting the abrasion resistance of concrete by non-destructive testing. The test is relatively simple, cheap and easy to perform, and therefore can be readily used. It has the added advantage of being more sensitive and reliable than the ISAT as an indicator of mechanical quality of the surface matrix. It should be noted, however, that the findings of the current work are laboratory based and future work should include the testing of in-service concrete floors in order to confirm the proposed classification.

8.4 Ball cratering

Ball cratering is a miniaturised abrasion test method which has been recently developed (Gee, 1998). There is now great interest in the use of the test for thin hard coatings such as TiN, polymeric films such as paints, and other monolithic materials (Owen-Jones & Gee, 1997). It is obvious from Table H.19 of Appendix H that very little work has been carried out utilising the ball-cratering test and especially on materials like concrete. Therefore the technique was included in the current research as an attempt to complement and contribute to the literature gaps.

One of the key points of this methods is that it enables a test to be carried out on a small area (about 0.5-1 mm across), with little damage to a component which can remain in service in many cases (Gee, 1998). The test could in principle be made portable, to carry round to the component rather than vice-versa (Owen-Jones & Gee, 1997).

The test system is shown in Figure 8.6 and consists of a loaded lever arm which counterbalances a ball, fixed in a split shaft. The test-piece is pressed against this rotating ball and, where appropriate, an abrasive is drip fed into the contact surface between the ball and the test-piece. To fully assess the suitability of this ball cratering technique, a range of specimen slabs were selected to cover several aspects of the main investigation presented in Chapter 6, namely:

- The influence of fibre inclusion and mix variation
- The influence of fibre type, shape and content.

Figure 8. 6 Schematic diagram of ball cratering test system (Gee, 1998)

8.4.1 Experimental Procedure

The 100 mm diameter cores taken for the microhardness and MIP investigations (See Chapter 7) also provided the samples for this study. A single 5 mm thick section was sliced from the surface matrix of each core using a diamond cutting wheel. The sample was cut parallel to the core power finished top surface. The face of each sample was approximately 50 x 20 mm and they were 5 mm thick. The ball cratering tests were performed 120 days after casting the concrete slabs using the procedure described below. A set of three tests was carried out on each of the selected samples. The study was limited to samples that were cured in polythene sheeting.

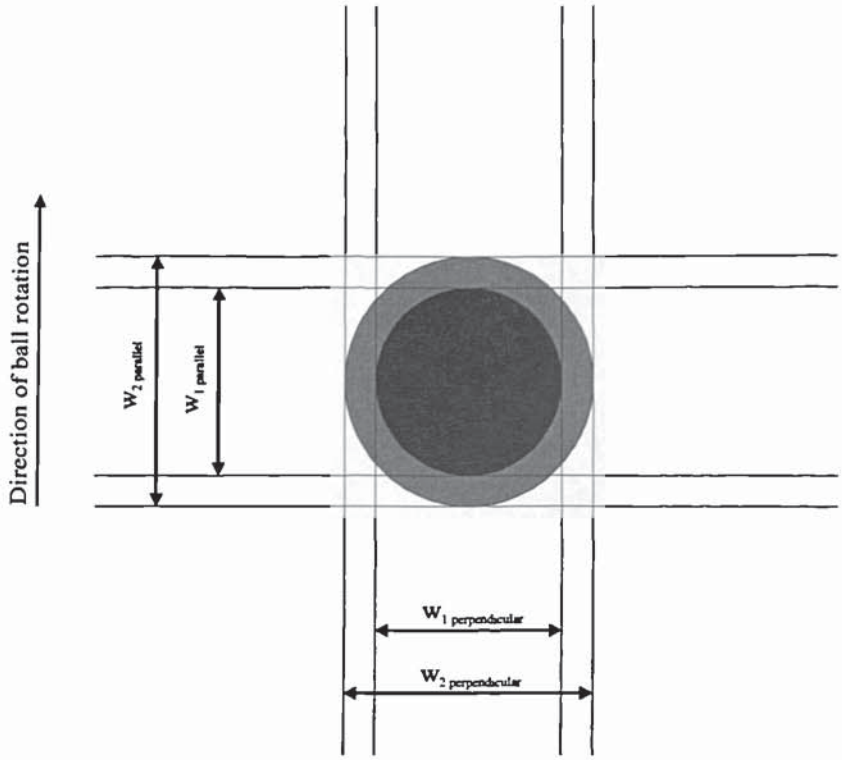
This part of the study was undertaken at the National Physical Laboratory (NPL) where a commercial test system (Figure 8.6) was made available. The loaded lever arm system uses

a 25 mm diameter hardened steel ball which is fixed in a split shaft with the test piece being pressed against this rotating ball. Normally a slurry of SiC abrasive is drip fed onto the contact interface between the ball and the test-piece. However, for the current study the test was carried out in its dry format, because the purpose of the test was to assess the relative performance of the samples under investigation. In particular, it was considered appropriate to use the test in its dry format to allow direct comparison with the results obtained from the abrasion resistance test, which was also carried out on a dry surface, to establish whether any relationships existed between the results of these two tests. A 5 N load was applied to the sample and the speed of the ball was controlled at a constant value of 80 rpm, with a total of 200 revs per test, throughout the set of tests. Two methods were adopted for measuring the wear: (a) by removing the ball and measuring the size of the wear scar on the sample at periodic intervals using a microscope and (b) by weighing the sample before and after the test.

A typical sample was cleaned by brushing away all the free dust particles from the surface and weighed before it was clamped firmly into position on the test system. The motor speed was adjusted to give the correct speed. The test system was adjusted to give the specified normal loading between the ball and the sample at a test point on the sample. After 200 revolutions the motor was stopped and the sample was moved so that a new position was worn on the sample and the next test in the sequence performed. When the sequence of tests has been completed, the sample was removed and cleaned by brushing away all the free dust particles from the surface. The size of the wear scars was measured both parallel and perpendicular to the direction of ball rotation. Both the full crater width (W_1) and the width of the substrate crater (W_2) were measured (Figure 8.7). The average of these measurements was used as the size of the wear scar. The sample was then weighed and the weight loss was determined. A typical tested sample is presented in Plate 8.4.

Plate 8. 4 *Example of ball craters on a typical concrete sample*

Figure 8. 7 Measurements on wear scar



8.4.2 Results and discussion

The results obtained by the ball cratering test are presented in Table 8.6 and appear to be somewhat contradictory. Table 8.6 shows that there is a scatter in the weight loss data which also appear to be inconsistent with the abrasion depths obtained with the accelerated abrasion test. This is attributed to the micro-scale of this testing method and it is suggested that this may be avoided by increasing the number of craters per sample, though future research may be required to investigate this possibility. On the contrary, the individual crater diameters were found to be consistent with the abrasion depths obtained with the accelerated abrasion test and suggest that this method is partially sensitive to the mix design variations. However, this technique does not appear to be sensitive to factors such as fibre inclusion, fibre type and volume. A statistical analysis considering these variations has been carried out and is presented in Tables H.20 and H.21 of Appendix H.

For comparison purposes the results in Table 8.6 were used to explore the relationships between both the abrasion depth and compressive strength and the crater diameter values. These plots are presented in Figures 8.8 and 8.9, and they illustrate that the abrasion

resistance varies inversely with the crater diameter whilst the compressive strength varies directly with the crater diameter.

Figure 8.8 illustrates a close and statistically significant (r = 0.8161) relationship between the abrasion depth and ball crater diameter of concrete. This is attributed to both tests being influenced by the micro-hardness of the surface and the quality of the surface matrix. The maximum coefficient of variation that was calculated for the ball cratering test results was 33.48 %. No published data have been retrieved which can be compared directly to the results and conclusions of the present study.

Considering the results generated from this investigation, the ball cratering test has potential to be a suitable method for predicting abrasion resistance of concrete non-destructively, however further work is required to supplement the findings of the current investigation and to refine the testing procedure.

Table 8. 6 Summary of ball cratering results for samples cured in polythene sheeting

Specimen ID *	Total weight loss (g)	Average crater diameter** (mm)	Mean compressive strength (N/mm^2)	Depth of wear (mm)
B4	0.00549	0.1541038526	60.00	0.29
B5	0.00631	0.1641541039	53.47	0.44
B6	0.00834	0.1943048576	42.00	0.61
A1, s/c, 0.51 % - 45 mm	0.00311	0.1574539363	64.33	0.22
A2, s/c, 0.51% - 45 mm	0.00619	0.1021775544	55.33	0.11
A3, s/c, 0.51 % - 45 mm	0.00735	0.1809045226	45.40	0.50
A2, s/c, 1.0 % - 45 mm	0.01958	0.1457286432	60.07	0.29
A2, s/c, 1.5 % - 45 mm	0.00722	0.1507537688	55.00	0.35
A2, s/c, 2.0 % - 45 mm	0.00656	0.1557788945	51.40	0.39
A2, s/c, 3.0 % - 45 mm	0.00526	0.1876046901	49.67	0.44
A2, s/t, 0.51 % - 32 mm	0.00516	0.1122278057	55.40	0.12
A2, s/t, 1.0 % - 32 mm	0.00568	0.1340033501	60.00	0.20
A2, s/t, 1.5 % - 32 mm	0.00269	0.1725293132	56.33	0.25
A2, s/t, 2.0 % - 32 mm	0.00280	0.2093802345	53.67	0.42
A2, s/fe, 0.51 % - 30 mm	0.00299	0.1206030151	58.67	0.12
A2, s/fe, 1.0 % - 30 mm	0.00249	0.1591289782	62.00	0.20
A2, s/fe, 1.5 % - 30 mm	0.00767	0.1574539363	61.33	0.25
A2, s/fe, 2.0 % - 30 mm	0.00807	0.1809045226	58.67	0.31
A2, s/s, 0.51 % - 35 mm	0.00705	0.1574539363	58.33	0.12
A2, s/s, 2.0 % - 35 mm	0.00173	0.1675041876	59.33	0.36
A2, p, 0.1 % - 12 mm	0.00292	0.1021775544	57.67	0.06
A2, p, 0.51 % - 12 mm	0.00272	0.1155778894	54.67	0.16
A2, sp, 0.1 % - 12.5, 60 mm	0.00377	0.1189279732	55.00	0.12
A2, sp, 0.5 % - 12.5, 60 mm	0.00904	0.1541038526	51.33	0.37

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

** Mean of three sets of test results

Figure 8. 8 Abrasion depth vs. Crater diameter for samples cured in polythene sheeting

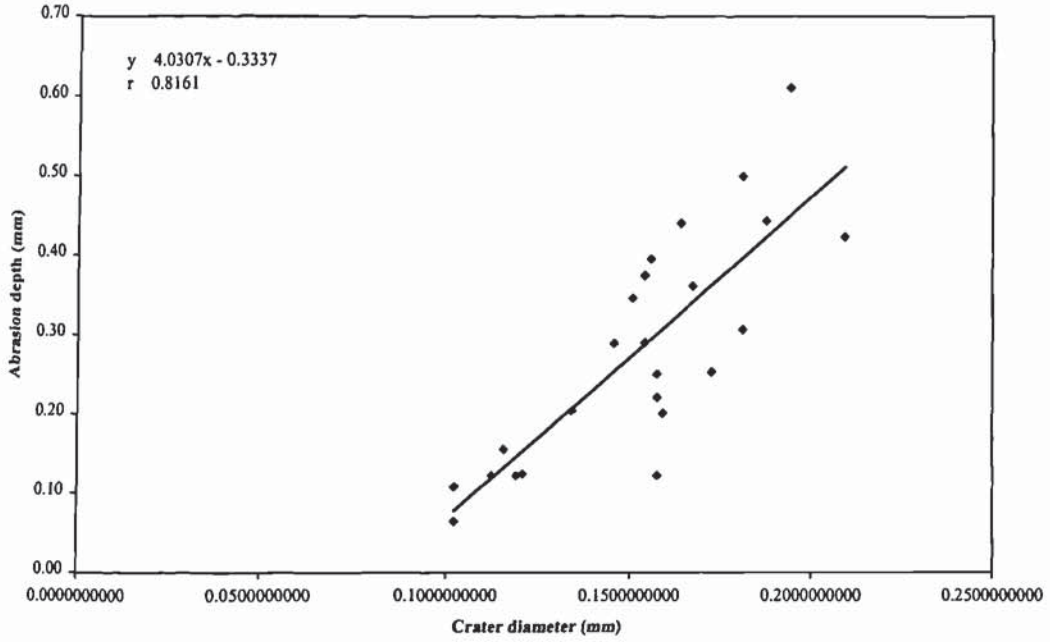
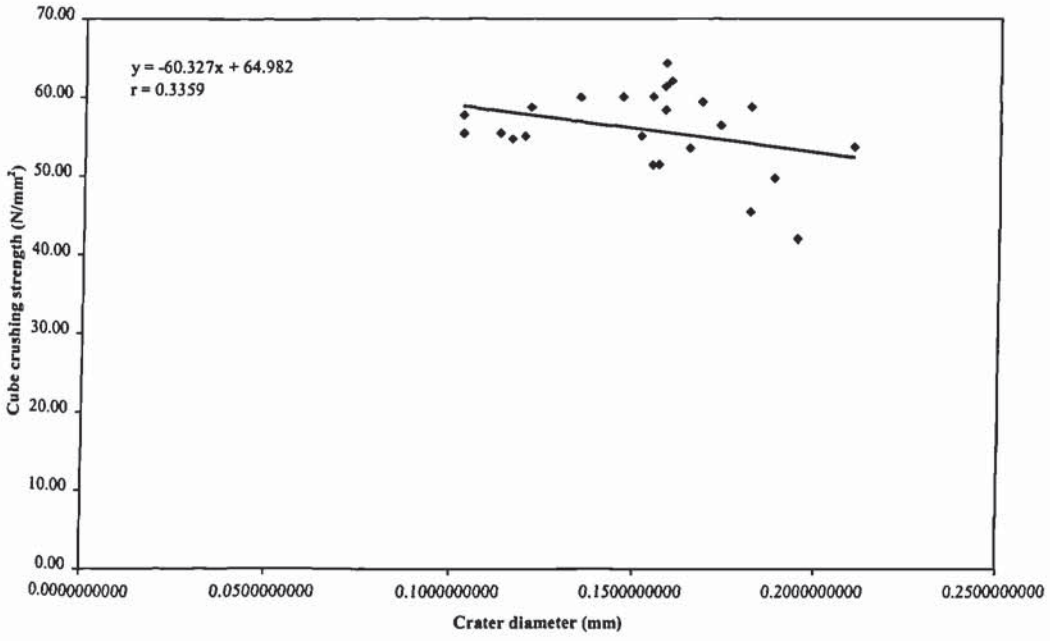


Figure 8. 9 Cube crushing strength vs. Crater diameter for samples cured in polythene sheeting



8.5 Scratch test

Scratch testing was originally developed as a quality control test for the measurement of the adhesion coatings (Gee, 1998). According to Owen-Jones & Gee (1997) it is widely used in this role, but it also offers potential as a model abrasion test method where the abrasion is caused by a single abrasive point (the indenter) as shown in Figure 8.10. The advantage of this approach is that the response of a material to abrasion under these simple conditions can be controlled and modelled much more easily than in most abrasion conditions, where a high number of abrasive particles act in very close succession.

This approach is useful in simulating industrial abrasive wear which is caused by the accumulation of many single scratching events; since the scratch test provides good quality data on one of these events, it can be often used successfully in the simulation of abrasive wear (Owen-Jones & Gee; 1997). A variant of the scratch test is to perform repeat scratches along the original scratch line, or at a carefully defined distance from the original scratch, to investigate the effect of multiple scratching and interactions between scratches.

Figure 8. 10 Schematic diagram of high load scratch testing system (Gee, 1998)

A survey was undertaken to assess the use of the scratch test and Tables H.22 (a) & (b) of Appendix H present a database of the papers, reports and conference proceedings relating to the scratch test. Clearly these researchers have dealt with materials such as ceramics, SiC, silicon nitride, silicon, glass, alumina, germanium, zirconia, plastics, metals, alloys coatings, titanium nitride, TiC, hard metals, sapphire and composites. It is therefore clear

that the test has been used to test brittle materials. Concrete itself is a brittle composite but to date there have been no reported investigations to explore any links between scratch test data and the abrasion resistance of concrete. It is for this reason that it was deemed necessary to include this technique.

To fully assess the suitability of this test method, a range of specimen slabs were selected for scratch testing to cover several aspects of the main investigation presented in Chapter 6. The specimens were selected in order to investigate the same factors as in Section 8.4.

8.5.1 Experimental Procedure

During this part of the study the scratch testing system (Figure 8.10) available at the National Physical Laboratory (NPL) was employed. The scratch tests were performed 120 days after casting the concrete slabs using the procedure described below. A set of six tests was carried out on each of the selected samples. The study was limited to samples that had been cured in polythene sheeting. The 100 mm diameter cores taken for the microhardness and MIP investigations (See Chapter 7) also provided the samples for this study. A 5 mm thick section was sliced from the surface matrix of each core using a diamond cutting wheel. One sample was selected from each core. The sample was cut parallel to the core power finished top surface. The face of each 5 mm sample was approximately 40 x 25 mm.

A typical sample was cleaned by brushing away all the free dust particles from the surface and subsequenlty clamped firmly into position on the test system. A diamond indenter of 0.2 mm in radius was used to simulate high stress abrasion. Measurements were carried out using an incremental applied load of 4 – 47 N and a horizontal speed of 1 mm/min. When the first scratch was completed, the motor was stopped and the sample was moved so that a new position on the sample was scratched and the next test in the sequence performed. When the sequence of tests had been completed, the sample was removed and cleaned by brushing away all the free dust particles from the surface. The damage to the sample was determined by measuring the width of each scratch by optical microscopy.

8.5.2 Results and discussion

The results obtained by the scratch testing technique are shown in Table 8.7 and suggest that this method is very sensitive to fibre inclusion, type and volume and partially sensitive to mix design variations. These variations are significant as illustrated in Tables H.23 and

H.24 of Appendix H and an initial visual comparison suggests that they are consistent with the abrasion depths obtained with the accelerated abrasion tests.

Table 8. 7 Summary of scratch test results for samples cured in polythene sheeting

Specimen ID *	Average scratch width ** (mm)	Mean compressive strength (N/mm^2)	Depth of wear (mm)
B4	0.097800	60.00	0.29
B5	0.102667	53.47	0.44
B6	0.112233	42.00	0.61
A1, s/c, 0.51 % - 45 mm	0.088833	64.33	0.22
A2, s/c, 0.51% - 45 mm	0.085800	55.33	0.11
A3, s/c, 0.51 % - 45 mm	0.091833	45.40	0.50
A2, s/c, 1.0 % - 45 mm	0.087233	60.07	0.29
A2, s/c, 1.5 % - 45 mm	0.100733	55.00	0.35
A2, s/c, 2.0 % - 45 mm	0.108967	51.40	0.39
A2, s/c, 3.0 % - 45 mm	0.123633	49.67	0.44
A2, s/t, 0.51 % - 32 mm	0.089900	55.40	0.12
A2, s/t, 1.0 % - 32 mm	0.095267	60.00	0.20
A2, s/t, 1.5 % - 32 mm	0.124533	56.33	0.25
A2, s/t, 2.0 % - 32 mm	0.129900	53.67	0.42
A2, s/fe, 0.51 % - 30 mm	0.089600	58.67	0.12
A2, s/fe, 1.0 % - 30 mm	0.103700	62.00	0.20
A2, s/fe, 1.5 % - 30 mm	0.120233	61.33	0.25
A2, s/fe, 2.0 % - 30 mm	0.137367	58.67	0.31
A2, s/s, 0.51 % - 35 mm	0.091067	58.33	0.12
A2, s/s, 2.0 % - 35 mm	0.093500	59.33	0.36
A2, p, 0.1 % - 12 mm	0.089400	57.67	0.06
A2, p, 0.51 % - 12 mm	0.111867	54.67	0.16
A2, sp, 0.1 % - 12.5, 60 mm	0.091333	55.00	0.12
A2, sp, 0.5 % - 12.5, 60 mm	0.114833	51.33	0.37

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

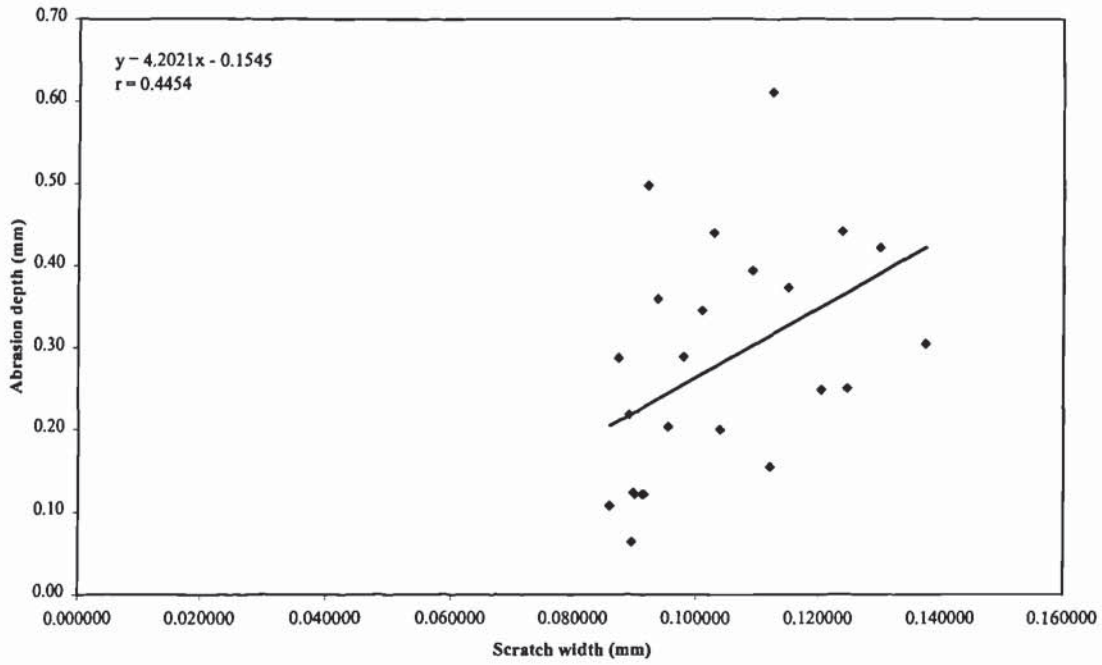
** Mean of thirty readings obtained from six sets of test results

The results in Table 8.7 have been used to produce the graphs of abrasion depth and compressive strength against the scratch width values as shown in Figures 8.11 and 8.12. Unlike the other non-destructive tests investigated, Figure 8.11 shows a very poor level of compatibility between abrasion resistance and scratch width. This is attributed to both the fashion in which the load was applied as well as the procedure adopted to measure the average scratch width. While incremental load was applied on the samples during the scratch test, which increased from 0 to 47 N and decreased from 47 to 0 N to generate one scratch, the average scratch width was obtained by measuring the width of thirty positions along the six scratches generated on each sample irrespective of the function of the load. With incremental loads, it is expected that at the higher loading levels, the scratch width would have higher values and vice versa, however this was not taken into account due to

the brittle nature of the concrete surface which made it difficult to determine the points at which the load was increasing or decreasing.

In retrospect, the above factors led to the poor correlation shown in Figure 8.11. Although, it is not strictly correct to try to establishing a relationship between two tests that are so different in terms of load application, other types of trend lines have also been considered, i.e. polynomial, with the same poor correlation. However, a linear relationship was considered to be more representative and its validity was confirmed by the findings of the Base hardness test, presented in Section 8.6.2 of this Chapter. Similarly, Figure 8.12 also suggests a weak inverse relationship between the compressive strength and the scratch width, with the scratch width increasing at lower strengths.

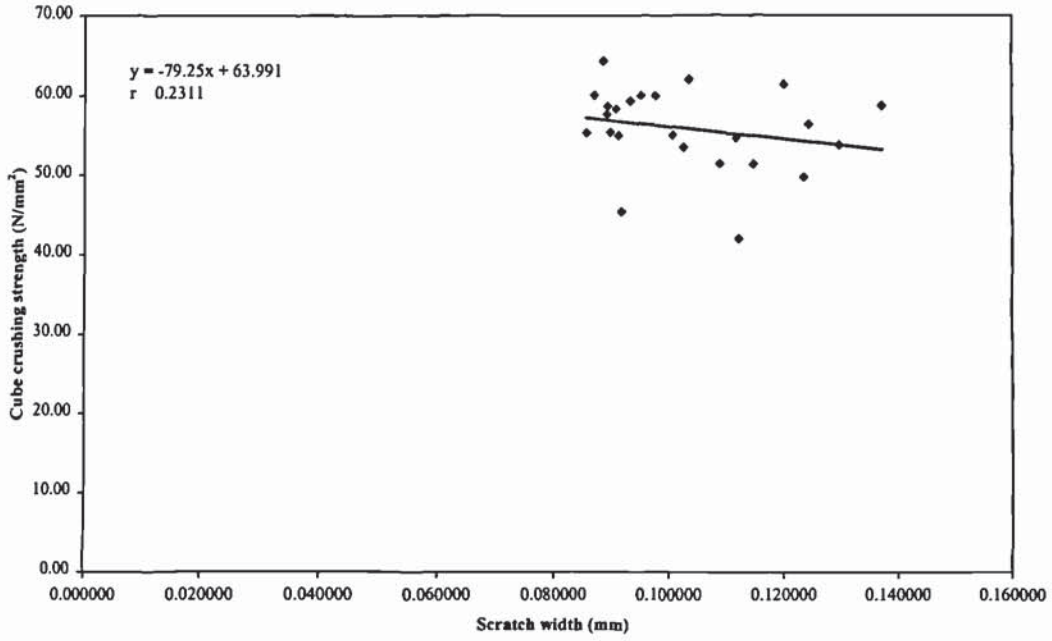
Figure 8. 11 Abrasion depth vs. Scratch width for samples cured in polythene sheeting



Even though, both the accelerated abrasion test and the scratch test are influenced by the micro-surface texture and the quality of the surface matrix, Figure 8.11 suggests that the relationship with abrasion resistance is not highly significant (r = 0.4454) so it is unlikely to be a useful predictor of abrasion resistance. It is believed that the micro-scale (maximum scratch length: 4 mm) of the scratch test limited this technique so that the localised surface variations severely influenced the results obtained and hence the low correlation coefficient. The maximum coefficient of variation that was calculated for the scratch was

22.10 %. No published data have been retrieved which can be compared directly to the results and conclusions of the current research.

Figure 8. 12 Cube crushing strength vs. Scratch width for samples cured in polythene sheeting



Overall, considering the results obtained from this part of the investigation the scratch test is considered to be an inadequate method for predicting abrasion resistance of concrete.

8.6 Base hardness test

According to the rules laid down by DIN 18365 (1992) – the duty of care of the flooring contractor includes testing the existing substrate surface. This standard states that when the contractor carries out this test, it must be stated whether:

- There is enough firm surface on the base and
- The surface is too porous or rough

The corresponding comments of DIN 18365 (1992) in this respect explain the rules of the art as follows:

"The screeds produced as a base must comply with the pertinent DIN norms in terms of their strength. Reference is made to the permissible impression depth for mastic asphalt screed. The contractor for the floor covering work cannot check these values at a later date nor he is obliged to commission such tests. He can assume that the existing bases, if provided by the client for laying the floor covering, comply with the technical values in every respect and that they have been approved by the client. The contractor, however, must assess the surface strength of the base within the scope of his inspection duty to determine whether the materials which he is to apply (e.g. filling or levelling compounds, adhesives) can form a firm bond with the existing base."

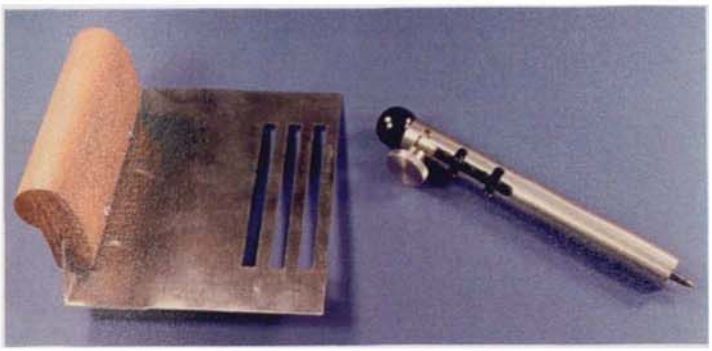
For many years, there has not been an industrial measuring device available for non-destructively determining the surface strength, so that the contractor has only been able to use such aids as a sharp chisel, a steel nail or other pointed metal objects to test the surface strength of a screed. Using these aids and the so-called grid scratch test has become common place in testing the surface of a base. There is no doubt that this is a subjective process, because the pressure applied by the person carrying out the test varies. Not only is experience required to make the right judgement but with this test method, the manual speed and pressure and the tools are not standardised and so it is difficult to be absolutely sure in each case whether the screed is sufficiently strong. The comments on the DIN 18365 (1992) contain the following principles:

"Weak surfaces usually prevent a permanent bond with filling and levelling compounds, adhesive beads and the floor covering. Such surfaces require special pre-treatment. The nature of the pre-treatment (e.g. sanding, vacuuming, priming) and the type of pre-treatment used (primer) depend on the type of screed and the degree of inadequate surface strength. The floor coverings cannot be simply laid on what are known as "wound spots". In the case of cement-bonded screeds, any (special) primers need to achieve the right adhesive strength of filing and levelling compounds and levelling compound is not part of the contractor's work; these are "special services" in accordance with DIN 18365; 1992."

The DIN 18560 (1992) requirements specify that the screed must have an adequate surface strength for the purpose for which it is intended. The comments on DIN 18365 (1992) explain that adhesion tensile tests (using special equipment and complicated methods) are not suitable as regular tests, because they are not a typical trade test for the floor contractor. Nor are there any standard tests. In fact there are no generally recognised

instructions and criteria for making these assessments. Recently (AP Werkzeuge GmbH; 2000) work has been reported on the development of a simple base hardness tester (Plate 8.5). In particular, maximum importance was attached to the principle of achieving an affordable device for the flooring contractor combined with an ease of use that would provide meaningful and comparable results. According to the manufacturer (AP Werkzeuge GmbH; 2000), the specific base hardness tester (Plate 8.5) allows flooring contractors to make comparative judgements of the surfaces available for covering. Depending on the result of the test, the customer can be informed of any additional work needed or the necessary reservations can be expressed.

Plate 8. 5 Base hardness tester



Even though the scratch test discussed in the previous section has proved to be unsuitable for predicting abrasion resistance, it is suggested that scratch testing has a potential for a simple test to provide more fundamental information on individual wear mechanisms. It could be used as a test, which simulates the interaction of a material with a single abrasion scratch event. The indenter tip is then a model of the abrasive particle, and so it was decided to include this testing method in this part of the study.

To fully assess the suitability of this technique, a range of specimen slabs were selected to cover several aspects of the main investigation presented in Chapter 6. The specimens were selected in order to investigate:

- The influence of fibre inclusion and mix variation
- The influence of fibre type, shape and content.

8.6.1 Experimental Procedure

The base hardness scratch tests were performed 56 days after casting the concrete slab specimens. These were carried out on the clean, dry surface of slabs that had been cured in polythene sheeting, three scratches were performed on each slab using the apparatus shown in Plate 8.5 and each test was located outside the circular groove cut during the accelerated abrasion test.

The base hardness tester is designed so that it has three adjustable levels as summarised in Table 8.8. In the first position, with the spring relaxed, a load of approximately 9 N is applied to the tungsten carbide tip of the tester, in the middle position it increases to approximately 18 N and with the spring fully tensioned 27 N is applied to the sample surface during the test.

Table 8. 8 Base hardness tester – Device settings

Level	Setting for spring	Spring load (N)	Surface description
1	Basic	9	For normal base surfaces in living areas
2	Middle	18	Highly frequented base surfaces, e.g. in public buildings such as schools, restaurants, offices, etc.
3	Fully taut	27	Base surfaces which are subject to extreme loads, e.g. industrial utilisation requirements and special areas

To test the samples surface, the spring tension was set at level 3 and the knurled screw was tightened. The base hardness tester was then placed on the sample surface with the metal tip on the mounting rail slot (Plate 8.5) so that the adjustment sleeve/tube touched the surface of the rail.

The base hardness tester was held by the tube and not the ball end during testing. With one hand, the template was pressed in place on the sample surface, and with the other, the base hardness tester was pulled horizontally across the template. Three parallel scratches were produced in the same direction. Since no objective method had been suggested by the manufacturer for assessing the damage to the sample, the depth gauge shown in Plates 8.6 and 8.7 was developed for measuring the depth of each of the scratches at three positions along their length. The pocket microscope shown in Plate 8.8 was utilised for determining the width of the scratches at the three same positions along the length of each scratch.

Plate 8. 6 *Depth gauge*

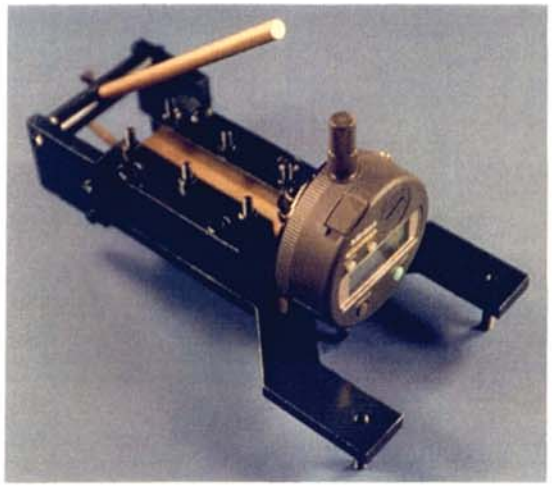


Plate 8. 7 *Depth gauge – measuring tip*

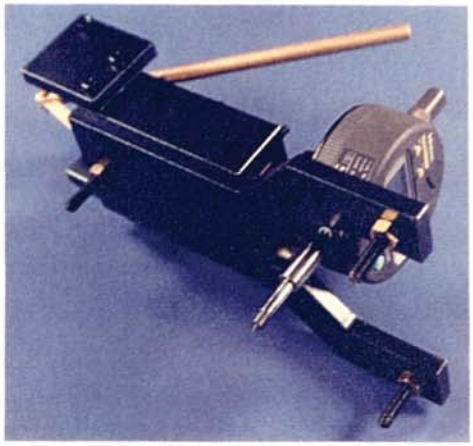
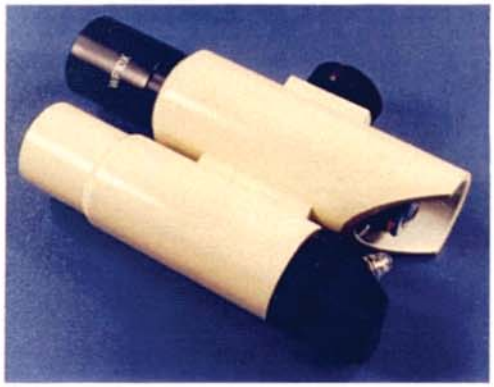


Plate 8. 8 *Pocket microscope*



8.6.2 Results and discussion

The results obtained from the base hardness test are summarised in Table 8.9 and suggest that this method is extremely sensitive to mix design variations and fibre inclusion. They also indicate that this technique is sensitive to fibre type and volume. These variations are statistically significant as illustrated in Tables H.25 – H.28 of Appendix H and are consistent with the abrasion depths obtained from the accelerated abrasion test. The results in Table 8.9 have been used to produce a series of graphs by separately plotting the abrasion depth and compressive strength against the scratch depth and width values. In addition, a plot of the scratch depth against the scratch width has been produced. These are presented in Figures 8.13 – 8.17 and they show that the abrasion depth varies directly with the scratch depth and width whilst the compressive strength varies inversely with the scratch depth and width.

Figures 8.13 and 8.14 show a close and statistically significant relationship between the scratch test results and the abrasion depth of fibre reinforced concrete, the strongest relationship being with the scratch depth (r = 0.9023) rather than with the scratch width (r = 0.7829). This is attributed the fact that both tests are influenced by the micro-surface hardness and the quality of the surface matrix.

Table 8. 9 Summary of base hardness test results for samples cured in polythene sheeting

Mix	Average depth of scratch (mm)	Average width of scratch (mm)	Mean compressive strength (N/mm^2)	Average depth of wear (mm)
B4	0.14	0.25	60.00	0.29
B5	0.25	0.27	53.47	0.44
B6	0.33	0.31	42.00	0.61
A1, s/c, 0.51 % - 45 mm	0.13	0.24	64.33	0.22
A2, s/c, 0.51% - 45 mm	0.05	0.18	55.33	0.11
A3, s/c, 0.51 % - 45 mm	0.24	0.31	45.40	0.50
A2, s/c, 1.0 % - 45 mm	0.10	0.20	60.07	0.29
A2, s/c, 1.5 % - 45 mm	0.15	0.23	55.00	0.35
A2, s/c, 2.0 % - 45 mm	0.19	0.27	51.40	0.39
A2, s/c, 3.0 % - 45 mm	0.25	0.30	49.67	0.44
A2, s/t, 0.51 % - 32 mm	0.03	0.14	55.40	0.12
A2, s/t, 1.0 % - 32 mm	0.06	0.23	60.00	0.20
A2, s/t, 1.5 % - 32 mm	0.13	0.25	56.33	0.25
A2, s/t, 2.0 % - 32 mm	0.15	0.30	53.67	0.42
A2, s/fe, 0.51 % - 30 mm	0.08	0.17	58.67	0.12
A2, s/fe, 1.0 % - 30 mm	0.12	0.20	62.00	0.20
A2, s/fe, 1.5 % - 30 mm	0.13	0.23	61.33	0.25
A2, s/fe, 2.0 % - 30 mm	0.17	0.33	58.67	0.31
A2, s/s, 0.51 % - 35 mm	0.07	0.20	58.33	0.12
A2, s/s, 2.0 % - 35 mm	0.14	0.22	59.33	0.36
A2, p, 0.1 % - 12 mm	0.05	0.10	57.67	0.06
A2, p, 0.51 % - 12 mm	0.17	0.28	54.67	0.16
A2, sp, 0.1 % - 12.5, 60 mm	0.09	0.20	55.00	0.12
A2, sp, 0.5 % - 12.5, 60 mm	0.18	0.26	51.33	0.37

In terms of the method of assessing the surface quality, it appears that the depth gauge (Plates 8.6 and 8.7) performed relatively better than the pocket microscope (Plate 8.8), as depicted by the higher coefficient of correlation (Figures 8.13 and 8.14). It is believed that the depth gauge is able to provide more accurate results, as it is designed to measure the scratch depth directly without any immediate input from the user. However, the close relationship between the scratch depth and width presented in Figure 8.17 (r = 0.827) suggests that both methods may be employed with confidence, but experience and consistency are paramount when the pocket microscope is used as this method requires a direct input from the user in determining the scratch width. Like all microscopic

examinations there exists a subjective factor in taking visual readings. Increasing the number of readings and using one person to produce such data can eliminate this problem.

Figure 8. 13 Abrasion depth vs. Scratch depth for samples cured in polythene sheeting

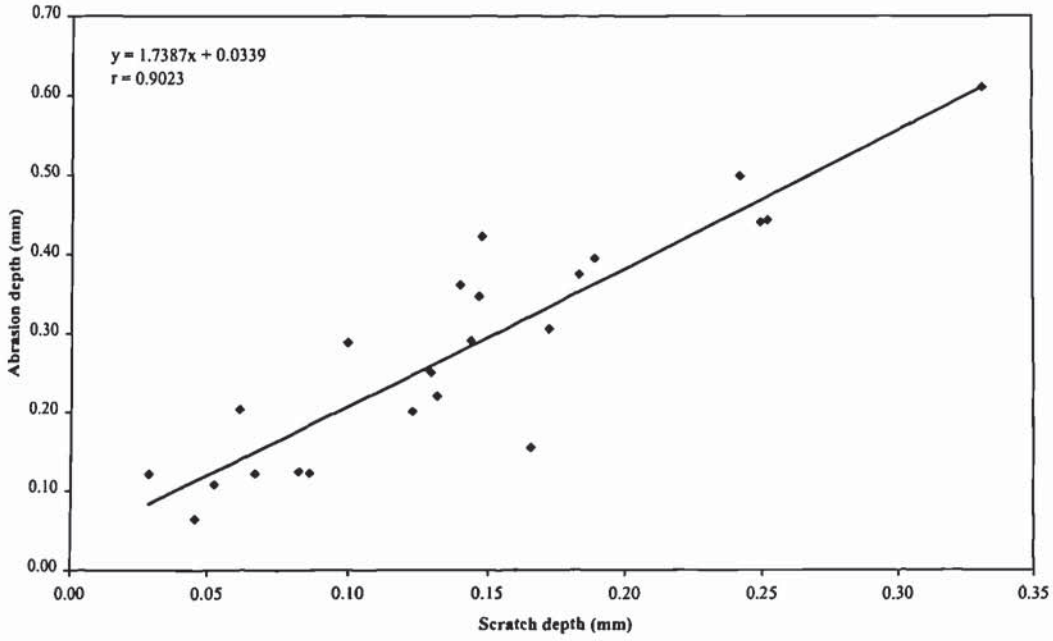


Figure 8. 14 Abrasion depth vs. Scratch width for samples cured in polythene sheeting

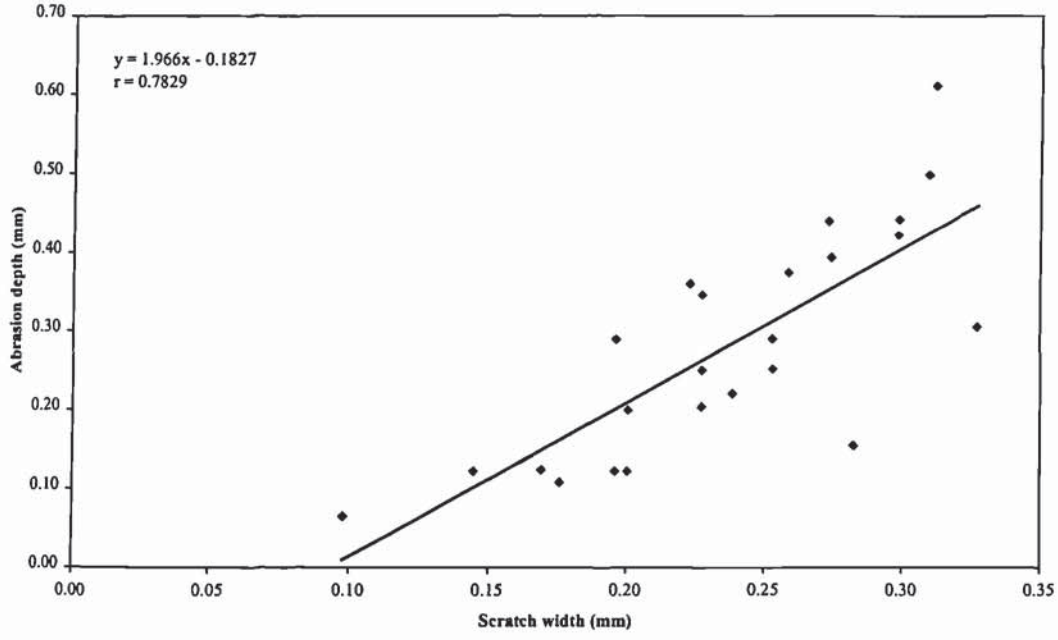


Figure 8. 15 Cube crushing strength vs. Scratch depth for samples cured in polythene sheeting

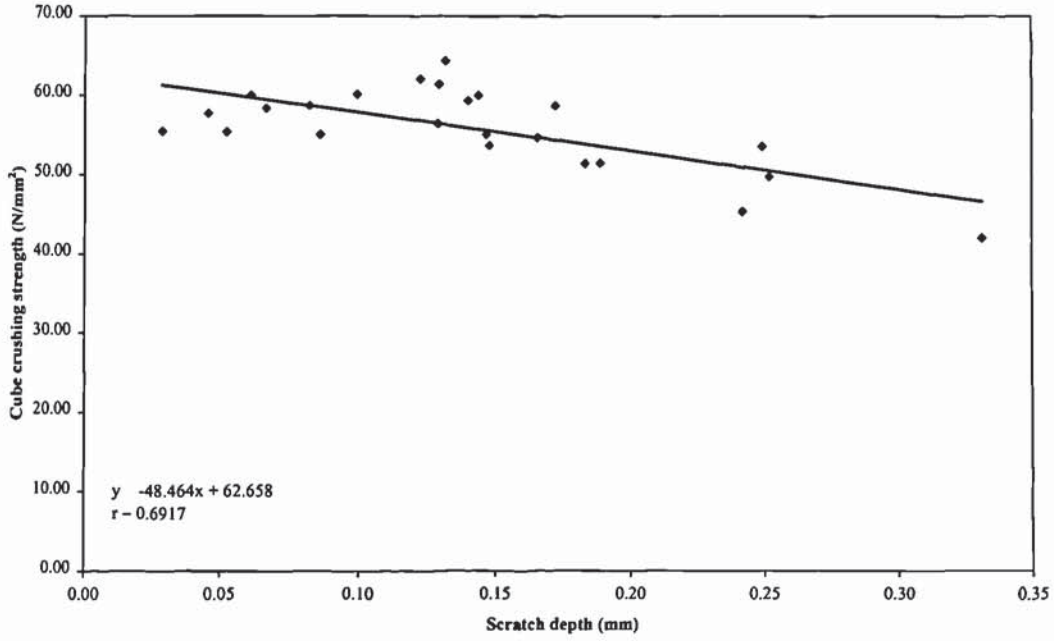


Figure 8. 16 Cube crushing strength vs. Scratch width for samples cured in polythene sheeting

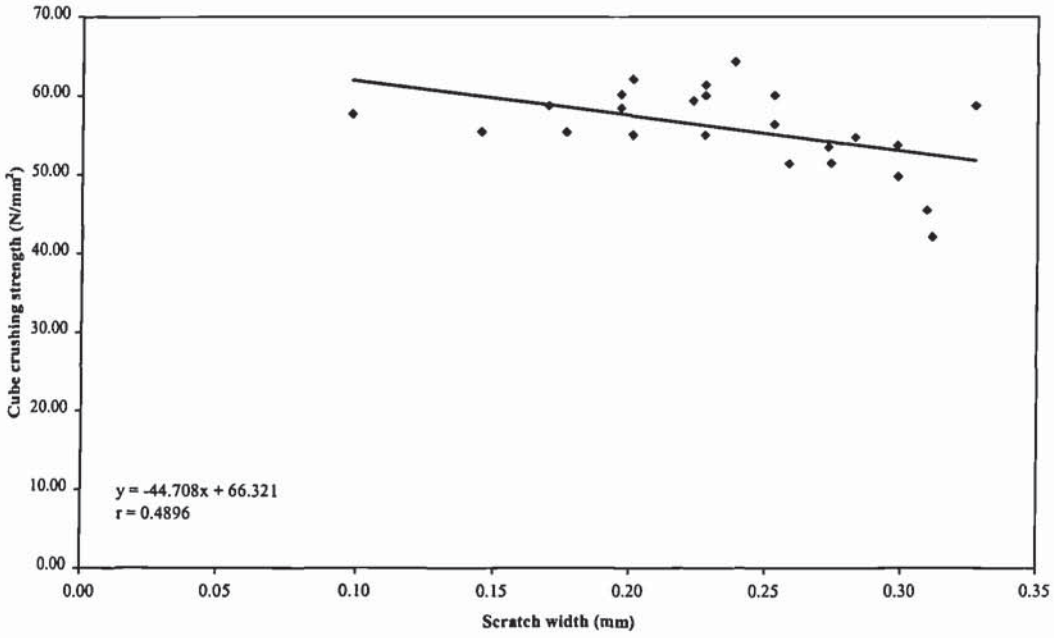
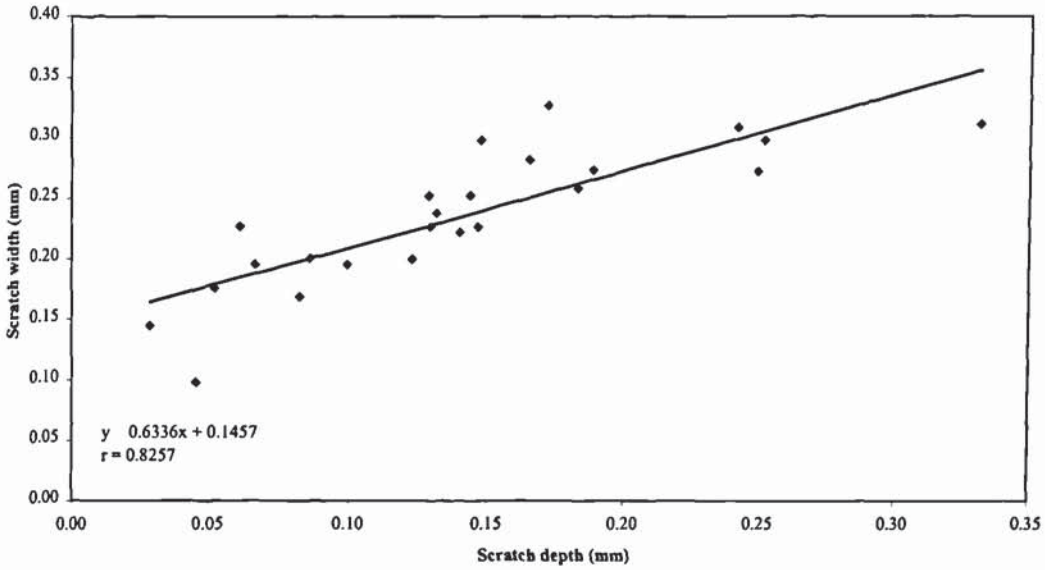


Figure 8. 17 Scratch width vs. Scratch depth for samples cured in polythene sheeting



The results of the base hardness test further confirm the conclusions of the microindentation hardness technique and the impact test, namely that variations in the mix details and the fibre characteristics can influence the hardness of the surface matrix. It has already been shown that the abrasion resistance of plain (Sadegzadeh, 1985) and fibre reinforced concrete is directly related to the hardness of the surface matrix (also see Section 7.2.3).

The maximum coefficient of variation that was calculated for the base hardness tester was 10.44 % when using the depth gauge and 7.07 % when using the pocket microscope to assess the surface quality. Although, this may suggest that the pocket microscope performed better than the depth gauge, it must be noted that the depth gauge is the preferred of the two methods as the pocket micrometer is highly subjective and so the lower coefficient of variation may be attributable to the experienced single operator, the author, who undertook this work. No published records have been traced which can be directly compared to the results and conclusions of the present investigation.

The base hardness test has proved to be a suitable method for predicting abrasion resistance of concrete non-destructively. The test is relatively simple, cheap and easy to perform, and therefore can be readily used as an indicator of mechanical quality of the surface matrix. Indeed Table 8.5 has been extended to include the findings of this part of

the study and the proposed classification is shown in Table 8.10. These have been produced by using the equations presented in Figures 8.13 and 8.14. It should be noted, however, that the findings of the current work are laboratory based and future work should include testing in-service concrete floors in order to confirm the proposed classification.

Table 8. 10 Classification of abrasion, impact and scratch resistance and limiting values

BS 8204 Class	Duty	Type of concrete	Concrete grade (N/mm^2)	Minimum cement content (kg/m^3)	Maximum wear depth (mm)	Maximum impact indentation (mm)	Maximum scratch depth (mm)	Maximum scratch width (mm)
Special	Severe Abrasion	Special mixes and resins	Special mixes and dry-shake or sprinkle finishes, resins etc.		0.05	0.02	0.01	0.1
AR1	Very high abrasion	High – strength toppings			0.1	0.05	0.04	0.15
AR2	High Abrasion	Direct finished concrete	C50	400	0.2	0.1	0.1	0.2
AR3	Moderate abrasion	Direct finished concrete	C40	325	0.4	0.2	0.2	0.3

8.7 Conclusions

In this part of the programme, five non-destructive test methods were investigated to assess their suitability as indirect methods for assessing abrasion resistance of concrete floor slabs. The Initial Surface Absorption was found to only be partially sensitive to factors, which are known to influence the abrasion resistance of concrete, and hence it is considered to be an inadequate method for predicting abrasion resistance. The impact resistance and base hardness test methods have proved to be very sensitive to the factors affecting the abrasion resistance of concrete and are therefore considered to be suitable non-destructive techniques for predicting the abrasion resistance of concrete. The ball cratering was found to be partially sensitive to factors, which are known to influence the abrasion resistance of concrete, and though it is considered to be a potentially suitable method for predicting abrasion resistance of concrete non-destructively, further work is required to supplement the findings of the current investigation and refine the testing procedure. The scratch test was found to be insufficiently sensitive to the factors affecting the abrasion resistance of concrete and are therefore considered to be unsuitable methods for predicting abrasion resistance of concrete indirectly.

Chapter 9: Abrasion resistance of heavy-duty industrial concrete floors

9.1 Introduction

In the UK alone, some 6 million square metres of industrial floor slabs are constructed annually, absorbing 1.5 million cubic metres of concrete and leading to an expenditure of several hundreds of million pounds (ACIFC and The Concrete Society, 1998).

The Civil Engineering Group within Aston University also provides consultancy services to the concrete floor industry so that the Aston accelerated abrasion test (AT), described in detail in Chapter 5, has been systematically used to test newly built and existing concrete floors. Much of the data collected are confidential and so it is not appropriate to include them in this part of the report. Nevertheless, through this industrial testing experience, a few authors (Vassou et al., 2001; Chaplin; 2001) have observed that the quality of current concrete floors is significantly better than of those constructed 15 – 20 years ago. This is attributed to the use of high quality materials, such as dry-shakes and liquid membrane forming curing compounds, and to the technological advancements of the power plant used to finish the concrete floor surface. As a consequence, with so many floors now being grouped in either "Special" or "AR1" classes (Table 5.4) of BS 8204: Part 2, attention has recently been focused on trying to more clearly distinguish between the potential performance of these floors through a more responsive assessment regime.

9.2 Purpose and scope of investigation

The AT is a long established machine and is still able to classify floors into the four categories presented in Table 5.4. However, there is a need to redefine the most demanding categories and develop the machine further so it may more clearly distinguish between the actual performance of such floors with very high abrasion resistance possibly by further subdividing these two categories through an enhanced test method. This should aid the classification of the dry-shake toppings that have been recently introduced to the market by

a number of manufacturers who claim increased abrasion resistance by the use of their products.

There is the separate problem that the real abrasion resistance of the floor may be masked by the presence of curing compounds. Sadegzadeh (1985) reported that the application of curing compounds may create a false high abrasion layer which blocks the abrasive action of the AT at its present form, but his experimental observations were very limited. Very often floors that have undergone such curing treatments, produce abrasion depths of the order of 0.00 - 0.05 mm when subjected to the standard test and so are classed as "special" floors (Table 5.4). Once the special class has been determined, the existing apparatus is not sufficiently sensitive to determine the differences between the several types of surface products that are now being brought to the market. A potential problem is foreseen, especially with the increasing availability of these materials, as the benefits of repeated power trowelling and good curing can also produce adequate results for a floor to be classed as "Special". In order to overcome this problem it is proposed that once the initial class of the floor is determined and it satisfies the "Special" class, further (more aggressive) testing needs to be carried out to determine the true quality of the surface matrix of the particular floor.

The current investigation therefore has been undertaken to:

- Assess the surface quality of existing materials, such as dry shakes, that are considered to contribute towards increased abrasion resistance.
- Establish the characteristics of the concrete immediately beneath the curing/sealing compound as far as abrasion resistance is concerned.
- Assess the life expectancy of curing/sealing compounds on the concrete surface.
- Initiate the development of an adequate method for assessing the abrasion resistance of heavy-duty industrial concrete floors.
- Validate and correlate the laboratory data with in-situ tests performed on existing floors.

9.3 Description of modified accelerated abrasion apparatus heads

In order to facilitate the assessment of heavy-duty floors it was considered reasonable to develop more aggressive head(s) that would potentially replace the existing head of

standard rolling wheels rather than of modifying the existing abrasion tester (Plate 5.1). The current study was set up to initially assess a number of more aggressive heads as potential replacements of the standard rolling wheel head (Plate 9.1) for a secondary test. An extensive investigation was beyond the scope of this work but the outcome of this pilot study would be used to provide the basis for a future more extensive study. Three different types of heads were selected for this initial study, namely:

- flat spot wheels (Plate 9.2)
- dressing wheels (Plate 9.3)
- diamond electroplated wheels (Plate 9.4)

Plate 9. 1 *Standard rolling wheel*

Plate 9. 2 *Flat spot wheel*

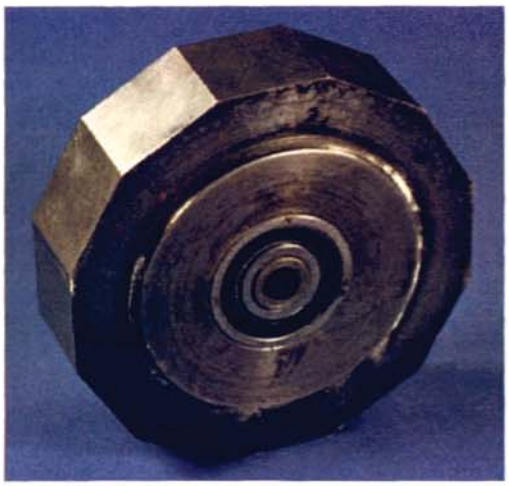


Plate 9. 3 *Dressing wheel*

Plate 9. 4 *Diamond electroplated wheel*

All four types of heads were manufactured from specially hardened steel (KEA 180 Steel). They have a 75 mm diameter and 20 mm width. The flat spot wheels (Plate 9.2) have 12 flat sides the dimensions of which are 20 x 20 mm. The dressing wheels (Plate 9.3) have 20 rises that are 20 x 5 x 3 mm in dimensions. The wheels shown in Plate 9.4 are electroplated in D356 diamond with a 100 % peripheral coverage.

9.4 Specimen fabrication, preparation and testing

9.4.1 Laboratory testing programme

Three types of concrete mixes were included in this programme: C35, C40 and a microsilica concrete. They were delivered to the laboratory by a ready mix supplier and their details are provided in Tables I.1 and I.2 (a – f) of Appendix I. These were used to produce test slabs measuring 2.0 x 1.5 x 0.1 m as shown in Plate 9.5. These slabs were subsequently subdivided to produce individual slabs measuring 1.0 x 0.5 x 0.1 m. A standard procedure was adopted for the preparation of the concrete slabs as presented in Plates 9.5 – 9.7, up to the curing stage (Plate 9.8). Some of the slabs were cured using curing compound (CC) in accordance with the manufacturer's instructions (Table I.3 of Appendix I), the remainder were cured with polythene sheeting (PS) for 28 days. A number of slabs, which had been cured with polythene sheeting, were sprayed with the curing compound 25 days after casting (PS+CC). Standard "thinner" solvent was used to remove the curing compound from the surface (CCR) on some of the slabs, which had received the curing compound at the completion of the casting process, following the procedure specified by the manufacturer of the particular curing compound.

In addition to the above specimens, two manufacturers of dry shake toppings provided a number of concrete slabs which had been finished with four different types of dry shake topping, half of which were cured using a curing compound (CC) and half with polythene sheeting (PS).

All the short-term accelerated abrasion tests were performed 28 days after casting using the same procedure described in Section 5.5.2 but only the AT was used for this part of the study. Longer-term abrasion tests were performed at 3, 6 and 9 months. Some C35 and microsilica concrete samples were tested using the modified heads described in more detail

in Section 9.3. In addition the dressing wheels were used to test some of the dry shake samples.

Plate 9. 5 *Fabrication of ready mix concrete specimens*

Plate 9. 6 *Screeding operations of ready mix concrete specimens*

Plate 9. 7 *Power finishing of ready mix concrete specimens*

Plate 9. 8 *Curing of ready mix concrete specimens*

The initial surface absorption test (ISAT) was performed on concrete mixes C35 and C40 in accordance with BS 1881: Part 5: 1970, at 28 days, 3, 6 and 9 months to provide a further assessment of the condition of the specimen surface over time.

9.4.2 In-situ industrial concrete floors testing programme

For this part of the study, five newly constructed (Site A, B, D, E and F) and two in-service industrial concrete floor slabs (Site C and G) were investigated. At Sites A and B, it was possible to make the necessary arrangements, so that some sections of the floor slab could be cured by curing/sealing compound (CC) with the other areas being subjected to curing by polythene sheeting (PS). Furthermore, 25 days after casting, part of the slab that had been cured by polythene was sprayed with the curing/sealing compound (CCA). Standard "thinner" solvent was also used to remove the curing compound (CCR), following a similar methodology to that employed in the laboratory study, for a part of the slab that had been subjected to curing by curing compound. For Sites D, E and F, it was only possible to use two sections on each site: one cured with polythene sheeting (PS) and one cured with curing/sealing compound (CC).

Both the in-service industrial concrete floors (Sites C and G) had already been exposed to normal traffic for 18 months at the time of testing. The accelerated abrasion test was performed at two separate areas on each of these concrete floor slabs, namely:

- Where the floor has been subjected to normal traffic i.e. loading area
- Where the floor has not been exposed to any type of traffic e.g. under shelving rack or stairs

9.5 Experimental results and discussion

9.5.1 Laboratory test results

The standard accelerated abrasion test results for the three plain concrete mixes: C35, C40 and microsilica, and the four types of dry shake toppings: 1, 2, 3 and 4, are summarised in Tables 9.1 and 9.2, respectively. The results of the accelerated abrasion and ISAT tests performed at 28 days 3, 6 and 9 months are summarised in Table 9.3. The abrasion results obtained using the modified abrasive heads on some of the concrete mixes and dryshakes are presented in Table 9.4.

The results in Table 9.1 show that the mean depth of wear for concrete slabs with the curing/sealing compound (CC) present on the surface during testing ranged between 0.02 – 0.03 mm, classifying the surface quality as "Special" in accordance with BS 8204: Part 2: 1999, irrespective of the time of application of the curing/sealing compound. On some occasions the curing/sealing compound was applied immediately after finishing while in other cases, it was applied 25 days after casting i.e. only 3 days before being tested. In contrast the mean depth of wear for identical concrete slabs, cured in polythene sheeting (PS), ranged from 0.28 to 0.32 mm categorising the surface quality as "AR3" in accordance with BS 8204: Part 2: 1999. The removal of the curing/sealing compound (CCR) provided a better reflection of the quality of the base concrete, as compared with results obtained with the curing/sealing compound present on the surface at the time of testing, and their performance is very similar to that of the PS cured slabs. These results clearly show that the presence of the curing compound on the test surface irrespective of when it was applied, significantly influenced the measured abrasion depths. Given that there are concerns over the permanency of the curing compound, throughout the (20 year) life of the slab, its removal may be necessary to predict the long-term abrasion performance of the slab. The limited test data presented in Table I.4 of Appendix I suggest that the application of a solvent, such as standard "thinner", on the concrete surface did not significantly affect the abrasion test results and so the tests on these slabs merely reinforce the influence of the curing compound in the assessment of abrasion performance. The microsilica concrete did not provide high abrasion resistance without the CC; this is attributed to its very low workability, which in turn resulted in poor surface finish.

The results from samples prepared by the dry shake manufacturers (Table 9.2) show that, in general, the application of dry shake toppings, which has been effectively finished, can provide very high abrasion resistance with or without the use of a curing/sealing compound. All these samples are classified as "Special" in accordance with BS 8204: Part 2: 1999, with the exception of a PS cured sample (Dry shake 4) which is classified as AR2. Furthermore the presence of the curing/sealing compound on the surface, at the time of testing, significantly reduced the measured depth of abrasion for both plain concrete and dry shake topping as indicated by the results in Tables 9.1 and 9.2. It is clear from these results that, for both the plain concrete and the dry shake toppings, the presence of curing/sealing compound on the concrete surface, at the time of testing, could generate misleading results particularly with regard to their potential long-term performance.

Table 9. 1 *Laboratory standard abrasion test results on samples prepared using ready mix concrete*

Type of concrete	Compressive strength (N/mm^2)	Type of curing	Mean* depth of wear (mm)	Classification
C35	24.47	PS	0.32	AR3
		CC	0.03	Special
		PS+CC	0.03	Special
		CCR	0.33	AR3
C40	36.60	PS	0.30	AR3
		CC	0.03	Special
		PS+CC	0.03	Special
		CCR	0.16	AR2
Microsilica concrete	95.67	PS	0.28	AR3
		CC	0.02	Special
		PS+CC	No specimen	-
		CCR	0.31	AR3

Key:
* Mean of three/six sets of results
PS: Sample cured in polythene sheet
CC: Sample cured with curing compound
PS+CC: Curing compound sprayed 25 days after casting on samples cured in polythene sheet
CCR: Curing compound removed 3 days prior to testing on samples cured with curing compound

Table 9. 2 *Laboratory standard abrasion test results on samples prepared by manufacturers of dry shake*

Specimen type	Type of curing	Mean* depth of wear (mm)	Classification
Plain concrete – Control	PS	0.15	AR2
	CC	0.01	Special
Dry shake type 1	PS	0.04	Special
	CC	0.01	Special
Dry shake type 2	PS	0.05	Special
	CC	0.01	Special
Dry shake type 3	PS	0.05	Special
	CC	0.01	Special
Dry shake type 4	PS	0.17	AR2
	CC	0.03	Special

Key:
* Mean of three sets of results
PS: Sample cured in polythene sheet
CC: Sample cured with curing compound

The long-term laboratory results for the accelerated abrasion and ISAT tests (Table 9.3) provide an indication that the surface film, formed by the application of the curing/sealing compound to the concrete surface, may degrade over time. Both the depths of wear and the surface absorption rates for the samples subjected to a curing/sealing compound (CC), given in Table 9.3, show that the values of both these parameters increased with time, particularly after 90 days suggesting a breakdown in the sealing layer produced by the curing compound. Between 28 and 270 days, the abrasion depths of these (CC) specimens

for both mixes have more than doubled, so that their abrasion category changed from Special to AR1, although the corresponding values at 270 days were still below those from the PS slabs. Indeed the values of both parameters from the PS slabs showed at most no change between 28 and 270 days, reinforcing the observation that something, adverse, was happening to the surface of the CC specimens.

Table 9. 3 *Longer term laboratory standard abrasion test results on samples prepared using ready mix concrete*

Type of concrete	Type of curing	Age (days)	Mean* depth of wear (mm)	Rate of surface absorption after 10 min* ($ml/m^2/s$)	Rate of surface absorption after 30 min* ($ml/m^2/s$)	Rate of surface absorption after 60 min* ($ml/m^2/s$)
C35	CC	28	0.03	0.0288	0.0163	0.0113
	PS		0.32	0.0675	0.0400	0.0200
	CC	90	0.05	0.0325	0.0175	0.0113
	PS		0.30	0.0500	0.0326	0.0200
	CC	180	0.08	0.1050	0.0625	0.0488
	PS		0.31	0.0588	0.0388	0.0175
	CC	270	0.11	0.1250	0.0813	0.0675
	PS		0.34	0.1163	0.0688	0.0500
C40	CC	28	0.03	0.0313	0.0175	0.0125
	PS		0.30	0.0725	0.0575	0.0275
	CC	90	0.02	0.0413	0.0200	0.0125
	PS		0.32	0.0725	0.0363	0.0213
	CC	180	0.06	0.0863	0.0500	0.0288
	PS		0.33	0.0638	0.0338	0.0163
	CC	270	0.10	0.1000	0.0588	0.0400
	PS		0.32	0.0650	0.0313	0.0225

Key:
* Mean of three sets of results
PS: Sample cured in polythene sheet
CC: Sample cured with curing compound

9.5.2 In-situ industrial concrete floors test results

The in-situ accelerated abrasion tests results obtained from the newly constructed concrete floor slabs are summarised in Table 9.4. These results show that when the accelerated abrasion test was performed on the floor slab with a curing/sealing compound present, they were again all categorised as "Special" in accordance with BS 8204: Part 2: 1999. However, when the testing was performed on the same floor slab, but without the curing/sealing compound present, the abrasion depths were significantly higher and the category was reduced to "AR2/AR3". The application of the same curing compound three days prior to testing also led to these floor slabs, previously cured for 25 days with polythene sheeting, to be categorised as "Special". The removal of curing/sealing compound with standard "thinner" solvent prior to testing appears to have reduced the

abrasion resistance to a level below that produced by the corresponding PS cured specimens. It is suggested that the application of the thinner may have roughened the surface leading to this consequence. However, overall, the results for these newly constructed industrial concrete floor slabs are generally consistent with and confirm the previous laboratory test results.

Table 9. 4 Summary of site test results for newly constructed concrete floor slabs

Site	Type of concrete	Type of curing	Mean* depth of wear (mm)	Classification
A	Plain/C40	PS	0.28	AR3
		CC	0.04	Special
		CCA	0.02	Special
		CCR	0.43	Out of spec.
B	Plain/C40	PS	0.22	AR3
		CC	0.03	Special
		CCA	0.01	Special
		CCR	0.38	AR3
D	Plain/C40	PS	0.38	AR3
		CC	0.03	Special
	Dry shake topping	PS	0.20	AR2
		CC	0.03	Special
E	Dry shake topping	PS	0.19	AR2
		CC	0.03	Special
F	Dry shake topping	PS	0.04	Special
		CC	0.03	Special

Key:
* Mean of three sets of results
PS: Selected floor cured in polythene sheet
CC: Floor cured with curing compound
CCA: Curing compound sprayed 25 days after casting on selected floor area cured in polythene sheet
CCR: Curing compound removed 3 days prior to testing on selected floor area cured with curing compound

Table 9.5 summarises the results of the abrasion tests carried out on the in-service concrete slabs, C and G. It is clear from these particular results that at locations where the floor slab has been subjected to normal traffic, the depth of wear is significantly more than at the locations where the concrete surface has not been exposed to traffic. This implies that once the curing compound has been removed from the surface, either by degradation or wear, the subsequent performance of the slab depended on the quality of the residual concrete and not on the now absent curing/sealing compound. This was further supported by the visual examination. Examination of these floor slabs indicated a general lack of "shine" on the floor slab, after 18 months, particularly at those locations where the floor slab has been subjected to normal traffic. The results from the in-service industrial concrete floor slabs suggest that the efficiency of the curing/sealing compound reduces with time and type of exposure to traffic.

Table 9. 5 Summary of site test results for in-service concrete industrial floor slabs

Site	Location	Type of concrete	Type of curing	Mean* depth of wear (mm)	Classification
C	Under racking	Plan/C40	CC	0.19	AR2
	Under stairs	Plan/C40	CC	0.20	AR2
	Under racking	Plan/C40	CC	0.17	AR2
	Loading area	Plan/C40	CC	0.38	AR3
	Loading area	Plan/C40	CC	0.38	AR3
	Loading area	Plan/C40	CC	0.57	Out of spec.
G	Under racking	Dry shake topping	CC	0.03	Special
	Under stairs	Dry shake topping	CC	0.05	Special
	Under racking	Dry shake topping	CC	0.04	Special
	Loading area	Dry shake topping	CC	0.10	AR1
	Loading area	Dry shake topping	CC	0.08	AR1
	Loading area	Dry shake topping	CC	0.08	AR1

Key:
* Mean of three sets of results
CC: Floor cured with curing compound

9.5.3 Preliminary investigations into future research

In order to both facilitate the assessment of heavy-duty floors and to overcome the masking problem associated with the use of curing compounds, as discussed in Sections 9.5.1 and 9.5.2, further development of the existing apparatus accelerated abrasion was considered to be necessary. Several more aggressive heads (Section 9.3) were considered as potential replacements of the standard rolling wheel head for a secondary test. To determine the suitability of the three proposed heads, initial tests were carried out on samples produced using a cementitious product known commercially as "five star repair concrete". The repair concrete was hand finished and some samples were cured in air while a curing compound was used for others. As this material is both rapid hardening and high strength, the accelerated abrasion tests could be carried out 7 days after these samples were cast. The interim abrasion results obtained from these tests are summarised in Tables 9.6 and 9.7.

It is interesting to note that a floor specimen is normally subjected to a standard abrasion resistance test for a standard period of 15 minutes in accordance to BS 8204: Part 2: 1999. In extreme cases, however, where the abrasion depth is higher than 1 – 2 mm, the abrasion tester can become unstable and therefore the test is terminated to avoid damaging the machine. Clearly the flat spot and dressing wheels produced abrasion depths much higher than those produced by the standard rolling wheels (Tables 9.6 and 9.7) and so these tests were only run for a period of 5 minutes. It was found that the flat spot wheels were the most aggressive type, for example with the specimens subjected to a curing compound, this test head produced 5 minute results some 5 times greater than those achieved with the

standard rolling wheels, while, for the air cured specimens, the corresponding figure was 8 times that achieved with the standard rolling wheels. Similarly the dressing wheels produced an abrasion depth 3 to 4 times greater than that produced by the standard rolling wheels over the same testing period while for the diamond electroplated wheels, the abrasion depth was double that of the standard rolling wheels. The coefficient of variation was also calculated for each head and on this limited data with one exception, these values for all the tests lay within the narrow range of 10 ± 3% suggesting that all four test heads produced a similar level of reliability for the test results on these particular samples (Tables 9.6 and 9.7).

Table 9. 6 *Performance of several abrasion heads on hand finished 5 star repair concrete samples cured with curing compound*

Test head	Average depth of wear (mm) *			Coefficient of Variation at 5 min (%)
	5 min 950 revs	10 min 1900 revs	15 min 2850 revs	
s	0.68	1.48	2.41	7.42
de	1.23	2.08	3.70	7.61
d	2.40	-	-	10.30
f	3.45	-	-	10.16

Key:
* Mean of three tests
s: standard wheels
de: diamond electroplated wheels
d: dressing wheels
f: flat spot wheels

Table 9. 7 *Performance of several abrasion heads on hand finished 5 star repair concrete samples cured in air*

Test head	Average depth of wear (mm) *			Coefficient of variation at 5 min (%)
	5 min 950 revs	10 min 1900 revs	15 min 2850 revs	
s	0.58	1.15	1.63	15.37
d	2.13	-	-	8.73
f	4.47	-	-	12.06

Key:
* Mean of three tests
s: standard wheels
d: dressing wheels
f: flat spot wheels

These initial results were encouraging and certainly demonstrated that all three proposed heads were more aggressive than the standard rolling wheels. This is an important breakthrough as it suggests that it may be possible to rank the performance of floors that are currently classified as "Special" so that the most suitable products and techniques can be selected for particularly demanding circumstances. A more aggressive test regime may

also rapidly wear through the false surface film created by curing compounds applied to the floor surface and so enable the AT to assess the true quality of such floors. However, the initial findings (Tables 9.6 and 9.7) also suggested that the flat spot wheels were much too aggressive for the proposed purpose of the current investigation, producing abrasion depths higher than 1 – 2 mm and causing the AT to rapidly become unstable. Further, practical problems were revealed when using the diamond electroplated wheels, i.e. dust particles became compacted and stuck to the rough surface of the wheels and subsequently acted as lubricants and/or abrasives on the floor surface. It was therefore considered that the most appropriate technique for further development and use would be the dressing wheels.

Additional work was therefore carried out to investigate the performance of the dressing wheels on several types of concretes and dryshakes, for samples cured both by polythene sheeting and curing compound. These results are presented in Table 9.8 and suggest that the dressing wheels are suitable for assessing the abrasion resistance of high quality concrete surfaces. In addition, it appears that these wheels are able to penetrate the thin surface film that was generated by the application of the curing/sealing compound. The coefficient of variation was calculated for both the standard rolling wheels and the dressing wheels and they varied between 6.09 – 49.41 % and 8.62 – 47.90 % respectively. These values are consistent with the values calculated for the standard rolling wheels in Chapter 5 (Table 5.2).

Further, due to the aggressive nature of the dressing wheels, the duration of the accelerated abrasion test was reduced to 5 minutes for most of the experimental work. However, in some cases this produced abrasion depths larger than 1 mm (Table 9.8) suggesting that this time period may not be appropriate for a standardised test as with depths of that order the AT becomes unstable. Consideration of the data in Table 9.9 show that test periods of 2 to 4 minutes produce abrasion depths of 0.20 to 1.05 mm. This suggests that a test duration between 2 – 3 minutes may be more suitable for producing measurable depths that do not also cause any damage to the AT. It should be noted that as the test period is reduced, there is also a reduction in the corresponding coefficient of variation so that it drops from 26.67 % at 2 minutes to 8.89 % at 4 minutes and then picks up again at 11.89 % at 5 minutes.

Table 9. 8 *Performance of several abrasion heads on different concrete mix and dryshake samples cured by two different curing methods*

Concrete / dryshake type	Curing regime	Test head	Mean* depth of wear (mm)		Coefficient of variation at 5 min (%)
			5 min 950 revs	15 min 2850 revs	
C35	CC	s	0.01	0.03	41.66
		d	1.65	-	28.36
Microsilica concrete	PS	s	0.06	0.30	33.75
		d	0.59	-	11.53
		de	0.40	-	23.28
Plain Concrete Control	PS	s	0.10	0.15	20.98
		d	0.64	-	33.17
	CC	s	0.01	0.01	21.84
		d	1.14	-	15.66
Dry shake type 1	PS	s	0.03	0.04	30.76
		d	0.12	-	8.62
	CC	s	0.01	0.01	43.30
		d	0.33	-	34.78
Dry shake type 2	PS	s	0.04	0.05	6.09
		d	0.22	-	14.09
	CC	s	0.01	0.01	24.74
		d	0.31	-	47.90
Dry shake type 3	PS	s	0.04	0.05	27.65
		d	0.09	-	27.49
	CC	s	0.01	0.01	43.68
		d	0.62	-	32.32
Dry shake type 4	PS	s	0.12	0.17	34.97
		d	-	-	-
	CC	s	0.02	0.03	49.41
		d	1.49	-	11.89

Key:
* Mean of three tests
PS: Sample cured in polythene sheet
CC: Sample cured with curing compound
s: standard wheels
d: dressing wheels

Table 9. 9 *Dressing wheels performance on a dryshake topping sample at different testing time periods*

Specimen description	Curing regime	Testing head	Test duration (min)	Mean* depth of wear (mm)	Coefficient of variation (%)
Dry shake type 4	PS	s	15	0.17	34.97
	CC	s	15	0.03	49.41
	CC	d	2	0.20	26.67
	CC	d	4	1.05	8.89
	CC	d	5	1.49	11.89

Key:
* Mean of three/six tests
PS: Sample cured in polythene sheet
CC: Sample cured with curing compound
s: standard wheels
de: diamond electroplated wheels
d: dressing wheels

9.6 General discussion

When a curing/sealing compound is applied to a concrete surface it forms a thin surface film i.e. like paint and it is the strength of this film that is mainly responsible for initially resisting the abrasion forces. However, once this layer is penetrated, the abrasion forces would act directly on the base concrete. Visual examination of the abrasion path, after the completion of the test, indicated that in some cases, this surface film compound showed signs of penetration and rupture. If the exposure to abrasion was to continue, as would be the situation in the working environment, then the long-term abrasion resistance would become primarily dependent on the properties of the base concrete, beneath the now abraded surface film. There is a further consequence due to the formation of this surface film as it results in a smoother concrete surface. This smooth surface is able to reduce the frictional forces between it and the rolling wheels of the accelerated abrasion machine, and so reduces the abrasive load from the rolling steel wheels. This, in turn produces misleading results and consequently an erroneous classification, particularly with respect to long-term (life-time) performance.

It has been noted that positive early curing leads to better abrasion resistance (Chaplin; 2001) and the effectiveness of the curing/sealing products is very valuable in this respect. Polythene sheeting is not a practical approach for large floor areas. Accordingly, the results of this work should not lead to the reduced use of curing/sealing compounds for they represent an effective curing stratagem. However additional vigilance and awareness is essential in interpreting the results of any subsequent abrasion test.

To address the problem created on in-situ floors by the use of dry-shakes and curing/sealing compounds preliminary work was carried out towards the further development of the AT. Dressing wheels were found to be more aggressive than the standard rolling wheels and more suitable than the other two proposed heads – flat spot and diamond plated. Nevertheless, further work should be carried out in order to standardise the proposed modified test and to confirm the initial laboratory findings with future data from laboratory and on-site testing.

The other issue to be assessed relates to the rate of wear of the test heads for the abrasion process invariably involves loss of material from both abrading surfaces, test heads and concrete. Clearly, if the modified wheels also wear rapidly, it will significantly increase the cost of the test, as replacements could be required after only a limited number of tests. This

was observed by Sadegzadeh (1985) when he investigated alternative test methods, although the rate of wear of the standard wheels was very low so replacements were only considered after 12 months of intensive testing, but the concrete that he was testing was not of the same high quality (hardness) as some of the mixes now being used for floors subjected to demanding abrasion exposure.

9.7 Conclusions

In this chapter the research work has indicated the following:

- The presence of a curing/sealing compound on the concrete surface, when it is subjected to standard accelerated abrasion testing, produces misleading results which can result in the floor slab being placed in a higher abrasion category than is justified by the underlying performance of the base concrete. This can have important implications with respect to the expected long-term performance of the floor slabs.
- Careful removal of the curing/sealing compound from the concrete surface by the use of standard "thinner" solvent does not appear to significantly influence concrete surface properties prior to the accelerated abrasion test. In fact, this technique produces more meaningful results than with the curing/sealing compound present at the time of testing, particularly with respect to predicting lifetime performance.
- The enhanced abrasion resistant characteristic produced by the curing/sealing compound on the concrete surface reduces with time and exposure to normal traffic. The abrasion resistant characteristic of the curing/sealing compound on industrial concrete floor slabs was significantly reduced after 18 months of service, unlike the polythene cured concrete surfaces which did not exhibit a similar reduction in abrasion resistance.
- The proposed dressing wheel head is expected to produce a more precise assessment in terms of abrasion resistance of heavy-duty floors. The preliminary testing presented in this chapter has shown that this test head is more aggressive than the standard rolling wheels and could form the basis for a modified test regime to assess particularly hard wearing surfaces.

Chapter 10: Conclusions and recommendations for future research

10.1 Introduction

The experimental results produced from this investigation have been presented and thoroughly discussed in the preceding Chapters of the thesis. A summary of the main conclusions and findings developed in these previous sections is presented below. Further, through the current study, it has become apparent that there are several aspects of the work that would benefit from further investigation and these are also summarised in this Chapter.

10.2 Test methods for assessing the abrasion resistance of concrete floors

10.2.1 Findings

- The Aston accelerated abrasion tester (AT) and the British Cement Association accelerated abrasion tester (BCAT) produced compatible and repeatable results.
- The commercial accelerated abrasion tester (CT) produced results that were significantly different to those obtained with both the AT and the BCAT for tests performed on standardised, control slabs.
- The incorporation of the CT into the BS 8204: Part 2: 1999 is inappropriate at this stage as the performance of the apparatus is not satisfactory, although data from the AT and BCAT can be used as these testers provided the original data to establish the performance criteria in BS 8204: Part 2: 1999.

10.2.2 Recommendations

- It is suggested that further work is carried out towards calibrating the CT for compatibility against the AT and the BCAT.

- Future work should focus on the design of the CT and amendments should be made to allow unrestricted vertical movement as the wheels pass over the concrete surface, a process that occurs with both the AT and BCAT machines.
- Microscopic analysis of the abrasion debris and the surface of the abrasion abrasion path should be undertaken to provide better understanding of the mode of action of the various abrasion machines and in particular the CT.

10.3 Macro-study of abrasion resistance of fibre reinforced concrete

10.3.1 Findings

- The inclusion of fibres into the concrete mix improved the abrasion resistance. This is primarily attributed to the fibres acting as a drainage path for excess water to escape to the surface, where it evaporates before the power finishing/compaction commences, thereby leading to a lower w/c ratio in the surface matrix which is further densified by the power finishing procedures.
- It was found that the most significant improvement was generally achieved with an optimum steel fibre content of 0.51 % by volume for unsuperplasticized mixes. The superplasticized mixes resulted in a higher abrasion resistance at a significantly higher fibre dose (2% by volume), with an optimum superplasticizer content of 0.75 % by weight of the cement content.
- While the shape of the steel fibres did not significantly affect the abrasion resistance, the type of fibre (in terms of metallic and non-metallic) was significant, with the largest improvement in abrasion resistance being obtained through the inclusion of polypropylene fibres. However, the length of the steel fibres did significantly affect the abrasion resistance, with the shorter fibre being most effective. This has been attributed to the reduction in workability with the longer fibres in unsuperplasticized concrete mixes.
- Efficient curing of the concrete specimens significantly increased the abrasion resistance. The experimental results indicate that fibre reinforced concrete specimens cured with a curing compound produced an abrasion resistance very similar to that of specimens cured by the use of a polythene sheets, both having significantly superior abrasion resistance to that of the equivalent air cured specimens.
- The experimental data clearly show that the abrasion resistance and the compressive strength are directly related. Whilst it would appear that a definite relationship exists

between the cube strength and the abrasion resistance, the strength was not an absolute indicator of abrasion resistance, since it did not adequately take account of other factors that affect the abrasion resistance of a concrete surface.

- The water-cement ratio and the inclusion of superplasticizing agents into the concrete mix are factors that both significantly influenced the abrasion resistance.

10.3.2 Recommendations

- It would be interesting to compare the performance of fibre reinforced specimens containing superplasticizers with that of the unsuperplasticized samples used during this study. This should include all the types of fibres in the current study at the same fibre volumes but at the optimum superplasticizer content.
- As an adjunct to this work, opportunity should also be taken to assess the influence of the presence of liquids such as water, milk, acids and solvents on the abrasion resistance of fibre reinforced concrete floors. Though extensive research work has been undertaken with metals, the same attention has not been given to wet abrasion resistance of concrete. In practice, many industrial concrete floors are now subject to wet wearing conditions and so it is important to develop a method that would be able to assess the quality of floors in such environments.
- Future research work should attempt to measure the bleed water evaporating from the surface of the concrete prior to and during the power finishing operations, the object being to explore whether there is a relationship between this quantity and the abrasion resistance. This should also improve our understanding of the factors and mechanisms that affect the abrasion resistance of concrete.

10.4 Micro-structural study of abrasion resistance of fibre reinforced concrete

10.4.1 Findings

- A standard procedure was adopted for assessing the microhardness of concrete specimens, this was based on previous research programmes but the technique was further developed to improve its reliability with fibre reinforced samples. The microhardness profiles were particularly sensitive to changes in the water-cement ratio.

Further more the microhardness profiles obtained from fibre reinforced specimens were significantly different to those from the equivalent plain concrete specimens.

- The abrasion resistance of plain and fibre reinforced concrete was directly related to the microhardness of the surface matrix. Confirming a previous investigation on plain concrete (Sadegzadeh, 1985), it has been shown that the ability of a fibre reinforced concrete surface to resist abrasion forces is also primarily controlled by the top 2 mm of the surface matrix.
- The fibre dose influences the microhardness of the surface matrix, with increased fibre volumes generally leading to decreased microhardness values and this was attributed to the reduced workability displayed by the unsuperplasticized concrete slab specimens.
- The paste around a steel fibre nearer to the surface produced higher hardness values that the paste around the fibre within the bulk body of the sample, but all the results showed the existence of a soft region roughly 40 to 60 μm away from the reinforcement. This suggested that even though the bond between the steel fibre and the matrix in general is probably quite weak, the bond of the steel fibre nearer the surface and the paste is stronger than the one between the main body fibre and the paste, again demonstrating the local benefits of power finishing.
- The Mercury Intrusion Porosimetry method is a very sensitive and valuable means of qualitatively investigating the influence of factors, which affect the abrasion resistance of concrete.
- It was possible to relate the abrasion resistance of the fibre reinforced concrete to the pore structure of its surface matrix. It was found that the total pore volume decreased with decreasing w/c ratio confirming the findings of previous investigators (Almudaiheem, 1992; Sadegzadeh, 1985; Odler & Röβler, 1985; Röβler & Odler, 1985) that the PSD is a function of w/c ratio for both plain and fibre reinforced concrete.
- It has also been observed that the total pore volume decreased with the addition of a constant volume of 0.51 % of steel crimped fibres into the equivalent plain concrete mixes and the total pore volume increased as the steel fibre content was increased. This suggested that, up to a certain percentage, fibre inclusion reduced the porosity of concrete.
- Of particular note is the observation that the mix containing polypropylene fibres produced the lowest pore volume value amongst any of the tested mixes. This was attributed to the reduced porosity and increased penetration resistance reported by the British Board of Agrément (1995), Certificate No. 92/2830, when Initial Surface

Absorption Tests were carried on a similar PFRC mixes. It was suggested that polypropylene fibres reduce the initial flow rate of water absorption and this has been further confirmed by the results on Initial Surface Absorption Tests (Chapter 8, Section 8.2.2).

- The results obtained generally suggested that the inclusion of fibres into the concrete mix influenced the pore structure of surface matrix of the concrete floors.
- The abrasion resistance of plain and fibre reinforced concrete was directly related to the porosity of the surface matrix.
- The microhardness of the surface matrix of the plain and fibre reinforced concrete specimens was directly related to the corresponding porosity of the surface matrix.
- Petrographic examination of polished surfaces and impregnated thin sections provided a qualitative means of assessing the microstructure of the specimens. This method provided a visual confirmation of the conclusions derived from the data obtained with the microhardness and Mercury Intrusion Porosimetry studies.

10.4.2 Recommendations

- The microhardness and Mercury Intrusion Porosimetry techniques can be used to investigate the hardness and porosity distribution throughout the depth of slabs containing superplasticizing agents and different volumes of polypropylene and glass fibres and so they should be used to further explore the influence of different curing regimes on abrasion resistance.

10.5 Indirect and non-destructive testing for predicting abrasion resistance of fibre reinforced concrete

10.5.1 Findings

- A modified Initial Surface Absorption Test (ISAT) rig was developed for this study. It was established that the use of the modified test rig did not significantly influence the results obtained, compared with those obtained from the standard rig.
- The ISAT was found to be partially sensitive to a number of the factors that have been shown to influence the abrasion resistance of concrete. The relationship between the abrasion resistance and the ISAT values was close but not as highly significant as had been expected. However, analysis of these data has indicated that the ISAT may be the

basis of a method for in-directly and non-destructively assessing abrasion resistance, but it is not sufficiently robust to be a reliable method for predicting abrasion resistance.

- The impact resistance and base hardness test methods proved to be very sensitive to the factors affecting the abrasion resistance of concrete and are therefore considered to be suitable non-destructive techniques for predicting abrasion resistance of concrete.
- In particular the data obtained from the impact test and the base hardness tester indicated close, and statistically significant, relationships between the impact resistance, scratch depth and scratch width and the depth of abrasion of fibre reinforced concrete floors. This has been attributed to the fact that all these parameters are influenced by the quality of the surface matrix.
- Since no objective method was suggested by the manufacturer for assessing the damage to the samples tested with the base hardness tester, a new device (depth gauge) was developed for measuring the depth of the scratches. A separate pocket microscope was used for determining the width depth of the scratches. Both performed satisfactorily and so may be used with confidence, however, experience and consistency are paramount when using the pocket microscope.
- Based on the laboratory study a new classification system has been proposed which suggests the acceptable limits for the impact and scratch depths together with the scratch width. These should be used to form the basis of an acceptable approach for predicting the abrasion resistance.
- The ball cratering and scratch tests carried out at the National Physical Laboratory were found to be insufficiently sensitive to the factors affecting the abrasion resistance of concrete and so these specific tests are considered to be unsuitable for predicting the abrasion resistance of concrete indirectly and non-destructively.

10.5.2 Recommendations

- Extensive work should be undertaken to further examine the relationship between both the impact and scratch resistance and the accelerated abrasion resistance of concrete floors including a field investigation. This will serve towards confirming the laboratory findings and establish the reliability of the proposed classification limits.
- Further laboratory work should be undertaken using the base hardness tester to study its sensitivity to factors such as the curing regime, fibre geometry (length) and

inclusion of superplasticizing agents, which have also been shown to influence abrasion resistance.

10.6 Abrasion resistance of heavy-duty industrial concrete floors

10.6.1 Findings

- The presence of a curing/sealing compound on the concrete surface at the time of accelerated abrasion testing produces misleading results when viewed on a longer term basis and consequently can classify the floor slab in a significantly higher category than is justified by the base concrete.
- To better understand the abrasion resistance of the concrete surface immediately below the curing/sealing compound, it is necessary to remove this compound with a standard "thinner" solvent. Separate tests demonstrated that the application of the thinner did not significantly influence the results of the standard abrasion test.
- The enhanced abrasion resistant characteristic produced by the application of a curing/sealing compound on the concrete surface reduces with time and exposure to normal traffic. The abrasion resistant characteristic of floors subjected to a curing/sealing compound was significantly reduced after 18 months of service.
- A dressing wheel head has been proposed to provide a more appropriate assessment of the abrasion resistance of heavy-duty floors. The preliminary testing has shown that this test head is more aggressive than the standard rolling wheels and so is likely to be more effective in rating the performance of these heavy-duty floors, particularly where they have also been subjected to a curing compound.

10.6.2 Recommendations

- In order to extend the above findings, future work should be concentrated on the long-term performance of curing compounds of samples exposed to light/medium trafficking (up to 3 years). This should include both laboratory and in-service concrete floor samples.
- Though the dressing wheels were found to be more aggressive than the standard rolling wheels and more suitable than the other two proposed heads, further work should be carried out to standardise the proposed modified test and to confirm the current laboratory findings with both laboratory and on-site testing data.

- The other issue to be assessed relates to the rate of wear of the test heads for the abrasion process invariably involves loss of material from the abrading surfaces, wheels and concrete. Clearly, if the modified wheels also wear rapidly, it will significantly increase the cost of the test, as replacements will be required after only a few tests.
- It is also important to use the proposed head more extensively to investigate thoroughly the properties and surface characteristics of heavy-duty floors relating to the use of materials such as dry-shake toppings, sealers and curing agents.
- The microhardness technique should be employed on the actual surface of the slab specimens, especially the specimens cured with a curing compound, rather than employing the procedure that was used in the present study, in order to determine the sensitivity of the method to localised surface variations.

10.7 Concluding remarks

This study has compared three accelerated abrasion testers and critically discussed their suitability for assessing the abrasion resistance of concrete floors. The testing programme has led to appropriate recommendations towards improving the performance of the commercial accelerated abrasion tester when used to assess the quality of concrete floors. Furthermore, it has clearly demonstrated that abrasion resistance of fibre reinforced concrete is influenced by various material and construction factors. These included mix variations (w/c ratio), fibre reinforcement, geometry, type and volume, curing method and the role of superplasticizing agents.

Indirect and non-destructive methods have been successfully developed for predicting abrasion resistance and it has been suggested that the impact resistance (BRE screed tester) and scratch resistance (Base hardness tester) are the most appropriate techniques for this purpose. The abrasion resistance of concrete was shown to be primarily dependent on the microstructure of the concrete nearest to the surface. However, the most important conclusion must be that the presence of curing/sealing compound on the concrete surface at the time of accelerated abrasion testing produces misleading results when viewed on a longer term basis and consequently classifies the floor slab in a significantly higher category. A preliminary investigation targetted at modifying the Aston accelerated abrasion tester has been carried out and a more aggressive head has been developed for assessing heavy-duty floors.

References

1. A'Court CL (1949) Dust nuisance of concrete floors, Engineering, Dec. 2, pp. 577 – 579.
2. A'Court CL (1954) Mix design and abrasion resistance of concrete, Proceedings of a Symposium on Mix Design and Quality Control of Concrete, London, Cement and Concrete Association, May, pp. 77 – 91.
3. Abbud-Klink SA (1967) Fycrete: A new material for structures, PhD thesis, Rensselaer Polytechnic Institute, November 1967, Troy, NY.
4. Abrams DA (1916) A method of making wear tests of concrete, Proceedings, American Society for Testing Materials, Vol. 16, Part 2, pp. 194 – 208.
5. Abrams DA (1921) Wear test of concrete, Proceedings, American Society for Testing Materials, Vol. 21, Part 2, pp. 1013 – 1038.
6. ACI Committee 116 (1967) Cement and Concrete Terminology, Publication SP – 19, ACI, Detroit, Michigan.
7. ACI Committee 210 (1955) Erosion resistance of concrete in hydraulic structures, ACI Journal, Vol. 27, No. 3 (November), pp. 259 – 271.
8. ACI Committee 302 (1989) Guide for concrete floor slab construction, ACI 302.1R – 89, ACI Materials Journal, Vol. 86, No. 3, pp. 252 – 296.
9. ACI Committee 544 (1986) State-of-the-art report on fibre reinforced concrete, in ACI Manual of concrete practice, Part 5 - 1990, American Concrete Institute, Michigan, USA.
10. ACI Committee 544 (1988a) Design considerations for steel fibre reinforced concrete, in ACI Manual of concrete practice, Part 5 – 1990, American Concrete Institute, Michigan, USA.
11. ACI Committee 544 (1988b) Measurement of properties of fibre reinforced concrete, in ACI Manual of Concrete Practice, Part 5 – 1990, American Concrete Institute, Michigan, USA.
12. ACI Committee 544 (1993) Guide for proportioning, mixing, placing and finishing steel fibre reinforced concrete, ACI Materials Journal, Vol. 90, No. 1, pp. 94 – 101.

13. ACIFC and The Concrete Society (1998) Good Concrete Guide 1: Guidance on specification, mix design and production of concrete for industrial concrete floors, Slough, 24 pp.
14. Ahlers JG, Lindon JJ & Bird MF (1929) Wear tests on floor finishes at warehouse of R. H. Macy Co., Long Island City, New York, Journal of American Concrete Institute, Vol. 25, pp. 778 – 788.
15. Ahuja M, Krishnamoorthy S & Ramaswamy HS (1982) Optimum sand content method for designing mixes for fibre reinforced concrete, Indian Concrete Journal, Vol. 56, pp. 95 – 97.
16. Alexanderson J. (1982) Polymer cement concrete for industrial floors, in Polymers in Concrete, International Congress on Polymers in Concrete, Vol. 1, pp. 360 – 373.
17. Alford NM & Rahman AA (1981) An assessment of porosity and pore sizes in hardened cement pastes, Journal of Materials Science, Vol. 16, pp. 3105 – 3114.
18. Ali MA, Majumdar AJ & Singh B (1974) Properties of glass fibre cement – the effect of fibre length and content, Building Research Establishment, Current Paper, CP 94/75, October.
19. Ali MA, Majumdar AJ & Singh B (1975) Properties of glass fibre cement – the effect of fibre length and content, Journal of Materials Science, Vol. 10, pp. 1732 – 1740.
20. Aligizaki KK & Cady PD (1999) Air content and size distribution of air voids in hardened cement pastes using the selection-analysis method, Cement and Concrete Research, Vol. 29, pp. 273 – 280.
21. Almudaiheem JA (1992) Nitrogen adsorption and mercury intrusion porosimetry of hydrated Portland cement pastes, Arabian Journal of Science and Engineering, Vol. 17, No. 3, pp. 357 – 369.
22. Alwahab T & Soroushian P (1987) Characterisation of "Fibreforce" collated fibrillated polypropylene fibres and their application to concrete, Research report, Michigan State University, Department of Civil & Environmental Engineering, 60 pp.
23. Anon (1985) Fibre reinforced concrete, Indian Highways, Dec., Vol.13, No.12, pp.3 – 5.
24. Anonymous (1987) Australia finds many uses for steel-fibre-reinforced concrete, Concrete Construction, June, pp. 517 – 521.
25. AP Werkzeuge GmbH (2000) Company's Literature, Werkzeugfabrikation, Bürnestr 11, D – 52531, Übach – Palenberg, Germany.

26. Archard JF (1953) Contact and rubbing of flat surfaces, Journal of Applied Physics, 24(8), pp. 981 – 988.
27. Arnell RD, Davies PB, Halling J & Whomes TL (1991) Tribology, principles and design applications, Basingstoke, Macmillan Education.
28. ASTM C131 – 96 (1999) Standard Test Method for Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine, in the Annual book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aggregates, American Society for Testing Materials, Philadelphia.
29. ASTM C235 – 68 (1968) Standard Test Method for Scratch Hardness of Coarse Aggregate Particles, in the Book of ASTM Standards, Part 10, Concrete and Mineral Aggregates, American Society for Testing Materials, Philadelphia.
30. ASTM C418 – 90 (1998) Standard test method for abrasion resistance of concrete by sandblasting, in the Annual book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aggregates, American Society for Testing Materials, Philadelphia.
31. ASTM C779 – 95 (1998) Standard test method for abrasion resistance of horizontal surface, in the Annual book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aaggregates, American Society for Testing Materials, Philadelphia.
32. ASTM C856 – $95^{\varepsilon 1}$ (2001) Standard Practice for Petrographic Investigation of Hardened Concrete, in the Annual book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aggregates, American Society for Testing Materials, Philadelphia.
33. ASTM C88 – 99a (1999) Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate, in the Annual book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aggregates, American Society for Testing Materials, Philadelphia.
34. ASTM E 384 - 89 (1998) Standard Test Method for Microhardness of Materials, Annual book of ASTM Standards, Section 3, Vol. 03.01, Metals – Mechanical Testing, Elevated and Low-Temperature Tests, Metallography, American Society for Testing Materials, Philadelphia.
35. ASTM G40 – 95 (1995) Standard Terminology Relating to Wear and Erosion, Annual book of ASTM Standards, Vol. 03.02, American Society for Testing Materials, Philadelphia.
36. Atepegba D & Regan PE (1981) Performance of steel and fibre reinforced concrete in axially loaded short columns, International Journal of Cement Composites & Lightweight Concrete, Vol. 3, pp. 255 – 259.

37. Auskern A & Horn W (1973) Capillary porosity in hardened cement paste, Journal of Testing and Evaluation, JTEVA, Vol. 1, No. 1, pp. 74 –79.
38. Aveston J, Cooper GA & Kelly A (1971) Single and multiple fracture, The properties of fibre composites, NPL Conference Proceedings, IPC Science and Technology Press Ltd, pp. 15 – 24.
39. Aveston J, Mercer RA & Sillwood JM (1974) Fibre reinforced cements – scientific foundations for specifications, Composites standard testing and design, NPL Conference Proceedings, April, pp. 93 – 103.
40. Aveston J, Mercer RA & Sillwood JM (1976) The mechanism of fibre reinforcement of cement and concrete, National Physical Laboratory Report No. SI, No. 90/11/98, Part1, January 1975, DMA 228, February.
41. Avient BWE, Goddard J & Willman M (1960) An experimental study of friction and wear during abrasion of metals, Proceedings of the Royal Society, A 258, pp. 159 – 180.
42. Aziz MA, Paramasivam P & Lee SL (1981) Prospects for natural fibre reinforced concrete in construction, International Journal of Cement Composites & Lightweight Concrete, Vol. 3, pp. 123 – 132.
43. Aziz MA, Paramasivam P & Lee SL (1984) Concrete reinforced with natural fibres, in Concrete Technology and Design, Volume 2: New Reinforced Concretes, ed. Swamy RN, Surrey University Press, London, pp. 107 – 140.
44. Bager DH & Sellevold EJ (1975) Mercury porosimetry of hardened cement paste: The influence of particle size, Cement and Concrete Research, Vol. 5 pp. 171 – 178.
45. Balaguru P & Ramakrishnan V (1988) Properties of fibre reinforced concrete: Workability, behaviour under long-term loading and air-void characteristics, ACI Materials Journal, May – June issue, pp. 189 – 196.
46. Balaguru PN & Shah SP (1985) Alternative reinforcing materials for less developed countries, Int. J. Res. Tech., Vol. 3, pp. 87 – 105.
47. Balasubramanian K, Bharatkumar BH, Gopalakrishnana S & Parameswaran VS (1996) Impact resistance of steel fibre reinforced concrete, The Indian Concrete Journal, Vol. 70, No. 5, pp. 257 – 262.
48. Balendran RV & Zhou FP (2001) Influence of steel fibres on strength and ductility of normal and lightweight high strength concrete, Building and Environment, In Press, Uncorrected Proof, Available online 28 December 2001.

49. Banthia N (1997) Fibre reinforced concrete: Present and the future, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 1 – 10.
50. Banthia N, Yan C & Mindess S (1996) Restrained cracking in fibre reinforced concrete: A novel test technique, Cement & Concrete Research, Vol. 26, No. 1, pp. 9 – 14.
51. Banthia N, Yan C & Sakai K (1998a) Impact resistance of fibre reinforced concrete at subnormal temperatures, Cement & Concrete Composites, Vol. 20, pp. 393 – 404.
52. Banthia N, Yan C, Sakai K (1998b) Impact resistance of concrete plates reinforced with a fibre reinforced plastic grid, ACI Materials Journal, Jan – Feb 1998, Vol. 95, No.1, pp.11 – 18.
53. Barnett RS (1955) Fretting and fretting corrosion, Lubrication, 41, pp. 85 – 96.
54. Barr B & Liu K (1982) General behaviour of polypropylene fibre reinforced concrete, Concrete, April, pp. 33 – 36.
55. Barros JA & Figueiras JA (1998) Experimental behaviour of fibre concrete slabs on soil, Mechanics of Cohesive – Frictional Materials, Vol. 3, No. 3, pp. 277 – 290.
56. Bauschinger J (1844), His Communications, Vol. XI.
57. Baxter M (1975) Better concrete floors, Civil Engineering, January, pp. 26 – 29.
58. Bayasi Z & Zeng J (1993) Properties of polypropylene fibre reinforced concrete, ACI Materials Journal, Vol. 90, No. 6, pp. 605 – 610.
59. Beaudoin JJ (1982) Microhardness-fracture studies – high alumina cement systems, Cement & Concrete Research, Vol. 12, No.3, pp. 289 – 299.
60. Beckett D (1990) Comparative tests on plain, fabric reinforced and steel fibre reinforced concrete ground slabs, Concrete, Volume 24, No. 3, pp. 43 – 45.
61. Bekaert (1990) Industrial floors with Dramix steel wire fibre reinforced concrete, NV Bekaert S. A. Zwevegem, Belgium.
62. Bekaert NV Ltd (1998) Trade literature on Dramix ®, 8550 Zwevegem, Belgium.
63. Belaid F, Arliguie G & François (2001) Porous structure of the ITZ around galvanised and ordinary steel reinforcements, Cement & Concrete Research, Vol. 31, pp. 1561 – 1566.
64. Beningfield N (1986) Assessing the quality of freshly laid cement: sand floor screeds, Chemistry and Industry, 21 July, No. 14, pp. 474 – 479.
65. Bentur A & Mindess S (1990) Fibre reinforced cementitious composites, Elsevier Applied Science, London, UK.

66. Bergström SG (1975) A Nordic research project on fibre reinforced, cement based materials, Fibre reinforced Cement & Concrete, RILEM Symposium, Vol. 2, pp. 505 – 600.
67. Bindiganavile V & Banthia N (2001) Polymer and steel fibre reinforced cementitious composites under impact loading – Part 2: Flexural toughness, ACI Materials Journal, Vol. 98, No. 1, pp. 17 – 24.
68. Biryukovich K, Yu L & Yu DL, (1965) Glass fibre reinforced cement, Kiev, Budivel'nik, translated by G. L. Cairns as CERA Translation No. 12, Civil Engineering Research Association, London, 41 pp.
69. Biryukovick KL, Biryukovick YL & Biryukovick DL (1966) Glass fibre reinforced cement, Budivelnik, Kiev, Translation No. 12, Civil Engineering Research Association, London.
70. Bischoff PH, Valsangkar AJ & Irving J (1997) A performance evaluation of steel fibre reinforced concrete slabs on grade, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 25 – 32.
71. Bitter JGA (1963) A study of erosion phenomena, Wear, 6, pp. 5 – 21, 169 – 190.
72. Bowden FP & Tabor D (1950) The wear and damage of metal surfaces with fluid lubrication, no lubrication and boundary lubrication, in Burwell JT (Ed.) Mechanical Wear, Proceedings of a Summer Conference on Mechanical Wear, June 1948, American Society for Metals, Cleveland, USA, pp. 109 – 144.
73. Bowden FP & Tabor D, The friction and lubrication of solids, Part 1 (1950) and Part 2 (1964), International series of monographs on physics, Oxford, Clarendon Press.
74. Boyer HE & Gall TL, Eds. (1985) Metals Handbook, American Society for Metals: Metal Park.
75. Brace WF (1960) Behaviour of rock salt, limestone and anhydrite during indentation, Journal of Geophysical Research, Vol. 65, No. 6, pp. 1773 – 1788.
76. British Board of Agrément (1995) Fibrin 23, Agrément Certificate No. 92/2830, Herts, UK.
77. British Standards Institution (1983) BS 1881: Part 102: Testing concrete – Method for determination of slump, BSI, London.
78. British Standards Institution (1983) BS 1881: Part 108: Testing concrete – Method for making test cubes from fresh concrete, BSI, London.
79. British Standards Institution (1983) BS 1881: Part 111: Testing concrete – Method of normal curing of test specimens (20°C method), BSI, London.

80. British Standards Institution (1983) BS 1881: Part 116: Testing concrete – Method for determination of compressive strength of concrete cubes, BSI, London.
81. British Standards Institution (1986) BS 1881: Part 125: Testing concrete – Methods for mixing and sampling fresh concrete in the laboratory, BSI, London.
82. British Standards Institution (1987) BS 8204: Part 2: Screeds bases and in-situ flooring – Concrete wearing surfaces, BSI, London.
83. British Standards Institution (1992) BS 882: Specification for aggregates from natural sources for concrete, BSI, London.
84. British Standards Institution (1996) BS 1881: Part 208: Testing concrete – Recommendations for the determination of the initial surface absorption of concrete, BSI, London.
85. British Standards Institution (1999) BS 8204: Part 1: Concrete bases and cement sand levelling screeds to receive floorings – Code of practice, BSI, London.
86. British Standards Institution (1999) BS 8204: Part 2: Screeds bases and in-situ flooring – Concrete wearing surfaces, BSI, London.
87. Brown AD & Hufford HH (1986) The structural properties of cement plates reinforced with carbon fibre/PVA prepreg, in Developments in Fibre Reinforced Cement & Concrete, Eds. Swamy RN, Wagstaffe RL & Oakley DR, Proc. RILEM Symposium, Vol. 1, Section 2.1, Sheffield.
88. Buckingham E & Talbourdet GJ (1950) Recent roll tests on endurance limits of materials, in Burwell JT (Ed.) Mechanical Wear, Proceedings of a Summer Conference on Mechanical Wear, June 1948, American Society for Metals, Cleveland, USA, pp. 289 – 307.
89. Buenfeld NR & Yang R (2001) On-site curing of concrete: microstructure and durability, CIRIA C530, London, UK.
90. Burwell JT & Strang CD (1952) On the empirical law of adhesive wear, Journal of Applied Physics, Vol. 23, No. 1, pp. 18 – 28.
91. Burwell JT (1950) Summary of factors in the wear process, in Burwell JT (Ed.) Mechanical Wear, Proceedings of a Summer Conference on Mechanical Wear, June 1948, American Society for Metals, Cleveland, USA, pp. 359 – 369.
92. Burwell JT, (1957), Survey of possible wear mechanisms, Wear, Vol. 1, pp. 119 – 141.
93. Bury MA, Burry JR & Martin D (1994) Testing effects of new admixtures on concrete finishing, Concrete International, Vol. 16, No. 1, pp. 26 – 31.

94. Cao J & Chung DDL (2001) Improving the dispersion of steel fibres in cement mortar by the addition of silane, Cement & Concrete Research, Vol. 31, pp. 309 – 311.

95. Carr K (1998) Making good concrete better, Concrete, November/December, pp. 16 – 17.

96. Cebeci OZ (1981) Pore structure of air-entrained hardened cement paste, Cement & Concrete Research, Vol. 11, pp. 257 – 265.

97. Cement and Concrete Association (1980) Report for the year 1979, pp. 12 – 13.

98. CEM-Fil International (2000) Company Data Sheets, 15 Pit Place, Skelmersdale, Lancashire, WN8 9PS

99. Chakraborty MDD, Basu S & Paul A (1979) Corrosion behaviour of a ZrO_2 containing glass in aqueous acid and alkaline media and in a hydrating cement paste, Int. J. Cem. Comp., Vol. 1, pp. 103 – 109.

100. Chaplin RG (1972) The abrasion resistance of concrete floors, Technical Report 42.471, Cement & Concrete Association, London, 9 pp.

101. Chaplin RG (1980) Abrasion resistance of concrete floors, in Advances in Concrete Slab Technology, Proceedings of the International Conference on Concrete Slabs, Dundee University 3 – 6 April 1979, Eds. Dhir RK & Munday JGL, Pergamon Press, England, pp. 532 – 543.

102. Chaplin RG (1987) The influence of cement replacement materials, fine aggregates and curing on abrasion resistance of concrete floor slabs, Proceedings of the International Colloqium Industrial Floors, Technische Akademie Esslingen, Stuttgart, Germany, pp. 361 – 374.

103. Chaplin RG (1991) Site testing for abrasion resistance of concrete floors, Proceedings of the International Colloqium Industrial Floors, Technische Akademie Esslingen, Stuttgart, Germany, pp. 629 – 639.

104. Chaplin RG (2001) Personal communication, 11 December 2001.

105. Cian D & Della Bella B (2001) Structural applications of GRC for precast floors, Proceedings of the 12th International Glass Fibre Reinforced Concrete Congress, GRCA, Dublin, Republic of Ireland, May, pp. 41 – 52.

106. Claisse PA, Elsayad HI, Shaaban IG (1997) Absorption and sorptivity of cover concrete, Journal of Materials in Civil Engineering, Vol. 9, No. 3, pp. 105 – 110.

107. Concrete Society (1988) Concrete Industrial ground floors – A guide to their design and construction, Technical Report No. 34, The Concrete Society, Slough.

108. Concrete Society (1994) Concrete Industrial ground floors – A guide to their design and construction, Technical Report No. 34, The Concrete Society, Slough.
109. Concrete Society Working Party (1987) Permeability testing of site concrete – A review of methods and experience, Technical Report No. 31, The Concrete Society, London, 95 pp.
110. Cook DJ (1980a) Natural fibre reinforced concrete and cement – recent developments, in Advances in Cement Matrix Composites, Eds. Roy DM, Majumdar AJ Shah SP & Manson JA, Proc. Symposium L, Materials Research Society Annual Meeting, Boston, pp. 251 – 258.
111. Cook DJ (1980b) Concrete and cement composites reinforced with natural fibres, in Fibrous Concrete, Proc. Symp., The Concrete Society, The Construction Press, UK, pp. 99 – 114.
112. Cook RA & Hover KC (1991) Experiments on the contact angle between mercury and hardened cement paste, Cement & Concrete Research, Vol. 21, No. 6, pp. 1165 – 1175.
113. Cook RA & Hover KC (1993) Mercury porosimetry of cement based materials and associated correction factors, ACI Materials Journal, Vol. 90, No. 2, pp. 152 – 161.
114. Covel CE (1928) Heavy-duty concrete floors, Journal of American Concrete Institute, Vol. 24, pp. 454 – 465.
115. Cox HL (1952) The elasticity and strength of paper and other fibrous materials, British Journal of Applied Physics, Vol. 3, pp. 72 – 79.
116. Cross WM, Sabnis KH, Kjerengtroen L & Kellar JJ (2000) Microhardness testing of fibre reinforced cement paste, ACI Materials Journal, Vol. 97, No. 2, March/April, pp. 162 – 167.
117. Dahl PA (1985) Plastic shrinkage and cracking tendency of mortar and concrete containing Fibermesh, FCB Cement & Concrete Research Institute, Norway.
118. Dardare J (1975) Contribution to the study of the mechanical behaviour of concrete reinforced with polypropylene fibres, Fibre Reinforced Cement & Concrete, RILEM Symposium, London, pp. 227 – 236.
119. Davies RM (1949) The determination of static and dynamic yield stresses using a steel ball, Proc. Roy. Soc., A 197, pp. 416 – 432.
120. Deacon RC (1990) Fibres for floors, Supplement to Concrete, Vol. 24, No. 4, April, pp. 19 – 20.

121. Dellaripa F & Reddy DV (1987) Impact capacity of fibre reinforced concrete closed shell structures, Proceedings of the International symposium on Fibre Reinforced Concrete, December, Madras, pp. 4.19 – 4.28.

122. Deuis RL, Subramanian C & Yellup JM (1998) Three-body abrasive wear of composite coatings in dry and wet environments, Wear, Vol.214, No.1, pp. 112 – 30.

123. Dhir RK & Byars EA (1991) PFA concrete: near surface absorption properties, Magazine of Concrete Research, Vol. 43, No. 157, pp. 219 – 232.

124. Dhir RK, Hewlett PC & Chan YN (1987) Near-surface characteristics of concrete: assessment and development of in situ tests methods, Magazine of Concrete Research, Vol. 39, No. 141, pp. 183 – 195.

125. Dhir RK, Hewlett PC & Chan YN (1991) Near-surface characteristics of concrete: abrasion resistance, Materials and Structures, Vol. 24, pp. 122 – 128.

126. Dhir RK, Shaaban IG, Claisse PA & Byars EA (1993) Preconditioning in situ concrete for permeation testing, Part 1: Initial surface absorption, Magazine of Concrete Research, Vol. 45, No. 163, pp. 113 – 118.

127. Diamond S (1971) A critical comparison of mercury porosimetry and capillary condensation pore size distributions of Portland cement pastes, Cement & Concrete Research, Vol. 1, pp. 531 – 545.

128. Diamond S (2000) Mercury porosimetry an inappropriate method for measurement of pore size distributions in cement based materials, Cement & Concrete Research, Vol. 30, pp. 1517 – 1525.

129. DIN 18365 (1992): Part C: Contract procedure for building works, general technical specifications for building works, flooring works, Konl, Beuth, Berlin, Germany.

130. DIN 18560 (1992): Part 1: Screeds in building construction, concepts, general requirements and testing, Konl, Beuth, Berlin, Germany.

131. DIN 52108 (1968) Beuth – Vertrieb GmbH, Berlin 30, August.

132. Eden MA (2001) Personal communication in January and March 2001, Geomaterials Research Services Ltd, 1 Falcon Park, Crompton Close, Basildon, Essex, SS14 3AL.

133. Edgington J & Hannant DJ (1972) Steel fibre reinforced concrete. The effect on fibre orientation of compaction by vibration, RILEM Materials and Structures, Vol. 5, No. 25, pp. 41 – 44.

134. Edgington J, Hannant DJ & Williams RIT (1974) Steel fibre reinforced concrete, Building Research Establishment, Current paper 69/74.

135. Emley WE & Hofer CE (1937), Test of floor coverings for post office work rooms, Journal of Research, National Bureau of Standards, Vol. 19, pp. 567 – 570.
136. Eren O, Marar K & Çelik T (1999) Effects of silica fume and steel fibres on some mechanical properties of high-strength fibre reinforced concrete, ASTM Journal of Testing and Evaluation, Vol. 27, No. 6, pp. 380 – 387.
137. Fairweather ES (1980) Direct finishing of concrete slabs using the early age power grinding technique, in Advances in Concrete Slab Technology, Proceedings of the International Conference on Concrete Slabs held at Dundee University 3 – 6 April 1979, Eds. Dhir RK & Munday JGL, Pergamon Press, England.
138. Falkner H & Henke V (1998) Application of steel fibre concrete for underwater concrete slabs, Cement & Concrete Composites, Vol. 20, No. 5, pp. 377 – 385.
139. Falkner H, Huang Z & Teutsch M (1995) Comparative study of plain and steel fibre reinforced concrete ground slabs, Concrete International, January, pp. 45 – 51.
140. Fanella D & Naaman AE (1985) Stress-strain properties of fibre reinforced concrete in compression, Journal of American Concrete Institute, Vol. 82, pp. 475 – 483.
141. Feb MBT, (1997) Company Data Sheets, Albany House, Swinton Hall Road, Swinton, Manchester, M27 4DT.
142. Febrillet N, Kido A, Ito Y & Ishibashi K (2000) Strength and abrasion resistance of ultra high strength steel fibre reinforced concrete, Transactions of the Japan Concrete Institute, Vol. 22, pp. 243 – 252.
143. Feldman RF & Beaudoin RF (1991) Pretreatment of hydrated cement pastes for mercury intrusion measurements, Cement & Concrete Research, Vol. 21, No. 2/3, pp. 297 – 308.
144. Feldman RF & Huang CY (1985) Properties of Portland cement – silica fume pastes: Mechanical properties, Cement & Concrete Research, Vol. 15, No. 6, pp. 943 – 952.
145. Fentress B (1973), Slab construction practices compared by wear tests, ACI Journal, Vol. 70, No. 7 (July), pp. 486 – 491.
146. Feric T, Krstulovic R, Peric J & Krolo P, (1997) Effect of Chrysotile Asbestos on Cement Hydration, Cement & Concrete Composites, Vol. 19, No. 4, pp. 301 – 305.
147. Fernandez L & Malhotra VM (1990) Mechanical properties, abrasion resistance and chloride permeability of concrete incorporating granulated blast-furnace slag, Cement, Concrete & Aggregates, Vol. 12, No. 2, pp. 87 – 100.
148. Fibermesh Company (1985 – 1988) Fibermesh Engineering Data Reports Nos 1 – 7, Fibermesh Co., 4019 Industry Drive, Chattanooga, TN, USA.

149. Fibermesh Europe (1998) Company Data Sheets, Fibermesh House, Smeckley Wood Close, Chesterfield, England, S41 9PZ.
150. Fibre Technology Ltd (1999) Company Data Sheets, Brookhill Road, Pinxton, Nottingham, NG16 6NT.
151. Fibrin (Humberside) Ltd (1998 & 2000) Company Data Sheets, Borwick Drive, Grovehill, Beverly, East Yorkshire, HU17 0HQ.
152. Finnie I (1960) Erosion of surfaces by solid particles, Wear, 3, pp. 87 – 103.
153. Foerdoes Z & Tram B (1986) Natural fibres as reinforcement in cement-based composites, in Developments in Fibre Reinforced Cement & Concrete, Eds. Swamy RN, Wagstaffe RL & Oakley DR, Proc. RILEM Symposium Vol. 1, Section 2.9, Sheffield.
154. Fosroc Ltd (1998), Company Data Sheets, Coleshill Road, Tamworth, Staffordshire, B78 3TL.
155. Franke L & Overbeck E (1987) Loss in strength and damage to glass fibres in alkaline solutions and cement extracts, Durab. Bldg. Mat., Vol. 5, pp. 73 – 79.
156. French WJ (1991) Concrete petrography: a review, Quarterly Journal of Engineering Technology, Vol. 24, pp.-17 – 48.
157. Gates JD, (1998) Two-body and three-body abrasion: a critical discussion, Wear, Vol. 214, No.1, pp.139 – 46.
158. Gatfield MJ (1998) Screeds, flooring and finishes: selection construction and maintenance, Report 184, CIRIA, London.
159. Gee MG (1998) Wear testing procedures and test conditions for project CAM9, NPL Report CMMT (D) 153, National Physical laboratory, Teddington, UK.
160. Gibbons W (1998) The exploitation and environmental legacy of amphibole asbestos: A late 20th century overview, Environmental Geochemistry and Health, Vol. 20, No. 4, pp. 213 – 230.
161. Gibbs G, Pigg BJ, Nicholson WJ, Morgan A, Lippmann M, Davis JMG, Mossman BT, McDonald JC, Landrigan P & Schreier H, (1998) Task Group on Enviromental Health Criteria for Chrysotile Asbestos Meeting, Geneva, Switzerland, 1 – 6 July 1996, Environmental Health Criteria, Issue 203, 1998, pp. 111 – 197.
162. Godfrey D & Bailey JM (1954) Early stages of fretting of copper, iron and steel, Lubrication Engineering, 10, pp. 155 – 159.
163. Godfrey D, (1980), Wear control handbook, New York, ASME.

164. Goldbeck AT & Jackson FH, Jr. (1912) The physical testing of rock and road building, US Department of Agriculture, Office of public roads, Bulletin 44, June 10, pp. 7.

165. Goldfein S (1963) Plastic fibrous reinforcement for Portland Cement, Technical report No. 1757-TR, US Army Engineer Research and Development Laboratories, Fort Belvoir, Va. Oct. 1963, pp. 16.

166. Gopalaratnam VS & Gettu R (1995) On the characterisation of flexural toughness in fibre reinforced concretes, Cement & Concrete Composites, Vol. 17, pp. 239 – 254.

167. Gopalatatnam VS & Shah SP (1986) Properties of steel fibre reinforced concrete subjected to impact loading, ACI Journal, Proceedings, Vol. 83, No. 1, pp. 117 – 126.

168. Gopalatatnam VS, Shah SP& John R (1984) A modified instrumented Charpy test for cement based composites, Experimental Mechanics, Vol. 24, No. 2, pp. 102 – 110.

169. Goto S & Roy DM (1981) The effect of w/c ration and curing temperature on the permeability hardened cement paste, Cement & Concrete Research, Vol. 11, pp. 575 – 579.

170. Grace Construction Products Ltd (2000) Company Data Sheets, 852 Birchwood, Warrington, Cheshire, England, WA3 7QZ.

171. Gray BH & Rice JL (1972) Pavement performance investigation, Fibrous concrete: Construction material for the seventies, CERL Conference Proceedings, M. 28, December, Champaig, Illinois 61820, pp. 147 – 157.

172. Gregory J, Galloway JW & Raithby KD (1975) Full scale trials of a wire fibre reinforced concrete overlay on a motorway, Fibre Reinforced Cement & Concrete, RILEM Symposium, Construction Press Ltd, pp. 383 – 394.

173. Grimer FJ & Ali MA (1969) The strengths of cements reinforced with glass fibres, Magazine of Concrete Research, V. 21, No. 66, pp. 23 – 30.

174. Grosse I, Huetter B, Hartmann I, Binde G, Gruber H & Kurz G (1998) Asbestos on textiles: Is there an endangering during washing and wearing?, Journal of Hazardous Materials, Vol. 63, No. 2 – 3, pp. 119 – 130.

175. Grzybowski M & Shah SP (1990) Shrinkage cracking of fibre reinforced concrete, ACI Materials Journal, Vol. 87, No. 2, pp. 138 – 148.

176. Hall C (1989) Water sorptivity of mortar and concretes: a review, Magazine of Concrete Research, Vol. 41,pp. 51 – 61.

177. Halliday JS & Hirst W (1956) The fretting corrosion of mild steel, Proc. Roy. Soc., A 236, pp. 411 – 425.
178. Halling J (1975) Principles of tribology, London, Macmillan Education.
179. Halvorsen GT (1976) Concrete reinforced with plain and deformed steel fibres, Report No. DOT – TST 76T – 20, US Department of transportation Washington, DC, 71 pp.
180. Hammit FG (1980) Wear control handbook, New York, ASME.
181. Hanna AN (1981) Preliminary evaluation of Forta fibre reinforced concrete, Performed for Forta Corporation by Construction Technology laboratories, Portland Cement Association.
182. Hannant DJ & Edgington J (1974) Fibre reinforced concrete, Conference Proceedings, Stevin Laboratory Delft, pp. 63 – 70.
183. Hannant DJ & Spring N (1974) Steel fibre reinforced mortar: A technique for producing composites with uniaxial fibre alignment, Magazine of Concrete Research, Vol. 26, No. 86, pp. 47 – 48.
184. Hannant DJ (1975) The effect of post-cracking ductility on the flexural strength of fibre cement and fibre concrete, Fibre Reinforced Cement & Concrete, RILEM Symposium, Vol. 2, Construction Press Ltd, pp. 499 – 508.
185. Hannant DJ (1978) Fibre cements and fibre concretes, John Wiley & Sons, New York.
186. Hannant DJ (1994) Fibres in industrial ground floor slabs, Concrete, Vol. 28, No. 1, pp. 16 – 19.
187. Hannant DJ, Hughes DC & Kelly A (1983) Toughening of cement and other brittle solids with fibres, Phil. Trans. Roy. Soc., A310, pp. 175 – 190.
188. Hardmeier S (1997) AR glass fibres as micro-reinforcement to limit crack formation and increase strength of floor screed and concrete, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 123 – 130.
189. Hearn N & Hooton RD (1992) Sample mass and dimension effects on mercury intrusion porosimetry results, Cement & Concrete Research, Vol. 22, No. 5, pp. 970 – 980.
190. Henrikes A (1957) The Vickers hardness of zinc blende, Arkiv for Mineralogi och Geologi, Vol.2, No. 15, pp. 283 – 297.
191. Hester WT (1986) Specifying high performance concrete industrial floors, The Construction Specifier, Vol. 39, No. 3, pp. 56 – 62.

192. Hibbert AP & Hannant DJ (1978) The design of an instrumented impact test machine for fibre concretes, Testing and Test Methods of Fibre Cement Composites, RILEM Symposium, April, Sheffield, UK.
193. Hikasa J & Genba T (1986) Replacement for asbestos in reinforced cement products – "Kularon" PVA fibres, properties, structure, paper presented at the International Man-Made Fibres Congress, Austrian Chemical Institute, Austria, September.
194. Hills DA & Ashelby DW (1979) On the application of fracture mechanics to wear, Wear, Vol. 54, pp. 321 – 330.
195. Hogan DJ (1987) Fibre reinforcement comes of age, Concrete, April, pp. 18 – 20.
196. Holiday L (1966) Composite materials, Elsevier, Amsterdam.
197. Holister GS & Thomas C (1966) Fibre reinforced materials, Elsevier, Amsterdam.
198. Holm R (1950) Hardness and its influence on wear, in Burwell JT (Ed.) Mechanical Wear, Proceedings of a Summer Conference on Mechanical Wear, June 1948, American Society for Metals, Cleveland, USA, pp. 309 – 329.
199. Hordon M J (1967) Adhesion of metals in high vacuum, Adhesion or cold welding of materials in space environment, ASTM, STP 431, pp. 109 – 107.
200. Hornbogen E (1975) The role of fracture toughness in the wear of metals, Wear, Vol. 33, pp. 251 – 259.
201. Hughes BP & Fattuhi NI (1977) Stress-strain curves for fibre reinforced concrete in compression, Cement & Concrete Research, Vol. 7, pp. 173 – 184.
202. Hughes BP (1981) Experimental test results for flexure and direct tension of fibre cement composites, International Journal of Cement & Lightweight Concrete, Vol. 3, pp. 13 – 18.
203. Hughes DC (1984) Stress transfer between fibrillated polyalkene and cement matrices, Composites, Vol. 15, pp. 153 – 158.
204. Hull D (1981) An introduction to composite materials, Cambridge Solid State Science Series, Cambridge University Press, UK.
205. Igarashi S & Kawamura M (1994) Effects of a size in bundled fibres on the interfacial zone between the fibres and the cement paste matrix, Cement & Concrete Research, Vol. 24, No. 4, pp. 695 – 703.
206. Igarashi S, Bentur A & Mindess S (1996a) The effects of processing on the bond and interfaces in steel reinforced cement composites, Cement & Concrete Composites, Vol. 18, pp. 313 – 322.
207. Igarashi S, Bentur A & Mindess S (1996b) Microhardness testing of cementitious materials, Advanced Cement Based Materials, Vol. 4, No. 2, pp. 48 – 57.

208. Jackson FH & Pauls JT (1924), Accelerated wear tests of concrete pavements, Proceedings, American Society for Testing Materials, Vol. 24, Part 2, pp. 864.

209. Jefferis SA (1988) Application of bleed and settlement theory problems of offshore grouting, In Grouts & grouting for construction & repair of offshore structures, A summary report, The London Centre of Marine Technology, Imperial College, London, UK, pp. 73 – 83.

210. Johnson & Nephew (1975) Ambergate Ltd., Trade Literature on Wirand Concretes, Derbyshire.

211. Johnson CD & Coleman RA (1974) Strength and deformation of steel-fibre reinforced mortar in uniaxial tension, American Concrete Institute Publication SP – 44, pp. 177 –194.

212. Johnston CD (1974) Steel fibre reinforced mortar and concrete: A review of mechanical properties, in Fibre Reinforced Concrete, ACI SP – 44, American Concrete Institute, Detroit, pp. 127 – 142.

213. Kajdas C, Harvey SSK & Wilusz E, (1990) Encyclopaedia of Tribology, Elsevier, Amsterdam.

214. Keer JG (1984) Fibre reinforced concrete, in Concrete Technology and Design, Volume 2: New Reinforced Concretes, Ed. Swamy RN, Surrey University Press, London, pp. 52 – 105.

215. Kelly A (1973) Strong solids, Clarenden Press, Oxford.

216. *Kelly A (1974)* Some scientific points concerning the mechanics of fibrous composites, Composite-Standards, Testing and Design, National Physical Laboratory Conference Proceedings, April, pp. 9 – 16.

217. Kennedy HL (1946) Homogeneity of air-entraining concrete, Proceedings, American Concrete Institute, Vol. 42, June, pp. 641 – 644.

218. Kesler CE & Halvorsen GT (1979) Fibre reinforced concrete – Workable and economical, The Military Engineer, Vol. 71, No. 462, pp. 234 – 237.

219. Kesler CE & Schwarz AW (1972) Steel fibre reinforced concrete – mix design considerations, Highway Focus, Vol. 4, October, pp. 22 – 35.

220. Kesler CE (1972) Mix design considerations, Proc. Conf. M – 28, Fibrous concrete – construction material of the seventies, May, Construction Engineering Research Laboratory, Champaign, Illinois, December, pp. 29 – 37.

221. Kessler DW (1928) The development of an apparatus for wear tests on flooring materials, Proceedings, American Society for Testing Materials, Vol. 28, Part 2, pp. 855 – 870.

222. Kettle RJ & Sadegzadeh M (1991) Influence of testing on abrasion resistance of concrete, International Colloquium Industrial Floors, January 15 – 17, Technische Akedemie Esslingen, Stuttgart, Germany.
223. Kettle RJ & Sadegzadeh M (1987), Field investigations of abrasion resistance, Materials and Structures, Vol. 20, No. 116, pp. 96 – 102.
224. Kettle RJ & Webb M (1999) The role of moisture in abrasion resistance, International Colloqium Industrial Floors, Technische Akademie Esslingen, Stuttgart, Germany.
225. Kettle RJ & Yassim M (1995) Influence of cement replacements on abrasion resistance, International Colloqium Industrial Floors, Technische Akademie Esslingen, Stuttgart, Germany.
226. Kettle RJ, Vassou V & Sedegzadeh M (2000) Comparative investigations using three accelerated abrasion testers, Proceedings of the 10th BCA Annual conference on higher education and the concrete industry, Concrete Communication Conference, 29 – 30 June, British Cement Association, Berkshire, UK, pp. 383–395.
227. Khatib JM & Mangat PS (1999) Influence of superplasticizer and curing on porosity and pore structure of cement paste, Cement & Concrete Composites, Vol. 21, No. 5 – 6, pp. 431 – 437.
228. Khatib JM & Wild S (1996) Pore size distribution of metakaolin paste, Cement & Concrete Research, Vol. 26, No. 10, pp. 1545 – 1553.
229. Khayat KH & Roussel Y (2000) Testing and performance of fibre reinforced, self-consolidating concrete, Materials & Structures, Vol. 33, July, pp. 391 – 397.
230. Kholmyansky M, Kogan E & Kovler K (1994) On the hardness determination of fine-grained concrete, Materials and Structures, Vol. 27 (174), pp. 584 – 587.
231. Killeen P & Dalgleish P (1997) Practical applications of steel fibre reinforced concrete floor slabs for industrial projects in Australia, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 137 – 144.
232. King RF & Tabor D (1954) The strength properties and frictional behaviour of brittle solids, Proceedings of the Royal Society London, Series A, Vol. 223, pp. 225 – 238.
233. Knapton J (1999) Single pour industrial floors, Thomas Telford, London.
234. Knoblauch H (1979) Manufacture and properties of steel fibre reinforced concrete and mortar with increasing fibre content, Part 2, Betonwerk und Fertigteil Technique, Vol. 11, pp. 683 – 691.

235. Konecny L & Naqvi SJ (1993) The effect of different drying techniques on the pore size distribution of blended cement mortars, Cement & Concrete Research, Vol. 23, No. 5, pp. 1223 – 1228.
236. Korczynskyj Y, Harris SJ & Morley (1981) The influence of reinforcing fibres on the growth of cracks in brittle matrix composites, J. Mater. Sci, Vol. 16, pp. 1533 – 1547.
237. Kotzé R (2000) Abrasion – a key durability issue, New Zealand Concrete, Vol. 44, No. 1, pp. 30 – 31.
238. Kragelsky IV, (1965) Friction and wear, London, Butterworths.
239. Krenchel H (1964) Fibre Reinforcement, Akademisk Forlag, Copenhagen.
240. Kruschov MM & Babihev MA (1960) Investigations into the wear of metals (in Russia), USSR Academy of Sciences, Moscow.
241. Kukreja C. B., Kaushik S. K., Kanchi M. B., Jain O. P. (1984) Economics and applications of steel fibre reinforced concrete, Indian Concrete Journal, August, Vol. 58, No. 8, pp. 202 – 206.
242. Kunterding R & Hilsdorf HK (1990) Measurement and evaluation of abrasion resistance of concrete surfaces, Durability of Building Materials & Components, pp. 527 – 538.
243. Lane RO (1978) Abrasion resistance, ASTM Special Technical Publication No. 169-B, pp. 332 – 350.
244. Langan BW, Joshi RC and Ward MA (1990) Strength and durability of concretes containing 50% Portland cement replacement by fly ash and other materials, Canadian Journal of Civil Engineering, Vol. 17, pp. 19 – 27.
245. Lankard DR (1972) Flexural strength predictions, Construction Engineering Research Laboratory, Conference Proceedings, M – 28, December, Champaign, Illinois, 61820, pp. 101 – 124.
246. Lansdown AR & Price AL (1986) Materials to resist wear, A guide to their selection and use, The Pergamon Materials Engineering Practice Series, Oxford, Pergamon.
247. Laplante P, Aitcin PC & Vezina D (1991) Abrasion resistance of concrete, Journal of Materials in Civil Engineering, Vol. 3, No. 1, pp. 19 – 28.
248. Larner LJ, Speakman K & Majumdar AJ (1976) Chemical interactions between glass fibres and cement, J. Non Cryst. Solids, Vol. 20, pp. 43 – 74.
249. Laskar MAI, Kumar R & Bhattacharjee B (1997) Some aspects of evaluation of concrete through mercury intrusion porosimetry, Cement & Concrete Research, Vol. 27, No. 1, pp. 93 – 105.

250. Levitt M (1969) Non-destructive testing of concrete by the initial surface absorption method, Proceedings Symposium on Non-destructive Testing of Concrete & Timber, ICE London, pp. 23 – 26.

251. Levitt M (1984) In-situ permeability of concrete, Developments in Testing Concrete for Durability, The Concrete Society, September, London.

252. Li F & Li Z (1997) Tensile behaviour of steel fibre reinforced concrete at different volume fractions, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 145 – 152.

253. Li ST (1959) Wear resistant concrete construction, Journal of the American Concrete Institute, Proceedings, Vol. 55, pp. 879 – 892.

254. Liang W, Cheg J, Hu Y & Luo H (2002) Improved properties of GRC composites using commercial E-glass fibres with new coatings, Materials Research Bulletin, Vol. 37, pp. 641 – 646.

255. Lipson C (1967) Wear considerations in design, Prentice-Hall, New York.

256. Litvin A (1985) Report to wire reinforcement Institute on properties of concrete containing polypropylene fibres, Construction Technology Laboratories, Portland Cement Association.

257. Liu T.C., (1980) Maintenance and preservation of concrete structures EM DASH 3. Abrasion-erosion resistance of concrete, Technical Report – US Army Engineer Waterways Experiment Station, Jul 1980, No.C-78-4, p.129

258. Liu TC (1981) Abrasion resistance of concrete, ACI Journal, September, pp. 341 – 350.

259. Livingston RA, Manghnani M & Prasad M (1999) Characterisation of Portland cement concrete microstructure using the scanning acoustic microscope, Cement & Concrete Research, Vol. 29, pp. 287 – 291.

260. Lok TS & Pei JS (1997) Ultimate flexural behaviour of steel fibre reinforced concrete, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 153 – 161.

261. Lok TS & Pei JS (1997) Ultimate flexural behaviour of steel fibre reinforced concrete, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 153 – 161.

262. Luo Xin, Sun Wei & Chan SYN (2000) Characteristics of high-performance steel fibre reinforced concrete subject to high velocity impact, Cement & Concrete Research, Vol. 30, pp. 907 – 914.

263. Ma Y & Tan M (2000) Research on mechanical properties and durability of ceramic fibre reinforced cement composites, Kuei Suan Jen Hsueh Pao / Journal of the Chinese Ceramic Society, Vol. 28, No. 2, pp. 105 – 110.
264. Magnat PS & Azari MM (1984a) Influence of steel fibre reinforcement on the fracture behaviour of concrete in compression, Int. J. Cement Composites & Lightweight Concrete, Vol. 6, pp. 219 – 231.
265. Magnat PS & Azari MM (1984b) A theory of free shrinkage of steel fibre reinforced cement matrices, J. Material Science, Vol. 19, pp. 2183 – 2194.
266. Magnat PS & Azari MM (1985a) Influence of steel fibre and stirrup reinforcement on the properties of concrete in compression members, Int. J. Cement Composites & Lightweight Concrete, Vol. 7, pp. 183 – 192.
267. Magnat PS & Azari MM (1985b) A theory for the creep of steel fibre reinforced cement matrices under compression, J. Materials Science, Vol. 20, pp. 1119 – 1133.
268. Magnat PS & Azari MM (1988) Shrinkage of steel fibre reinforced cement composites, Materials & Structures (RILEM), Vol. 21, pp. 163 – 171.
269. Maidl, B (1995) Steel fibre reinforced concrete, Bernhard R. Maidl / in co-operation with Jörg Dietrich ...[et al.], Ernst & Sohn, Berlin, Germany.
270. Majumdar AJ & Nurse RW (1974) Glass fibre reinforced cement, Building Research Establishment Current Paper, CP79/74, Building Research Establishment, England.
271. Majumdar AJ & Ryder JF (1968) Glass fibre reinforcement of cement products, Journal of Glass Technology, V. 9, No. 3, pp. 78 – 84.
272. Majumdar AJ & Ryder JF (1970) Reinforcement of cement and gypsum plasters by glass fibres, Science of Ceramics, V. 5, pp. 539 – 564.
273. Majumdar AJ (1970) Glass fibre reinforced cement and gypsum products, Proceedings, Royal Society of London, Vol. 319, pp. 69 – 78.
274. Majumdar AJ (1975) Properties of fibre-cement composites, Fibre reinforced Cement & Concrete, RILEM Symposium, London, pp. 279 – 314.
275. Majumdar AJ (1980a) Properties of GRC, In Fibrous Concrete, Proc. Symp., The Concrete Society, London, pp. 48 – 68.
276. Majumdar AJ (1980b) Some aspects of glass fibre reinforced cement research, Proc. Symp. on Advances in Cement-Matrix Composites, Materials Research Society, Boston, pp. 37 – 39.
277. Malhotra VM & Carino NJ, Eds. (1991) Handbook of non-destructive testing of concrete, CRC Press: Boca Raton, FL.

278. Malisch W.R.; (1986) Polypropylene fibres in concrete, Concrete Const., April; pp. 363 – 368.

279. Mallick PK (1988) Fibre reinforced composites: Materials, manufacturing and design, Marcel Dekker Inc., New York.

280. Malmberg B & Skarendahl A (1978) Method of studying the cracking of fibre concrete under restrained shrinkage, In Testing and Test Methods of Fibre Cement Composites, Ed. Swamy RN, The Construction Press, Lancaster, pp. 173 – 179.

281. Marfil SA & Maiza PJ (2001) Deteriorated pavements due to the alkali-silica reaction: A petrographic study of three cases in Argentina, Vol. 31, pp. 1017 – 1021.

282. Marikunte S, Aldea C & Shah SP (1997) Durability of glass fibre reinforced cement composites: Effect of silica fume and metakaolin, Advanced Cement Based Materials, Vol. 5, No. 3 – 4, pp. 100 – 108.

283. Marsh HN & Clarke LL (1974) Glass fibres in concrete, ACI publication SP 44, Fibre reinforced concrete, pp. 247 – 264.

284. Marten B (1998) Glass fibres for cement and concrete, Concrete, Nov./Dec., pp. 20 – 22.

285. Masuya H, Kajikawa Y & Zardoum (1997) Experimental study on perforation on steel fibre reinforced concrete slab under impact, Proceedings of the Asia-Pacific Speciality Conference on Fibre Reinforced Concrete, Singapore, August 28 – 29, pp. 163 – 170.

286. Mather K (1966) Petrographic examination of hardened concrete, In: Symposium of Significance of tests and Properties of Concrete and Concrete Making Materials, ASTM 169A, American Society of Testing Materials, pp. 125 – 143.

287. McColllin IS (1990) Ceramic Hardness, Plenum Press: New York.

288. McCurrich LH & Adams MAJ (1973) Fibres in cement and concrete, Current Practice Sheets, Concrete, No. 5, April, pp. 51 – 53.

289. Mehta PK & Monteiro RJM (1988) Effect of aggregate cement and mineral admixtures on microstructure of transition zone, Bonding in Cementitious Composites, Materials Research Society, Vol. 114, pp. 65 – 75.

290. Meissner HS & Smith SE (1938) Concrete curing compounds, Proceedings, American Concrete Institute, Vol. 34, May-June, pp. 549 – 560 (1 – 6).

291. Micrometrics Instrument Corporation (1988) Instruction Manual, Poresizer 9310, V1.05, Gergia, USA.

292. Mielenz RC (1962) Petrography applied to Portland Cement concrete, In: Fluhr T & Legget RF (Eds.) Reviews in Engineering Geology, Geological Society of America, GAEGA, Vol. 1, pp. 1 – 38.

293. Misra A & Finnie I, (1980), A classification of three-body abrasive wear and design of a new tester, Wear, Vol. 60, pp. 111 – 121.

294. Misra A & Finnie I, (1981), Correlations between two-body and three-body abrasion and erosion of metals, Wear, Vol. 68, pp. 33 – 39.

295. Monfore GE (1968) A review of fibre reinforcement of Portland cement paste, mortar and concrete, Journal PCA Research and Development Laboratories, V. 10, No. 3, pp. 36 – 42. Also, Research Department Buletin No. 226, Portland Cement Association.

296. Montgomery FR, Long AE & Basheer PAM (1989) Assessing surface properties of concrete by in-situ measurements, IBASE Report, Vol. 57, Part 2, pp. 871 – 876.

297. Moore MA & King FS (1980) Abrasive wear of brittle solids, Wear, Vol. 60 pp. 123 – 140.

298. Morris AD & Garrett GG (1981) A comparative study of the static and fatigue behaviour of plain and steel fibre reinforced mortar in compression and direct tension, Int. J. Cement Composites and Lightweight Concrete, Vol. 3, pp. 73 – 91.

299. Mott BW (1956) Micro-indentation hardness testing, Butterworths, London.

300. Mulhearn TO & Samuels LE (1962) The abrasion of metals: a model of the process, Wear, Vol. 5, pp. 478 – 498.

301. Murdock LJ, Brook KM & Dewar JD (1991) Concrete materials and practice, Sixth edition, Edward Arnold, London, UK.

302. N. V. Bekaert S.A. (1997) Company Data Sheets, Bekaertstrsst 2 B–8550 Zwevegem, Belgium.

303. N. V. Bekaert S.A. (1999) Company Data Sheets, Bekaertstrsst 2 B–8550 Zwevegem, Belgium.

304. Naaman AE & Gopalatatnam VS (1983) Impact properties of steel fibre reinforced concrete in bending, International Journal of Cement Composites & Lightweight Concrete, Vol. 5, No. 4, pp. 225 – 237.

305. Naaman S, Shah S & Throne J (1984) Some development in polypropylene fibres for concrete, Fibre Reinforced Concrete - International Symposium, SP – 81, American Concrete Institute, Detroit, pp. 375 – 396.

306. Nagaraja R (1986) Strength and behaviour of concrete elements reinforced with bamboo fibres and strips, in Developments in Fibre Reinforced Cement & Concrete,

Eds. Swamy RN, Wagstaffe RL & Oakley DR, Proc. RILEM Symposium, Vol. 1, Section 2.10, Sheffield.

307. Naghash AR, Prokopovich SA & Sorrell CC (1994) Wear resistance of alumina-based ceramics, International Ceramic Monographs, Proceedings of the International Ceramics Conference, Austceram 94, Australasian Ceramic Soc. Part vol.2, Sydney, NSW, Australia, pp.1369 – 1376.
308. Naik TR, Singh SS & Hossain MM (1994) Abrasion resistance of concrete as influenced by inclusion of fly ash, Cement & Concrete Research, Vol. 24, No. 2, pp. 303 – 312.
309. Naik TR, Singh SS & Hossain MM (1995) Abrasion resistance of high strength concrete made with class C fly ash, ACI Materials Journal, Vol. 92, No. 6, pp. 649 – 659.
310. Nanda VK & Hannant DJ (1969) Fibre reinforced concrete, Concrete Building & Concrete Products, Vol. XLIV, No. 10, Oct., pp. 179 – 181.
311. Nanni A & Johari A (1989) RCC pavement reinforced with steel fibres, Concrete International, Vol. 11, No. 3, pp. 64 – 69.
312. Nanni A (1985) Splitting tension test for fibre reinforced concrete, American Concrete Institute Materials Journal, Vol. 85, pp. 229 – 233.
313. Nanni A (1989) Abrasion resistance of Roller-compacted concrete, ACI materials Journal, Vol. 86, No. 53, pp. 559 – 565.
314. Neville AM (1999) Properties of concrete, Fourth Edition, Longman, England.
315. Nishioka K, Yamakawa S & Shirakawa K (1986) Properties and applications of carbon fibre reinforced cement composites, in Developments in Fibre Reinforced Cement and Concrete, Eds. Swamy RN, Wagstaffe RL & Oakley DR, Proc. RILEM Symposium, Vol. 1, Section 2.2, Sheffield.
316. Odler I & Röβler M (1985) Investigations on the relationship between porosity, structure and strength of hydrated Portland cement pastes: Effect of pore structure and of degree of hydration, Cement & Concrete Research, Vol. 15, No. 3, pp. 401 – 410.
317. OECD Research Group on Wear of Engineering Materials, (1969), Glossary of terms and definitions in the field of friction, wear and lubrication – Tribology, Organisation for Economic Co-operation and Development, Paris.
318. Ohama Y, Miyara M & Endo M (1985) Properties of steel and polyethylene fibre hybrid reinforced polymer modified concrete, Proceedings of the 28th Japan Congress on Materials Research, March, pp. 151 – 155.

319. Olson RA, Neubauer CM & Jennings (1997) Damage to the pore structure of hardened Portland cement paste, Journal of the American Ceramic Society, Vol. 80, No. 9, pp. 2454 – 2458.

320. Omoregie FA, Gutschow RA & Russell ML (1994) Cement-hardened materials for abrasion-erosion in hydraulic structures, Concrete International, Vol. 16, No. 7, pp. 47 – 50.

321. Ounanian DW & Kesler CE (1976) Design of fibre reinforced concrete for pumping, Report No. DOT – TST – 76T – 11, Federal Railroad Administration, DC, 53 pp.

322. Owen-Jones S & Gee MG (1997) Wear testing papers, reports and proceedings database, NPL Report CMMT (A) 90, National Physical Laboratory, Teddington, UK.

323. Ozturan T & Kocataskin F (1987) Abrasion resistance of concrete a two-phase composite material, International Journal of Cement Composites & Lightweight Concrete, Vol. 9, No. 3, pp. 169 – 176.

324. Page LW (1913) Relations between the tests for the wearing qualities of road-building rocks, Proceedings, American Society for Testing Materials, Vol. XIII, p. 983.

325. Paradine CG & Rivett BHP (1960) Statistical methods for technologists, England, Unibooks, English Universities Press.

326. Paradine CG & Rivett BHP (1970) Statistical methods for technologists, 2nd edition, London, English Universities Press.

327. Parameswaran VS, Krishnamoorthy TS, Balasubramanian K & Lakshmanan N (1987) Behaviour of fibre reinforced concrete beams with equal tension and compression reinforcement, Proceedings of the International Symposium of Fibre Reinforced Concrete, December 16 – 19, 1987, Madras, India, pp. 1.57 – 1.67.

328. Parameswaran VS (1996) Research and applications of FRC - Indian scenario, Indian Concrete Journal, October, Vol.70, No.10, pp. 553 – 557.

329. Parratt NJ (1972) Fibre reinforced materials technology, Van Nostrand Reinhold Company, London, UK.

330. Patent No. 3,429,094 (1969) & No. 3,500,728 (1970) to Battelle Memorial Institute, Columbus, Ohio & Patent No. 3,650,785 (1972) to US Steel Corporation, Pittsburgh, United States Patent Office, Washington, DC.

331. Patent No. GB 2 308 592 A (1997) Fire-resistant mortar for slabs and panels to Environmental Seals Ltd, Ward DA.

332. Perkins PH (1993) Concrete floors, finishes and external paving, Butterworth – Heineman, Oxford.
333. Philip Jones Construction Materials Ltd. (1998) Company Data Sheets, Enaldoow-y-Trof, 40 Wood Lane Hawarden, Flintshire, Wales, UK, CH5 3JE.
334. Philip Jones Construction Materials Ltd (1998a) Company Data Sheets, Enaldoow-y-Trof, 40 Wood Lane Hawarden, Flintshire, Wales, UK,CH5 3JE
335. Philip Jones Construction Materials Ltd., (1998b) Company's Literature Airfield pavement design, Dipl. – Ing. Arnold Gollan, Vulkan Harex, Stahlfasertechnik, GmbH & Co. KG., Federal Republic of Germany.
336. Phitides M (1991) The abrasion resistance of concrete with pulverised fuel ash, MPhil Thesis, Aston University, Birmingham.
337. Pickard SS (1981) Vacuum dewatered concrete, Concrete International, November, pp. 49 – 55.
338. Plassmann E (1954), Method for testing hard concrete surface through the pressure of rolling balls, Zement-Kalk-Gips, May 1954, pp. 213 – 216.
339. Plowman JM (1956) Maturity and strength of concrete, Magazine of Concrete Research, Vol. 8, No. 22, pp. 15 – 22.
340. Pogany A (1935) Determining the abrasion resistance of concrete from that of the mortar and aggregates, Zement, Vol. 24, pp. 522.
341. Potrebowski J (1983) The splitting test applied to steel fibre reinforced concrete, International Journal of Cement Composites & Lightweight Concrete, Vol. 5, pp. 49 – 53.
342. Powers TC, Copeland LE, Hayes JC & Mann HM (1954) Permeability of Portland cement paste, Journal of the American Concrete Institute, Vol. 26, No. 3, pp. 285 – 298.
343. Price WF & Widdows SJ (1991) The effect of permeable formwork on the surface properties of concrete, Magazine of Concrete Research, Vol. 43, pp. 93 – 104.
344. Price WH & Bamforth PB (1993) Initial surface absorption of concrete: examination of modified test apparatus for obtaining uniaxial absorption, Magazine of Concrete Research, Vol. 45, No. 162, pp. 17 – 24.
345. Price WH & Wallace GB (1950) Resistance of Concrete and Protective Coatings to Forces of Cavitation, ACI Journal, Vol. 46, pp. 109 – 120.
346. Price WH (1947) Erosion of concrete by cavitation and solids in flowing water, Journal of the American Concrete Institute, Proceedings, Vol. 43, pp. 1009 – 1023.

347. Prior ME (1966) Abrasion resistance, Significance of tests and properties of concrete and concrete making materials, ASTM STP No. 169 – A, pp. 246 – 260.
348. Proctor BA & Yale B (1980) Glass fibres for cement reinforcement, Phil. Trans. R. Soc. Lond. A, Vol. 294, pp. 427 – 436.
349. Pye PW & Warlow WJ (1978) A method of assessing the soundness of some dense floor screeds, Garston: BRE, Current Paper CP 72/78.
350. Pye PW (1984) BRE Screed tester: Classification of screeds, sampling and acceptance limits, Garston: BRE, Information Paper IP11/84.
351. Pye PW (1986) Assessing the quality of dense floors screeds, Chemistry & Industry, 21 July, No. 14, pp. 479 – 480.
352. Qian CX & Stroeven P (2000) Development of hybrid polypropylene-steel fibre reinforced concrete, Cement & Concrete Research, Vol. 30, pp. 63 – 69.
353. Rabinowicz E, (1965), Friction and wear of materials, New York, London, Sydney, John Wiley and Sons.
354. Rabinowicz E, Dunn LA & Russel PG, (1961) A study of abrasive wear under three-body conditions, Wear, Vol. 4, pp. 345 – 355.
355. Ramachandran VS & Feldman RF (1973) Hydration characteristics of monocalcium aluminate at a low water cement ratio, Cement & Concrete Research, Vol. 3, pp. 729 –750.
356. Ramakrishnan V & Coyle WV (1983) Steer fibre reinforced superplasticised concretes for rehabilitation of bridge decks and highway pavements, Report No. DOT – RSPA – DMA – 50 / 84 / 2, US Dept. of Transportation, November, 250 pp.
357. Ramakrishnan V (1988) Materials and properties of fibre reinforced concrete, Civil Engineering (London), April, pp. 29 – 40.
358. Ramakrishnan V, Brandshaug T, Coyle WV, & Schrader EK (1980) A comparative evaluation of concrete reinforced with straight steel fibres and fibres with deformed ends glued together into bundles, ACE Journal, Proceedings, Vol. 77, No. 3, pp. 135 – 143.
359. Ramakrishnan V, Coyle WV, Dhal FL & Schrader EK (1981) A comparative evaluation of fibre shotcrete, Concrete International: Design and construction, Vol. 3, No. 1, pp. 56 – 69.
360. Ramakrishnan V, Gollapudi S & Zellers R (1987) Performance characteristics and fatigue strength of polypropylene fibre reinforced concrete, Fibre Reinforced Concrete Properties & Applications, SP – 105, American Concrete Institute, Detroit, pp. 141 – 158.

361. Ramu S (1983) Fibre reinforced concrete – What it has to offer?, Journal of the Institute of Engineers (India), Vol. 64 – S, pp. 61 – 64.

362. Rapoport L, Salganik RL & Gotlib VA (1995) A model of brittle-dominated wear due to delayed fracture (vertical crack growth), Wear, Vol. 188, pp. 166 – 174.

363. Rettburg WA (1986) Steel Reinforced concrete makes older dam safer, more reliable, Hydro Review, Spring, pp. 18 – 22.

364. Ritchie AGB & Al – Kayyali OA (1975) The effects of fibre reinforcement on lightweight aggregate concrete, Proc. RILEM Symp., Construction Press Ltd, pp. 247 – 256.

365. Röβler M & Odler I (1985) Investigations on the relationship between porosity, structure and strength of hydrated Portland cement pastes: Effect of porosity, Cement & Concrete Research, Vol. 15, No. 2, pp. 320 – 330.

366. Robens E, Benzler B, Buchel G, Reichert H & Schumacher K (2002) Investigation of characterising methods for the microstructure of cement, Cement & Concrete Research, Vol. 32, pp. 87 – 90.

367. Roberts NK (1964) The surface tension of mercury and the adsorption of water vapour and some saturated hydrocarbons of mercury, Journal of the Chemical Society, pp. 1907 – 1915.

368. Robins P, Austin S, Chandler J & Jones P (2001) Flexural strain and crack width measurement of steel fibre reinforced concrete by optical grid and electrical gauge methods, Cement & Concrete Research, Vol. 31, pp. 719 – 729.

369. Robins PJ & Calderwood RW (1978) Explosive testing of fibre reinforced concrete, Concrete, Vol. 12, No. 1, pp. 26 – 28.

370. Robinson C, Colasanti A & Boyd G (1991) Steel fibres reinforced auto assembly floor, Concrete International, Vol. 13, No. 4, pp. 30 – 35.

371. Romualdi JP & Batson GB, (1963) Mechanics of crack arrest in concrete, Proceedings ASCE, V. 89, EM3, June 1963, pp. 147 – 168.

372. Romualdi JP & Mandel JA (1964) Tensile strength of concrete affected by uniformly distributed closely spaced short lengths of wire reinforcement, ACI Journal, Proceedings, V. 61, No. 6, pp. 657 – 671.

373. Rootare HM (1970) A review of mercury porosimetry, Eds. Hirschhorn JS & Roll KH, Advanced Experimental Techniques in Powder Metallurgy, Volume 5: Perspectives in Powder Metallurgy, Plenum Pess, New York, pp. 225 – 252.

374. Rosenfield AR (1980) A fracture mechanics approach to wear, Wear, Vol. 61, pp. 125 – 132.

375. Sadegzadeh M & Kettle RJ (1986), Indirect and non-destructive methods for assessing abrasion resistance of concrete, Magazine of Concrete Research, Vol. 38, No. 137, pp. 183 – 190.

376. Sadegzadeh M & Kettle RJ (1987) Development of an accelerated abrasion test apparatus with a standardised testing procedure, Magazine of Concrete Research., Vol. 21, pp. 47 – 56.

377. Sadegzadeh M & Kettle RJ (1988) Abrasion resistance of surface treated concrete, ASTM, Cement, Concrete & Aggregates, Vol. 10, No. 1, pp. 20 – 28.

378. Sadegzadeh M (1985) Abrasion resistance of concrete, PhD thesis, Aston University, Birmingham.

379. Sadegzadeh M, Kettle RJ & Page CL (1989) Influence of curing on surface characteristics of concrete, Materials Research Society Symposium, Proceedings, Vol. 137, pp. 307 – 312.

380. Sadegzadeh M, Kettle RJ & Vassou V (2001) Influence of glass, polypropylene and steel fibres on physical properties of concrete, Proceedings of the 12th International Glass Fibre Reinforced Concrete Association, Dublin, Republic of Ireland, May, pp. 209 – 216.

381. Sadegzadeh M, Page CL & Kettle RJ (1987) Surface microstructure and abrasion resistance of concrete, Cement & Concrete Research, Vol. 17, No. 4, pp. 581 – 590.

382. Saito M & Kawamura M (1986) Resistance of cement-aggregate interfacial zone to the propagation of cracks, Cement & Concrete Research, Vol. 16, pp. 653 – 661.

383. Sargent PM & Page TF (1978) Influence of microstructure on microhardness of ceramic materials, Journal of the British Ceramic Society, Vol. 26, pp. 209 – 224.

384. Savastano H Jr. & Agopyan V, (1999) Transition zone studies of vegetable fibre-cement paste composites, Cement & Concrete Composites, Vol. 21, No. 1, pp. 49 – 57.

385. Sawyer JL (1957) Wear tests on concrete using the German standard method of test and machine, Proceedings, American Society for Testing Materials, Vol. 57, pp. 1143 – 1153.

386. Schneider J & Woitowitz HJ (1997) Dangerous exposure to asbestos fibre dust of the employees of the waterworks when working with asbestos cement pipes. A cross-sectional study in four drinking water-supplying plants in Rhineland-Palatinate, Zentralblatt fur Arbeitsmedizin, Arbeitsschutz und Ergonomie, Vol. 47, No. 1, pp. 2 – 6.

387. Scholer CH & Allen H (1928), Wear tests of concrete, Kansas State Agricultural College Bulletin, Vol. XII, No. 3, Feb. 15.

388. Schrader EK & Munch AV (1976) Deck slab repaired by fibrous concrete overlay, Proceedings ASCE, Vol. 102, March, pp. 179 – 196.

389. Schrader EK (1981) Impact resistance and test procedure for concrete, ACI Journal, Proceedings, Vol. 78, No. 2, pp. 141 – 146.

390. Schrader EK (1989) Fibre reinforced concrete, ICOLD Buletin 40, International Committee on Large Dams, Paris, May, 22 pp.

391. Schuman L & Tucker J Jr. (1939) A portable apparatus for determining the relative wear resistance of concrete floors, Journal of Research, National Bureau of Standards, Research Paper 1252, Vol. 23, No. 5, pp. 549 – 570.

392. Scofield HH (1925) Significance of Talbot-Jones Rattler as test for concrete in road slabs, Proceedings, Highway Research Board, pp. 127-137.

393. Scott D, Wear, in Eds. Scott D & Jones MH (1983) Industrial tribology, the practical aspects of friction, lubrication and wear, Tribology series, 8, Amsterdam, Oxford, Elsevier Scientific, pp. 12 – 30.

394. Scripture EW (1936) Metallic aggregate in concrete floors, Proceedings of the American Concrete Institute, Journal of American Concrete Institute, Vol. 36, pp. 17 – 27.

395. Scripture EW, Benedict SW & Bryant DE (1953) Floor aggregates, Proceedings, American Concrete Institute, Vol. 50, No. 4, pp. 305 – 316.

396. Sellevold EJ (1974) Mercury porosimetry of hardened cement paste cured or stored at 97°C, Cement & Concrete Research, Vol. 4, pp. 399 – 404.

397. Senbetta E (1992), New test procedure for impact resistance of industrial floor products, ACI Materials Journal, Vol. 89, No. 5, pp. 495 – 498.

398. Sereda PJ (1972) Significance of microhardness of porous inorganic materials, Cement and Concrete Research, Vol. 2, pp. 717 – 729.

399. Sergi G & Page CL (1992) The effects of cathodic protection on alkali – silica reaction in reinforced concrete, Contractor Report 310, Transport and Road Research Laboratory, Berkshire.

400. Shah SP & Rangan BV (1970) Effects of reinforcement on ductility of concrete, Proceedings of the American Society of Civil Engineers: Journal of the Structural Division, pp. 1167 – 1184.

401. Shah SP & Rangan BV (1971) Fibre reinforced concrete properties, Journal American Concrete Institute, Vol. 68, pp. 126 – 135.

402. Shah SP (1978) Complete stress-strain curves for steel fibre reinforced concrete in uniaxial tension and compression, In Testing & Test Methods of Fibre Cement Composites, Ed. Swamy RN, RILEM Symposium Construction Press Ltd, Lancaster, pp. 399 – 408.

403. Shank JR (1935) A wear test for flooring materials, Proceedings, American Society for Testing Materials, Vol. 35, Part 2, pp. 533 – 541.

404. Sikorski C (1982) Improvement of properties of steel fibre reinforced concrete by magnetic linearisation, In Mechanika Kompozytow Betonopodobnych, Ossolineim, Warsaw, pp. 251 – 256.

405. Smith FL (1958) Effect of aggregate quality on resistance of concrete to abrasion, ASTM Special Technical Publication No. 205, pp. 91 – 106.

406. Soda N, Kimura Y & Tanaka A (1977) Wear of some F.C.C. metals during unlubricated sliding – 4 effects of atmospheric pressure on wear, Wear, Vol.43, No.2, pp.165 – 174.

407. Sonebi M & Kahayat KH (2001) Testing abrasion resistance of high-strength concrete, Cement, Concrete & Aggregates, CCAGDP, Vol. 23, No. 1, pp. 34 – 43.

408. Soroka I & Sereda PJ (1968a) Interrelation of hardness, modulus of elasticity and porosity in various gypsum systems, Journal of the American Ceramic Society, Vol. 51, No. 6, pp. 337 – 340.

409. Soroka I & Sereda PJ (1968b) Supplementary paper III – 34 The structure of cement-stone and the use of compacts as structural models, Proceedings 5th Int. Symp. on the Chemistry of Cement, Tokyo, Vol. 3, pp. 67 – 73.

410. Soroka I (1965) Abrasion resistance of concrete terrazzo flooring tiles, Wear, Vol. 8, pp. 220 – 221.

411. Soroushian P & Bayasi Z (1991) Fibre type effects on the performance of steel fibre reinforced concrete, ACI Materials Journal, Vol. 88, No. 2, pp. 129 – 134.

412. Spero C, Hargreaves DJ, Kirckaldie RK & Flitt HJ (1991) Review of test methods for abrasive wear in ore grinding, Wear, 146, pp. 389 – 408.

413. Sri Ravindrarajah R & Tam CT (1984) Flexural strength of steel fibre reinforced concrete beams, Int. J. Cement Composites & Lightweight Concrete, Vol. 6 pp. 273 – 278.

414. St John DA, Poole AW & Sims I (1998) Concrete petrography, Arnold Publishers, UK.

415. Stachowiak GW & Batchelor AW (1993) Engineering Tribology, Tribology Series 24, Elsevier, Amsterdam, pp. 561 – 562.

416. Stiffler AK (1969) relation between wear and physical properties of roadstones, HRB Special report 101, Highway Research Board, Washington DC.

417. Suaris W & Shah SP (1983) Properties of concrete subjected to impact, Journal of Structural Engineering, ASEC, Vol. 109, No. 7, pp. 1727 – 1741.

418. Subrahmanyam BV (1984) Bamboo reinforcement for cement matrices, in Concrete Technology & Design, Vol. 2: New Reinforced Concretes, ed. Swamy RN, Surrey University Press, London, pp. 141 – 195.

419. Sun W, Chen H Luo X & Qian H (2001) The effect of hybrid fibres and expansive agent on the shrinkage and permeability of high-performance concrete, Cement & Concrete Research, Vol. 31, pp. 595 – 601.

420. Sustersic J, Mali E & Urbancic S (1991) Erosion-abrasion resistance of steel fibre reinforced concrete, in Durability of Concrete, Second International Conference, 1991, Montreal, Canada, Ed. by Malhotra VM, American Concrete Institute, Detroit, MI, Vol. 2, (ACI SP-126), pp 729 – 743.

421. Swamy RN & Al-Noori KA (1975) Flexural behaviour of fibre reinforced concrete with conventional steel reinforcement, RILEM Symposium, Fibre Reinforced Cement & Concrete, The Construction Press Ltd, Hornby, pp. 187 – 196.

422. Swamy RN & Stavrides H (1975) Some properties of high workability steel fibre reinforced concrete, Fibre Reinforced Cement & Concrete, RILEM Symposium, Construction Press Ltd., pp. 197 – 208.

423. Swamy RN & Stavrides H (1979) Influence of fibre reinforcement in restrained shrinkage and cracking, J. American Concrete Institute, Vol. 76, pp. 443 – 460.

424. Swamy RN (1974) The technology of steel fibre-reinforced concrete for practical applications, Proceedings of the Institution of Civil Engineers, London, May 1974, Vol. 56, No. 1, pp. 143 – 159.

425. Swamy RN (1975) Fibre reinforcement of cement and concrete, Materials & Structures RILEM Journal, Vol. 8, No. 45, pp. 235 – 254.

426. Swamy RN (1982) Structural properties of fly ash concrete, Proc. Internat. Symposium on The use of PFA in concrete, University of Leeds, Vol. 1, pp. 343 – 355.

427. Swamy RN (1986) Steel fibre reinforced concrete for bridge deck and building floor applications, The Structural Engineer, Vol. 64 A, No. 6, pp. 149 – 157.

428. Swamy RN, Ali SA & Theodorakopoulos DD (1983) Early strength fly ash concrete for structural applications, ACI Journal, Proc., Vol. 80, No. 5, pp. 414 – 423.

429. Swamy RN, Magnat PS & Kameswara Rao CVS (1974) The mechanics of fibre reinforcement cement matrices, Publication SP 44, Fibre reinforced concrete, ACI, pp. 1 – 28.
430. Tabor D (1951) The hardness of metals, The Clareton Press, Oxford.
431. Tantall PC & Kuitenbrouwer L (1992) Steel fibre reinforced concrete in industrial floors, Concrete International, Vol. 14, No. 12, pp. 43 – 47.
432. Tatro SB (1987) Performance of steel fibre reinforced concrete using large aggregates, Transportation Research Record 1110, Transportation Research Board, Washington DC, pp. 127 – 129.
433. Tavernelli JF & Coffin LF (1959) Trans. Am. Soc. Metals, Vol. 51, pp. 438.
434. Taylor WH (1977) Concrete Technology and Practice, 4th Edition McGraw Hill, Sydney, Australia.
435. Tomsett HN (1974), Non-destructive testing of floor slab, Concrete, Vol. 8, No. 3, pp. 71 – 74.
436. Trefil ARBED Ltd (1998) Company Data Sheets, Frederic House, Nantwich, Cheshire, CW5 6RE.
437. Troxtell GE, Davis HE & Kelly JW (1968) Composition and properties of concrete, Second Edition, McGraw Hill Book Company, USA.
438. Tylczak JH (1992) Abrasive wear, in Blau PJ et al. (Eds.) ASM Handbook, Vol. 18, Friction, Lubrication & Wear Technology, ASM International, USA, pp. 184 – 190.
439. Tyo B (1991) Surface treatments for industrial floors, Concrete International, April, pp. 36 – 38.
440. United States Army Corps Engineers (1949) Handbook for Concrete & Cement, Central Concrete Laboratory, New York.
441. Unwalla BT (1982) Steel fibre reinforced concrete, Chemical Age of India, Vol. 33, No. 7, pp. C – 1/ 1 – 4.
442. Uomoto T & Kobayashi K (1984) Measurement of fibre content of steel fibre reinforced concrete by electromagnetic methods, in Fibre Reinforced Concrete – International Symposium, ACI SP – 81, American Concrete Institute, Detroit, pp. 233 – 246.
443. Vander Voort GF & Lucas GM (1998) Microindentation hardness testing, Advance Materials & Processes, No. 9, September, pp. 21 – 25.
444. Vassou V, Kettle RJ & Sadegzadeh M (2001) The concrete abrasion test apparatus in accordance with the BS 8204 (Part 2: 1999). The reality!, Proceedings of the 9th

International Conference on Structural Faults & Repair – 2001, ed. Forde MC, CD – ROM: ISBN 0-947644-47-4, Engineering Technics Press, Edinburgh.

445. Visavanich K & Naaman AE (1983) Fracture model for fibre reinforced concrete, Journal of the American Concrete Institute, Vol. 80, pp. 128 – 138.
446. Vocka R, Galle C, Dubois M & Lovera P (2000) Mercury intrusion porosimetry and hierarchical structure of cement pastes – Theory and experiment, Cement & Concrete Research, Vol. 30, No. 4, pp. 521 – 527.
447. Vondran GL (1994), Applications of steel fibre reinforced concrete, In Steel fibre reinforced concrete, Detroit, American Concrete Institute, ACI compilation, no.27: pp. 14-19
448. Wang AG & Hutchings IM (1989) The number of particle contacts in two-body abrasive wear of metals by coated abrasive papers, Wear, Vol. 129, pp. 23 – 35.
449. Wang Y (1988) Effects of bond characteristics between steel slag, fine aggregate and cement paste on mechanical properties of concrete and mortar, Bonding in Cementitious Composites, Materials Research Society, Vol. 114, pp. 49 – 54.
450. Wang Y, Backer S & Li VC (1987) An experimental study of the synthetic fibre reinforced cementitious composites, Journal of materials science, Vol. 22, pp.4281 – 4291.
451. Washburn EW (1921) Note on a method of determining the distribution of pore sizes in a porous material, Proceedings, National Academy of Sciences, PNASA, Vol. 7, pp. 115 – 116.
452. Wastlund G. & Erikson A. (1946) Wear resistance tests on concrete floors and methods of dust prevention, Journal of American Concrete Institute, Vol. 18, Part 2, pp. 181 – 199.
453. Waterhouse RB (1988), Fretting Corrosion, Oxford, Pergamon Press.
454. Watkins RD & Samarin A (1975) Cavitation Erodobility of Concrete, National conference publication, 75/6 IE Australian Symposium, on Serviceability of Concrete, Melbourne.
455. Webb M (1996) The effect of low-grade aggregates on the abrasion resistance of concrete, PhD thesis, Aston University, Birmingham.
456. Webb M, Kettle RJ & Collins RJ (1996) Abrasion resistance of concrete containing lower grade aggregates, in Concrete for Environment Enhancement & Protection, Eds. Dhir RK and Dyer TD, E & F Spon, London, pp. 549 – 585.

457. Wei S, Mandel JA & Said S (1986) Study of interface strength in steel-fibre reinforced cement-based composites, ACI Journal, Vol. 83, No. 4, July – August, pp. 597 – 605.

458. Welsh N C (1957) Frictional heating and its influence of wear of steel, J. Appl. Phys., Vol. 28, pp. 960 – 968.

459. Wexham Developments (1998) Chaplin abrasion tester – Instruction manual, Unit 8 Youngs Industrial Estate, Paices Hill, Aldermaston, Reading, RG7 4PW.

460. Wigum BJ, French WJ, Howarth RJ & Hills C (1997) Accelerated tests for assessing the potential exhibited by concrete aggregates for alkali-aggregate reaction, Cement & Concrete Composites, Vol. 19, pp. 451 – 476.

461. Williamson GR (1965) Fibrous reinforcement for Portland cement concrete, Technical report No. 2-40, US Army Corps of Engineers Ohio River Division Laboratories, Cincinnati, May 1965, pp. 56.

462. Williamson GR (1965) The use of fibrous reinforced concrete in structures exposed to explosives hazards, Miscellaneous Paper No. 5 – 5, U.S. Army Ohio River Division Laboratories.

463. Williamson GR (1966) Response of fibrous reinforced concrete to explosive loading, Technical report No. 2-48, US Army Corps of Engineers Ohio River Division Laboratories, Cincinnati, Jan, pp. 83.

464. Williamson GR (1974) The effect of steel fibres on the compressive strength of concrete, in Fibre Reinforced Concrete, ACI SP – 44, American Concrete Institute, Detroit, pp. 195 – 207.

465. Wilson MA, Taylor SC & Hoff WD (1998) The initial surface absorption test (ISAT): An analytical approach, Magazine of Concrete Research, Vol. 50, No. 2, pp. 179 - 185.

466. Winslow DN & Diamond S (1970) A mercury porosimetry study of the evolution of porosity in Portland cement, Journal of Materials, JMLSA, Vol. 5, No. 3, pp. 564 – 585.

467. Witte LP & Backstrom JE (1951) Some properties affecting the abrasion resistance of air-entrained concrete, Proceedings, American Society for Testing Materials, Vol. 51, pp. 1141 – 1155.

468. Ytterberg RF (1971) Wear resistance of industrial floors of Portland cement concrete, American Society of Civil Engineers, Civil Engineering New York, January, pp. 68 – 71.

469. Zhijiang Z & Tian C Y (1986) High tenacity PVA fibres: A suitable alternative for asbestos, paper presented at the International Man-Made Fibres Congress, Austrian Chemical Institute, Austria, September.

470. Zollo R (1984) Collated fibrillated polypropylene fibres in FRC, Fibre Reinforced Concrete – International Symposium, SP – 81, American Concrete Institute, Detroit, pp. 397 – 409.

471. Zonsvelt JJ (1976) Polypropylene fibre concrete, Fibre Cement & Fibre Concrete, Course Notes for Practising Civil Engineers, University of Surrey, April.

472. Zum Gahr KH (1961) A study of abrasive wear under three-body conditions, Wear 4, pp. 95.

473. Zum Gahr KH (1982) A review of the abrasive wear of metals, J. Eng. Mater. Technol. (Trans ASME), 104, pp. 80 – 84.

474. Zum Gahr KH (1989) The number of particle contacts in two-body abrasive wear of metals by coated abrasive papers, Wear, Vol. 129, pp. 120 – 121.

Appendix A: Concrete mix design

Mix A1

Dry weight:		
Cement	365 kg/m^3	
20 – 10 mm Aggregate	940 kg/m^3	
10 – 5 mm Aggregate	315 kg/m^3	
Fine Aggregate	620 kg/m^3	
Fibres	40 kg/m^3	$v_f = 0.51$ %
Free-Water Cement ratio	0.44	
Aggregate – Cement ratio	5.1:1	

Mix A2

Dry weight:		
Cement	345 kg/m^3	
20 – 10 mm Aggregate	875 kg/m^3	
10 – 5 mm Aggregate	290 kg/m^3	
Fine Aggregate	685 kg/m^3	
Fibres	40 kg/m^3	$v_f = 0.51$ %
Free-Water Cement ratio	0.52	
Aggregate – Cement ratio	5.4:1	

Note: Superplasticizer was added in a limited number of mixes at various fibre dosages and at volumes of 0.1, 0.2, 0.5, 0.75 and 1.0 % of cement content. This corresponded to 0.35, 0.69,1.73, 2.59 and 3.45 kg/m^3 respectively.

Mix A3

Dry weight:		
Cement	300 kg/m^3	
20 – 10 mm Aggregate	770 kg/m^3	
10 – 5 mm Aggregate	255 kg/m^3	
Fine Aggregate	840 kg/m^3	
Fibres	40 kg/m^3	$v_f = 0.51$ %
Free-Water Cement ratio	0.65	
Aggregate – Cement ratio	6.2:1	

Mix B4

Dry weight:	
Cement	365 kg/m^3
20 – 10 mm Aggregate	940 kg/m^3
10 – 5 mm Aggregate	315 kg/m^3
Fine Aggregate	620 kg/m^3
Free-Water Cement ratio	0.44
Aggregate – Cement ratio	5.1:1

Mix B5

Dry weight:	
Cement	345 kg/m^3
20 – 10 mm Aggregate	875 kg/m^3
10 – 5 mm Aggregate	290 kg/m^3
Fine Aggregate	685 kg/m^3
Free-Water Cement ratio	0.52
Aggregate – Cement ratio	5.4:1

Mix B6

Dry weight:	
Cement	300 kg/m^3
20 – 10 mm Aggregate	770 kg/m^3
10 – 5 mm Aggregate	255 kg/m^3
Fine Aggregate	840 kg/m^3
Free-Water Cement ratio	0.65
Aggregate – Cement ratio	6.2:1

Table A. 1 *Summary of trial mixes*

Mix ID	Fibre (%)	Cement (kg/m^3)	20 mm Aggregate (kg/m^3)	10 mm Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	w/c	a/c	Slump (mm)	7 days compressive strength (N/mm^2)	28 days compressive strength (N/mm^2)
B4	–	365	940	315	620	0.44	5.1:1	75	47.51	61.67
B5	–	345	875	290	685	0.52	5.4:1	100	39.59	50.00
B6	–	300	770	255	840	0.65	6.2:1	150	25.69	40.00
A1 – steel	0.51	365	940	315	620	0.44	5.1:1	70	45.83	60.67
A1 – steel	2.00	365	940	315	620	0.44	5.1:1	10	50.32	63.67
A2 – steel	0.51	345	875	290	685	0.52	5.4:1	100	36.24	52.67
A2 – steel	2.00	345	875	290	685	0.52	5.4:1	50	34.68	53.67
A2 – steel	3.00	345	875	290	685	0.52	5.4:1	10	24.10	55.73
A2 – steel	4.00	345	875	290	685	0.52	5.4:1	0	40.60	56.93
A2 – poly.	0.10	345	875	290	685	0.52	5.4:1	70	40.00	56.33
A2 – poly.	0.50	345	875	290	685	0.52	5.4:1	15	33.21	43.93
A2 – poly.	2.00	345	875	290	685	0.52	5.4:1	0	5.89	7.67
A2 – blend	0.10	345	875	290	685	0.52	5.4:1	75	38.33	56.67
A2 – blend	0.50	345	875	290	685	0.52	5.4:1	10	36.50	51.67
A3 – steel	0.51	300	940	255	840	0.65	6.2:1	125	16.59	44.53
A3 – steel	2.00	300	940	255	840	0.65	6.2:1	10	19.13	50.40

Appendix B: Material characteristics

Table B. 1 Chemical analysis of Blue Circle Ordinary Portland Cement

Chemical Name	% Present
SiO_2	19.6
I.R.	1.65
Al_2O_3	4.96
Fe_2O_3	2.74
CaO	63.8
MgO	1.62
SO_3	3.20
K_2O	0.71
Na_2O	0.11
Cl	0.020
Loss on ignition	1.91

Specific Surface Area: 336 m^2/kg

45 μ sieve retained: 16.4 %

Table B. 2 Chemical analysis of Weeford sand

Chemical Name	% Present
SiO_2	92.89
Al_2O_3	3.29
Fe_2O_3	1.05
MgO	0.18
MnO	0.02
CaO	0.04
K_2O	1.57
Na_2O	0.28
Loss on ignition	0.48

Table B. 3 Hanson aggregate grading report

Unit: 288	Material: 27	Specification
Weeford	Concrete Sand	Concrete Sand BS882:1992 Table 4 Grade M

% Passing Sieve sizes

B.S.	Upper>	100	100	100	100	80	48	15	4	10
Limits	Lower>	100	89	65	45	25	5	0	0	0
Date	Ref.	10 mm	5 mm	2.36 mm	1.18 mm	600µm	300µm	150µm	75 µm	M/C
12/4/99	P307	100.0	96.0	80.0	68.0	62.0	43.0	10.0	1.8	
15/4/99	P424	100.0	97.0	81.0	70.0	64.0	44.0	11.0	2.1	
21/4/99	P559	100.0	98.0	82.0	67.0	57.0	36.0	9.0	1.6	
27/4/99	P711	100.0	98.0	83.0	72.0	65.0	43.0	9.0	2.5	
30/4/99	P785	100.0	98.0	84.0	75.0	69.0	48.0	6.0	1.5	
04/5/99	P820	100.0	97.0	82.0	71.0	63.0	40.0	6.0	2.1	
11/5/99	P987	100.0	97.0	82.0	70.0	63.0	40.0	6.0	1.9	
14/5/99	P065	100.0	98.0	76.0	63.0	56.0	36.0	5.0	1.5	
18/5/99	P152	100.0	97.0	80.0	67.0	59.0	35.0	5.0	1.7	
19/5/99	P172	100.0	97.0	80.0	67.0	60.0	34.0	4.0	0.7	
24/5/99	P526	100.0	97.0	79.0	68.0	61.0	35.0	5.0	1.4	

Table B. 4 BS 882 (1992) grading limits for sand

Sieve size	Percentage by mass passing BS sieve			
	Overall limits	Additional limits for grading		
		C	M	F
10.00 mm	100	—	—	—
5.00 mm	89 – 100	—	—	—
2.36 mm	60 – 100	60 – 100	65 – 100	80 – 100
1.18 mm	30 – 100	30 – 90	45 – 100	70 – 100
600 μm	15 – 100	15 – 54	25 – 80	55 – 100
300 μm	5 – 70	5 – 40	5 – 48	5 – 70
150 μm	0 – 15*	—	—	—

Table B. 5 *Properties of the five types of steel fibres (Trefil ARBED Ltd, 1998; Philip Jones Construction Materials Ltd., 1998; Fibermesh Europe, 1998; N. V. Bekaert S.A., 1997; Fibre Technology Ltd, 1999)*

Company details	Type and specifications of fibre	Fibre applications	Improved properties of concrete
Trefil ARBED Ltd, Frederic House, Nantwich, Cheshire, CW5 6RE	**TABIX 1/45, 1/50, 1/60** Undulated fibres manufactured from draw steel wire **Dimensions:** Fibre diameter: 1mm Fibre length: 45, 50, 60 mm Wave depth: 0.65 mm Wave length: 8 mm **Material characteristics:** Tensile strength of wire: 1000 N/mm^2 Packaging: Type: recyclable cardboard boxes Sizes: 27x27x18 cm Net weight/Box: 30 kg Boxes/Palette: 48 Boxes Weight/Palette: 48 Boxes The fibres are oriented in one direction.	Industrial floors	• Excellent impact strength • Enhanced edge protection • Reduced shrinkage behaviour • Enhanced abrasion resistance • Reinforcement mistakes are excluded • Excellent resistance against corrosion • Material savings due to the suppression of concrete covering • Shorter construction periods as there is no interference with traditional rebars • Increased tensile compression and flexural strength, equal in all directions • Controllable cracking pattern and improved ductile behaviour after matrix failure • Additional bearing capacities due to plastic moment redistribution
Philip Jones Construction Materials Ltd., Enaldoow-y-Trof, 40 Wood Lane Hawarden, Flintshire, Wales, UK, CH5 3JE	**HAREX SF 01 – 32** End hooks longitudinal twisting **Dimensions:** Length: 32 mm Triangular cross section **Material characteristics:** Tensile strength ≥ 800N mm^2 Manufactured from steel ingots, grade ST 52-3, according to DIN 17100. HAREX steel fibres can be used without any special machinery. When added to the truck-mixer, HAREX steel fibres distribute absolutely homogeneously and without fibre-balling.	Industrial floors	Using HAREX SFRC the flexural strength can be increased up to 100% depending on the fibre content and therefore the thickness can be reduced compared to the conventional reinforced concrete slab down to 85 %. Another advantage of HAREX SFRC is the crack reduction and control so that the interlock of the irregular faces provides structural integrity and usually improves pavement performance. Greater abrasion resistance and surface strength against impact loads are other important factors that have to be kept in mind when HAREX SFRC is compared to plain concrete. A homogeneous distribution is guaranteed so that the concrete quality at any time can be ensured. In addition steel fibres lead to a cost-effective solution.
Fibermesh Europe, Fibermesh House, Smeckley Wood Close, Chesterfield, England S41 9PZ	**Novotex 0730** Flattened ends with round shaft **Dimensions:** Fibre length: 30 mm Diameter: 0.7 mm Aspect ratio: 43 **Material characteristics:** Tensile strength: 1150 MPa Appearance: bright and clean wire	Precast, Airport runways and taxiways, shotcrete, slabs on ground, metal decks.	• Composite, multi-directional reinforcement throughout concrete section. • Superior crack control • Unequalled impact resistance • Superior load transfer stability at contraction joints – no more "rocking" • Increased flexural toughness • Increased fatigue endurance • Increased shear strength
Fibre Technology Ltd Brookhill Road, Pinxton, Nottingham, NG16 6NT	**Fibrex SS 35** Stainless steel fibres **Dimensions:** Fibre Length: 35 mm Diameter: 0.7 mm Aspect ratio: 50 **Material characteristics:** Melting temperature: 1480/1530 °C Tensile strength: 47 MN m^2 Modulus of elasticity: 83 GN m^2	Industrial floors.	• Improved crack stopping mechanism. • Increase in impact resistance. • Increase in resistance to damage from thermal shock. • Outstanding oxidation resistance. • Increased toughness.

Table B. 6 Properties of the two types of polypropylene fibres (Fibrin (Humberside) Ltd, 1998; Grace Construction Products Ltd, 2000)

Company details	Type and specifications of fibre	Fibre applications	Improved properties of concrete
Fibrin (Humberside) Ltd, Borwick Drive, Grovehill, Beverly, East Yorkshire, HU17 0HQ	**Fibrin 23** Crimped monofilament polypropylene fibres **Dimensions:** Fibre Length: 12 mm Diameter: 18 μm For use in the most concrete mixes of normal aggregate sizes of 10 mm to 20 mm. Manufactured in a continuous process by extrusion of polypropylene granules. The extruded material is heated, stretched to improve tensile strength, coated, cut to 12 mm nominal length and crimped.	Industrial floors	• Improved durability • No cover problems • No rusting • Improved surface finish • Improved abrasion resistance • Improved impact resistance • Reduces permeability • Reduces wet absorption • Resists plastic settlement • Resists plastic cracking • Improved freeze/thaw resistance • Reduced plastic shrinkage • Improved fire damage properties • Improved water and chemical penetration resistance.
Grace Construction Products Ltd, 852 Birchwood, Warrington, Cheshire England, WA3 7QZ	**GRACE Structural Fibres** Monofilament fibres manufactured from a synthetic polymer blend consisting of polypropylene and polyethylene **Dimensions:** Fibre Length: 50 mm **Material characteristics:** Specific gravity: 0.92 Modulus of elasticity: 4.3 GPa Tensile strength: 550 MPa Melt point: 160 °C Ignition point: 590 °C	Slabs on grade, bridge decks overlays, pipes, vaults, septic tanks, tunnel and channel linings, slope stabilisation, and pools.	Improved flexural toughness, impact and fatigue resistance, and control of plastic shrinkage cracking, resulting to a minimal impact on workability and placement.

Table B. 7 Properties of the two types of glass (CEM-Fil International, 2000)

Company details	Type and specifications of fibre	Fibre applications	Improved properties of concrete
CEM-Fil International 15 Pit Place, Skelmersdale, Lancashire, WN8 9PS	**Cem-Fil Anticrak HD** Special purpose AR glass fibre chopped strand **Dimensions:** Fibre Length: 12 mm Diameter: 14 μm **Material characteristics:** Elastic Modulus: 72 GPa Specific gravity: 2.68 **Product form:** Bundles of 800 filaments, which disperse on contact with moisture. These fibres may be used with normal concrete mixes at very low addition levels – typically 0.6 kg/m^3 of concrete.	Industrial floors	• Improved surface quality • Greater impact resistance • Increased damage resistance • High modulus of elasticity for effective reinforcement • A reinforcing material which does not rust and requires no minimum cover • Highly effective in suppressing plastic shrinkage cracking
	Cem-Fil Anticrak HP High integrity AR glass fibre chopped strand **Dimensions:** Fibre Length: 12 mm Diameter: 14 μm **Material characteristics:** Elastic Modulus: 72 GPa Specific gravity: 2.68 **Product form:** 100 filaments bonded together to form a multi-fibre strand These fibres are normally used at higher addition levels – usually from 5 – 10 kg/m^3 of concrete.	Industrial floors	• Improved surface quality • Greater retained toughness • Increased impact strength and abrasion resistance • Higher flexural strength • Increased damage resistance • High modulus of elasticity for effective reinforcement • A reinforcing material which does not rust and requires no minimum cover

Table B. 8 Properties of the hybrid fibres (Fibrin (Humberside) Ltd, 2000; N. V. Bekaert S.A., 1999)

Company details	Type and specifications of fibres	Fibre applications	Improved properties of concrete
Tinsley Wire Ltd. Bekaert Building Products P.O. Box 119 Shepcote Lane, Sheffield, S9 1TY	**Dramix Duo 100** This blend consists of steel wire fibres (Dramix -80/60-) and synthetic fibres (Grace microfibre) and is especially designed for lightly loaded floors. **Dramix -80/60-** Steel fibres glued together into bundles made from hard-drawn steel-wire to ensure high tensile strength and close tolerances. The hooked-end is generally considered as the best form of anchorage. Dimensions: Fibre Length: 60 mm Diameter: 0.75 mm Aspect ratio: 80 Material characteristics: Tensile strength: 1100 N mm^2 **Grace microfibre** Circular and crimped monofilament polypropylene fibres. These fibres have been developed exclusively to act as reinforcement for concrete, during the first hours of the hardening process. Dimensions: Fibre Length: 12.7 mm Diameter: 22 μm Material characteristics: Young's Modulus: 4158 MPa Tensile strength: 557 MPa Melt point: 160 °C	Industrial floors	• First class reinforcement due to "the complementary duo". Polypropylene fibres absorb the tension caused by plastic shrinkage and significantly reduce the occurrence of micro cracks. Steel fibres contribute towards tough and durable concrete. • Faster installation compared with time consuming mesh reinforcement. • Minimises risk of reflective cracking when used as a base for ceramic tiles, glass grin, epoxy coatings, parquet floor...

Table B. 9 Glenium 51 – Technical data / Typical properties. (Feb MBT, 1997)

Form	Viscous liquid
Colour	Brown
Specific gravity	1.1
PH	6
Alkali content (as Na_2O equivalent)	< 5 g/lt.
Chloride ion content	< 0.1 % w/v (NIL)
Hazardous ingredients	None

Appendix C: Comparative Investigations

Table C. 1 Summary of compressive strength results

Specimen ID	Compressive strength (N/mm^2)			Mean compressive strength (N/mm^2)
	Cube No. 1	Cube No. 2	Cube No. 3	
2 – B4	67.60	58.90	67.30	64.60
8 – B4	56.00	63.00	59.00	59.33
12 – B4	59.00	66.00	59.00	61.33
15 – B4	61.00	69.50	62.00	64.17
1 – B5	51.00	48.30	50.00	49.77
3 – B5	52.00	50.00	53.00	51.67
6 – B5	52.00	52.00	53.00	52.33
9 – B5	52.00	49.50	55.00	52.17
10 – B5	53.00	52.00	53.50	52.83
11 – B5	52.00	54.00	53.50	53.17
4 – B6	41.90	40.20	42.00	41.37
5 – B6	34.60	35.20	36.80	35.53
7 – B6	45.70	46.20	45.20	45.70
13 – B6	46.50	49.00	44.00	46.50
14 – B6	42.00	44.00	43.00	43.00
16 – B6	40.00	41.00	39.00	40.00

Table C.2 Abrasion test results

Specimen ID: Trial Mix No. 1
Test No.: 1 (AT)
Date: 10/02/99

Reading No.	1	2	3	4	5	6	7	8	Av. Depth of Wear (mm)
Initial	-0.70	-0.36	0.06	0.00	-0.05	-0.17	-0.09	-0.02	
Final (15 min)	1.28	0.95	0.53	0.18	0.10	0.09	0.16	0.17	
Depth (mm)	1.98	1.31	0.47	0.18	0.15	0.26	0.25	0.19	0.60

Table C.3 (i) Abrasion resistance – Comparative tests

Specimen ID: Mix No. 1 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT
1	0.60	
2		0.29
3	0.44	
4		0.17
5	0.46	
6		0.24
7	0.45	
8		0.39
9	0.46	
10		0.32
11	0.42	
12		0.25
13	0.42	
14		0.35
15	0.48	
16		0.41
17	0.40	
Av. Depth of wear (mm)	0.46	0.30
M. Res.1985	0.48	

n_{AT}= 9
n_{CT}= 8
s_{AT}= 0.0585
s_{CT}= 0.0815
v_{AT}= 13 %
v_{CT}= 27 %

Specimen ID: Mix No. 2 (B4)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT
1	0.28	
2		0.17
3	0.29	
4		0.19
5	0.23	
6		0.18
7	0.35	
8		0.13
9	0.31	
10		0.15
11	0.27	
12		0.13
13		
14		0.22
15		
16		0.29
17	0.21	
18		0.17
Av. Depth of wear (mm)	0.28	0.18
M. Res.1985	0.30	

n_{AT}= 7
n_{CT}= 9
s_{AT}= 0.0483
s_{CT}= 0.0491
v_{AT}= 18 %
v_{CT}= 27 %

Specimen ID: Mix No. 3 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.26		
2		0.08	
3			0.17
4			0.31
5	0.21		
6		0.07	
7		0.17	
8			0.20
9	0.47		
10	0.45		
11			0.25
12		0.19	
13		0.20	
14	0.41		
15			0.21
16			0.22
17		0.11	
18	0.36		
Av. Depth of wear (mm)	0.36	0.14	0.22
M. Res. 1985	0.48		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.1058
s_{CT}= 0.0587
s_{BCAT}= 0.0480
v_{AT}= 29 %
v_{CT} 43 %
v_{BCAT}= 21 %

Specimen ID: Mix No. 4 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.64		
2		0.57	
3			0.39
4			0.39
5	0.51		
6		0.42	
7		0.23	
8			0.25
9	0.46		
10	0.67		
11			0.36
12		0.41	
13		0.52	
14	0.59		
15			0.40
16			0.40
17		0.54	
18	0.70		
Av. Depth of wear (mm)	0.59	0.45	0.36
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.0941
s_{CT}= 0.1238
s_{BCAT}= 0.0573
v_{AT}= 16 %
v_{CT} 28 %
v_{BCAT}= 16 %

AT = Aston Abrasion tester
CT = Chaplin Abrasion tester
BCAT = BCA Abrasion tester
NPF = Errut Model 600 power float
OPF = Fyne Model RT 9002 power float
SBS = Steel beam screeder
WF = Finished by the use of wooden hand-tamping beam

Table C.3 (ii) Abrasion resistance – Comparative tests

Specimen ID: Mix No. 5 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	1.12		
2		0.35	
3			0.21
4			0.69
5	0.24		
6		0.15	
7		0.01	
8			0.29
9	0.41		
10	0.46		
11			0.18
12		0.03	
13		0.14	
14	0.23		
15			0.17
16			0.48
17		0.00	
18	0.73		
Av. Depth of wear (mm)	0.53	0.11	0.34
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.3406
s_{CT}= 0.1350
s_{BCAT}= 0.2080
v_{AT}= 64 %
v_{CT}= 118 %
v_{BCAT}= 62 %

Specimen ID: Mix No. 6 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.28		
2		0.46	
3			0.19
4			0.35
5	0.54		
6		0.83	
7		0.11	
8			0.20
9	0.30		
10	0.33		
11			0.22
12		0.17	
13		0.44	
14	0.39		
15			0.22
16			0.07
17		0.30	
18	0.36		
Av. Depth of wear (mm)	0.37	0.38	0.21
M. Res. 1985	0.48		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.0957
s_{CT}= 0.2592
s_{BCAT}= 0.0917
v_{AT}= 26 %
v_{CT}= 67 %
v_{BCAT}= 44 %

Specimen ID: Mix No. 7 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.77		
2		1.41	
3			0.47
4			0.74
5	0.69		
6		0.34	
7		2.55	
8			0.72
9	0.58		
10	0.72		
11			0.66
12		1.41	
Av. Depth of wear (mm)	0.69	1.43	0.64
M. Res. 1985	0.66		

n_{AT}= 4
n_{CT}= 4
n_{BCAT}= 4
s_{AT} 0.0473
s_{CT}= 0.9040
s_{BCAT}= 0.1222
v_{AT}= 7 %
v_{CT} 63 %
v_{BCAT}= 19 %

Specimen ID: Mix No. 8 (B4)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.41		
2		0.31	
3			0.38
4			0.57
5	0.25		
6		0.30	
7		0.23	
8			0.27
9	0.44		
10	0.30		
11			0.11
12		0.10	
13		0.11	
14	0.25		
15			0.45
16			0.25
17		0.09	
18	0.58		
Av. Depth of wear (mm)	0.37	0.19	0.34
M. Res. 1985	0.30		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.1302
s_{CT}= 0.1039
s_{BCAT}= 0.1629
v_{AT}= 35 %
v_{CT}= 55 %
v_{BCAT}= 48 %

Table C.3 (iii) Abrasion resistance – Comparative tests

Specimen ID: Mix No. 9 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - WF

Test No.	AT	CT	BCAT
1	0.48		
2		0.69	
3			0.64
4			0.52
5	0.48		
6		0.55	
7		1.19	
8			0.51
9	0.65		
10	0.49		
11			0.63
12		0.77	
13		0.60	
14	0.46		
15			0.81
16			0.09
17		0.88	
18	0.48		
Av. Depth of wear (mm)	0.51	0.78	0.53
M. Res. 1985	0.48		

n_{AT} = 6
n_{CT} = 6
n_{BCAT} = 6
s_{AT} = 0.0700
s_{CT} = 0.2338
s_{BCAT} = 0.2438
v_{AT} = 14 %
v_{CT} = 30 %
v_{BCAT} = 46 %

Specimen ID: Mix No. 10 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.40		
2		0.24	
3			0.68
4			0.56
5	0.57		
6		0.31	
7		0.41	
8			0.59
9	0.38		
10	0.49		
11			0.15
12		0.36	
13		0.20	
14	0.26		
15			0.47
16			0.46
17		0.16	
18	0.46		
Av. Depth of wear (mm)	0.43	0.28	0.48
M. Res. 1985	0.48		

n_{AT} = 6
n_{CT} = 6
n_{BCAT} = 6
s_{AT} = 0.1056
s_{CT} = 0.0958
s_{BCAT} = 0.1837
v_{AT} = 25 %
v_{CT} = 34 %
v_{BCAT} = 38 %

Specimen ID: Mix No. 11 (B5)
Curing Conditions: Polythene Sheet
Finishing technique: OPF - SBS

Test No.	AT	CT	BCAT
1	0.66		
2		0.66	
3			0.46
4			0.77
5	0.44		
6		1.37	
7		1.41	
8			1.00
9	0.42		
10	0.73		
11			0.49
12		0.69	
13		0.67	
14	0.60		
15			0.96
16			0.38
17		1.16	
18	0.76		
Av. Depth of wear (mm)	0.60	0.99	0.68
M. Res. 1985	0.48		

n_{AT} = 6
n_{CT} = 6
n_{BCAT} = 6
s_{AT} = 0.1453
s_{CT} = 0.3585
s_{BCAT} = 0.2694
v_{AT} = 24 %
v_{CT} = 36 %
v_{BCAT} = 40 %

Specimen ID: Mix No. 12 (B4)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.32		
2		0.17	
3			0.17
4			0.17
5	0.28		
6		0.34	
7		0.32	
8			0.23
9	0.29		
10	0.31		
11			0.31
12		0.70	
13		0.61	
14	0.28		
15			0.35
16			0.29
17		0.49	
18	0.32		
Av. Depth of wear (mm)	0.30	0.44	0.25
M. Res. 1985	0.30		

n_{AT} = 6
n_{CT} = 6
n_{BCAT} = 6
s_{AT} = 0.0186
s_{CT} = 0.1979
s_{BCAT} = 0.0766
v_{AT} = 6 %
v_{CT} = 45 %
v_{BCAT} = 30 %

Table C.3 (iv) Abrasion resistance – Comparative tests

Specimen ID: Mix No. 13 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.77		
2		0.33	
3			0.47
4			0.50
5	0.56		
6		0.26	
7		0.34	
8			0.46
9	0.27		
10	0.47		
11			0.72
12		0.33	
13		0.35	
14	0.74		
15			0.67
16			0.44
17		0.33	
18	0.43		
Av. Depth of wear (mm)	0.54	0.32	0.54
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.1892
s_{CT}= 0.0294
s_{BCAT}= 0.1207
v_{AT}= 35 %
v_{CT}= 9 %
v_{BCAT}= 22 %

Specimen ID: Mix No. 14 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: OPF - SBS

Test No.	AT	CT	BCAT
1	0.84		
2		0.81	
3			0.62
4			0.35
5	0.67		
6		1.94	
7		1.10	
8			0.43
9	0.55		
10	0.95		
11			0.79
12		1.24	
13		2.58	
14	0.78		
15			0.51
16			0.91
17		2.01	
18	0.71		
Av. Depth of wear (mm)	0.75	1.61	0.60
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.1381
s_{CT}= 0.6681
s_{BCAT}= 0.2171
v_{AT}= 18 %
v_{CT}= 41 %
v_{BCAT}= 36 %

Specimen ID: Mix No. 15 (B4)
Curing Conditions: Polythene Sheet
Finishing technique: OPF - SBS

Test No.	AT	CT	BCAT
1	0.46		
2		0.45	
3			0.30
4			0.37
5	0.43		
6		0.27	
7		0.39	
8			0.31
9	0.48		
10	0.26		
11			0.43
12		0.14	
13		0.43	
14	0.42		
15			0.31
16			0.39
17		0.44	
18	0.35		
Av. Depth of wear (mm)	0.40	0.35	0.35
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.0814
s_{CT}= 0.1248
s_{BCAT}= 0.0512
v_{AT}= 20 %
v_{CT}= 35 %
v_{BCAT}= 15 %

Specimen ID: Mix No. 16 (B6)
Curing Conditions: Polythene Sheet
Finishing technique: NPF - SBS

Test No.	AT	CT	BCAT
1	0.88		
2		2.57	
3			0.54
4			0.79
5	0.80		
6		1.96	
7		1.43	
8			0.84
9	0.33		
10	0.64		
11			0.88
12		2.58	
13		2.08	
14	0.60		
15			0.33
16			0.54
17		1.59	
18	0.50		
Av. Depth of wear (mm)	0.62	2.04	0.65
M. Res. 1985	0.66		

n_{AT}= 6
n_{CT}= 6
n_{BCAT}= 6
s_{AT}= 0.2009
s_{CT}= 0.4809
s_{BCAT}= 0.2177
v_{AT}= 32 %
v_{CT}= 24 %
v_{BCAT}= 33 %

"Student – t" tests

Student–t tests for small samples:

$$t=\frac{m_1-m_2}{\sigma_e}\sqrt{\frac{n_1 n_2}{n_1+n_2}}$$

$$\sigma_e^2=\frac{n_1 s_1^2+n_2 s_2^2}{n_1+n_2-2}$$

$$s_1^2=\frac{1}{n_1}\sum_{1}^{n_1}(x-m_1)^2$$

$$s_2^2=\frac{1}{n_2}\sum_{1}^{n_2}(x-m_2)^2$$

Where: n_1 = number of reading 1

n_2 = number of readings 2

m_1 = mean of reading 1

m_2 = mean of reading 2

σ_e = estimated variance

s_1 = variance of reading 1

s_2 = variance of reading 2

The calculated "t" parameter is compared with the appropriate value from "student–t" tests tables to determine if there is significant difference between two sets of results (Paradine & Rivett, 1960 & 1970).

Table C.4 Summary of significance tests on AT, CT and BCAT

Machine 1	Machine 2	Sample ID	Mean m_1	Mean m_2	Variance s_1^2	Variance s_2^2	σ	t_{actual}	$t_{critical}$	Significant difference
AT	CT	1 – B5	0.4576	0.3022	0.0030	0.0058	0.0702	4.5600	2.1310	Yes
AT	CT	2 – B4	0.2750	0.1803	0.0236	0.0021	0.1148	1.6372	2.1450	No
AT	CT	3 – B5	0.3592	0.1350	0.0093	0.0029	0.0856	4.5381	2.2280	Yes
AT	BCAT	3 – B5	0.3592	0.2247	0.0093	0.0019	0.0822	2.8345	2.2280	Yes
CT	BCAT	3 – B5	0.1350	0.2247	0.0029	0.0019	0.0536	2.8996	2.2280	Yes
AT	CT	4 – B6	0.5931	0.4470	0.0056	0.0128	0.1050	2.4102	2.2280	Yes
AT	BCAT	4 – B6	0.5931	0.3648	0.0074	0.0027	0.0779	5.0778	2.2280	Yes
CT	BCAT	4 – B6	0.4470	0.3648	0.0128	0.0027	0.0965	1.4760	2.2280	No
AT	CT	5 – B6	0.5302	0.1144	0.0967	0.0152	0.2591	2.7796	2.2280	Yes
AT	BCAT	5 – B6	0.5302	0.3354	0.0967	0.0361	0.2822	1.1955	2.2280	No
CT	BCAT	5 – B6	0.1144	0.3354	0.0152	0.0361	0.1753	2.1829	2.2280	No
AT	CT	6 – B5	0.3659	0.3844	0.0076	0.0560	0.1954	0.1638	2.2280	No
AT	BCAT	6 – B5	0.3659	0.2081	0.0076	0.0070	0.0937	2.9164	2.2280	Yes
CT	BCAT	6 – B5	0.3844	0.2081	0.0560	0.0070	0.1944	1.5704	2.2280	No
AT	CT	7 – B6	0.6888	1.4266	0.0050	0.6129	0.6418	1.6257	2.4470	No
AT	BCAT	7 – B 6	0.6888	0.6447	0.0050	0.0112	0.1040	0.5990	2.4470	No
CT	BCAT	7 – B6	1.4266	0.6447	0.6129	0.0112	0.6450	1.7142	2.4470	No
AT	CT	8 – B4	0.3708	0.1875	0.0141	0.0090	0.1178	2.6964	2.2280	Yes
AT	BCAT	8 – B4	0.3708	0.3369	0.0141	0.0221	0.1475	0.3988	2.2280	No
CT	BCAT	8 – B4	0.1875	0.3369	0.0090	0.0221	0.1366	1.8935	2.2280	No
AT	CT	9 – B5	0.5075	0.7796	0.0041	0.0455	0.1725	2.7313	2.2280	Yes
AT	BCAT	9 – B5	0.5075	0.5317	0.0041	0.0496	0.1794	0.2333	2.2280	No
CT	BCAT	9 – B5	0.7796	0.5317	0.0455	0.0496	0.2389	1.7978	2.2280	No
AT	CT	10 – B5	0.4260	0.2792	0.0093	0.0077	0.1008	2.5226	2.2280	Yes
AT	BCAT	10 – B5	0.4260	0.4848	0.0093	0.0281	0.1498	0.6791	2.2280	No
CT	BCAT	10 – B5	0.2792	0.4848	0.0077	0.0281	0.1465	2.4308	2.2280	Yes
AT	CT	11 – B5	0.6017	0.9930	0.0176	0.1071	0.2735	2.4777	2.2280	Yes
AT	BCAT	11 – B5	0.6017	0.6760	0.0176	0.0605	0.2164	0.5953	2.2280	No
CT	BCAT	11 – B5	0.9930	0.6760	0.1071	0.0605	0.3171	1.7312	2.2280	No
AT	CT	12 – B4	0.2981	0.4388	0.0003	0.0326	0.1405	1.7331	2.2280	No
AT	BCAT	12 – B4	0.2981	0.2525	0.0003	0.0049	0.0557	1.4183	2.2280	No
CT	BCAT	12 – B4	0.4388	0.2525	0.0326	0.0049	0.1500	2.1502	2.2280	No
AT	CT	13 – B6	0.5405	0.3215	0.0298	0.0007	0.1354	2.8015	2.2280	Yes
AT	BCAT	13 – B6	0.5405	0.5427	0.0298	0.0121	0.1587	0.0241	2.2280	No
CT	BCAT	13 – B6	0.3215	0.5427	0.0007	0.0121	0.0879	4.3615	2.2280	Yes
AT	CT	14 – B6	0.7492	1.6108	0.0159	0.3720	0.4824	3.0937	2.2280	Yes
AT	BCAT	14 – B6	0.7492	0.5998	0.0159	0.0393	0.1819	1.4222	2.2280	No
CT	BCAT	14 – B6	1.6108	0.5998	0.3720	0.0393	0.4967	3.5253	2.2280	Yes
AT	CT	15 – B4	0.4009	0.3529	0.0055	0.0130	0.1053	0.7889	2.2280	No
AT	BCAT	15 – B4	0.4009	0.3513	0.0055	0.0022	0.0680	1.2644	2.2280	No
CT	BCAT	15 – B4	0.3529	0.3513	0.0130	0.0022	0.0954	0.0303	2.2280	No
AT	CT	16 – B6	0.6213	2.0353	0.0336	0.1927	0.3685	6.6457	2.2280	Yes
AT	BCAT	16 – B6	0.6213	0.6540	0.0336	0.0395	0.2095	0.2704	2.2280	No
CT	BCAT	16 – B6	2.0353	0.6540	0.1927	0.0395	0.3733	6.4096	2.2280	Yes

Table C.5 *Summary of significance tests on sensitivity of AT, CT and BCAT to different mix designs*

Mix 1	Mix 2	Machine	Mean m_1	Mean m_2	Variance s_1^2	Variance s_2^2	σ	t_{actual}	$t_{critical}$	Significant difference
B4	B5	AT	0.3147	0.4022	0.0017	0.0017	0.0486	2.3578	2.5710	No
B4	B6	AT	0.3147	0.5948	0.0017	0.0033	6.3847	6.3847	2.5710	Yes
B6	B5	AT	0.5948	0.4022	0.0033	0.0017	4.9585	4.9585	2.5710	Yes
B4	B5	CT	0.2688	0.2752	0.0144	0.0081	0.1230	0.0675	2.5710	No
B4	B6	CT	0.2688	0.8689	0.0144	0.5437	0.6784	1.2112	2.5710	No
B6	B5	CT	0.8689	0.2752	0.5437	0.0081	0.6269	1.4120	2.5710	No
B4	B5	BCAT	0.2947	0.3059	0.0018	0.0120	0.1137	0.1137	2.7760	No
B4	B6	BCAT	0.2947	0.5083	0.0018	0.0640	0.2544	1.0037	2.7760	No
B6	B5	BCAT	0.5083	0.3059	0.0640	0.0120	0.2293	1.3159	2.7760	No

Appendix D: Standard letters

ASTON UNIVERSITY
BIRMINGHAM

SCHOOL OF ENGINEERING & APPLIED SCIENCE

Civil Engineering

Aston Triangle
Birmingham
B4 7ET
United Kingdom

Tel. +44 (0) 121 359 3611
Fax. +44 (0) 121 333 3389

LETTER A

Dear Sir or Madam,

Our research group at Aston University is currently conducting an experimental research, which is targeted at the role of fibres in controlling/influencing, the abrasion resistance of concrete floors. The study is at the initial stages and I therefore seek information on the different kinds of fibres that are presently used in the industry.

I am certain that the above study will be both beneficial to the industry and to the academic world. Any relevant information provided from your company will be appreciated and your help will be acknowledged. In the future I will keep you informed with the progress of the research.

I look forward to hearing from you in the near future.

Yours faithfully,

Vassoulla Vassou

ASTON UNIVERSITY
BIRMINGHAM

SCHOOL OF ENGINEERING & APPLIED SCIENCE

Civil Engineering

Aston Triangle
Birmingham
B4 7ET
United Kingdom

Tel. +44 (0) 121 359 3611
Fax. +44 (0) 121 333 3389

LETTER B

Dear Sir or Madam,

Further to our telephone conversation this morning, I am writing to inform you that our research group at Aston University is currently conducting experimental research which is targeted at the role of fibres in controlling/influencing the abrasion resistance of concrete floors. To the best of our knowledge research evidence on this subject is not readily available. In addition the research undertaken on this area has so far been industrially funded and we therefore we have reason to believe that the results may be biased, which is why we decided to undertake this project. The study is at the initial stages and I therefore seek information on the different types of fibres that are presently available in the industry. Further, even though the experimental project is carried out in the laboratory, we try, wherever possible, to apply the conditions that exist in the industry. I would therefore be very grateful if you could provide information on the following:

- Which fibres are most commonly used for the construction of concrete floors?
- Which are the most popular fibres in terms of metallic and non-metallic nature?
- Which is/are the most popular mix design(s)?
- Is there a need to use a plasticiser in order to modify the workability? and
- Which methods are currently used in the industry for the addition of fibres into the concrete?

In addition, I would appreciate it if you could provide us with some samples for testing. I am certain that the present study will be both beneficial to the industry and to the academic world. Any relevant information provided from your company will be appreciated and your help will be acknowledged. In the future I will keep you informed with the progress of the research.

I look forward to hearing from you as soon as possible.

Yours sincerely,

Ms Vassoulla Vassou.

Appendix E: Macro-study of fibre reinforced concrete

Table E.1 Compressive strength results

No	Sample ID *	Mean crushing strength (N/mm^2)			Mean compressive strength (N/mm^2)
		Cube No.1	Cube No.2	Cube No.3	
1	B4	60.00	60.00	60.00	60.00
2	B5	49.00	49.40	62.00	53.47
3	B6	41.00	40.00	45.00	42.00
4	A1, s/c, 0.51 % - 45 mm	68.00	62.00	63.00	64.33
5	A2, s/c, 0.51% - 45 mm	55.00	59.00	52.00	55.33
6	A3, s/c, 0.51 % - 45 mm	44.00	46.00	46.20	45.40
7	A2, s/c, 1.0 % - 45 mm	60.20	60.00	60.00	60.07
8	A2, s/c, 1.5 % - 45 mm	55.00	55.00	55.00	55.00
9	A2, s/c, 2.0 % - 45 mm	49.20	53.00	52.00	51.40
10	A2, s/c, 3.0 % - 45 mm	49.00	52.00	48.00	49.67
11	A2, s/t, 0.51 % - 32 mm	55.40	55.60	55.20	55.40
12	A2, s/t, 1.0 % - 32 mm	60.00	60.00	60.00	60.00
13	A2, s/t, 1.5 % - 32 mm	55.00	58.00	56.00	56.33
14	A2, s/t, 2.0 % - 32 mm	53.00	55.00	53.00	53.67
15	A2, s/fe, 0.51 % - 30 mm	57.00	62.00	57.00	58.67
16	A2, s/fe, 1.0 % - 30 mm	62.00	61.00	63.00	62.00
17	A2, s/fe, 1.5 % - 30 mm	62.00	61.00	61.00	61.33
18	A2, s/fe, 2.0 % - 30 mm	58.00	61.00	57.00	58.67
19	A2, s/s, 0.51% - 35 mm	57.00	59.00	59.00	58.33
20	A2, s/s, 2.0% - 35 mm	54.00	56.00	68.00	59.33
21	A2, p, 0.1 % - 12 mm	58.00	60.00	55.00	57.67
22	A2, p, 0.51 % - 12 mm	57.00	50.00	57.00	54.67
23	A2, sp, 0.1 % - 12.5, 60 mm	56.00	53.00	56.00	55.00
24	A2, sp, 0.5 % - 12.5, 60 mm	50.00	52.00	52.00	51.33
25	A2, HP, 0.04 % - 12 mm	58.00	57.00	54.00	56.33
26	A2, HP, 0.21 % - 12 mm	50.00	54.00	44.00	49.33
27	A2, HP, 0.41 % - 12 mm	48.00	49.00	48.00	48.33
28	A2, HP, 0.83 % - 12 mm	45.00	49.00	48.00	47.33
29	A2, HD, 0.02 % - 12 mm	49.00	47.00	49.00	48.33
30	A2, GSF, 0.54 % - 50 mm	47.30	46.10	47.10	46.83
31	A2, s/c, 0.26% - 45 mm	43.00	56.50	55.50	51.67
32	A2, s/c, 0.51% - 45 mm	52.00	57.00	58.50	55.83
33	A2, s/c, 0.26% - 50 mm	53.00	48.00	49.50	50.17
34	A2, s/c, 0.51% - 50 mm	55.00	55.00	52.00	50.17
35	A2, s/c, 0.26% - 60 mm	45.50	45.50	46.00	45.67
36	A2, s/c, 0.51% - 60 mm	57.00	54.50	55.50	55.67
37	A2, s/c, 0.51% - 60 mm	48.00	48.00	46.60	47.53
38	A2, s/c, 0.64% - 60 mm	54.00	55.00	57.00	55.33
39	A2, s/c, 2.0 % - 45 mm - SP: 0.25 %	36.80	38.00	38.80	37.87
40	A2, s/c, 2.0 % - 45 mm - SP: 0.50 %	35.40	44.80	47.60	42.60
41	A2, s/c, 2.0 % - 45 mm - SP: 0.75 %	39.20	44.20	46.00	43.13

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table E.2 *Summary of significance tests on sensitivity of the abrasion resistance test to mix variation and fibre inclusion for samples cured in polythene sheeting (PS)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.2204	0.1085	0.0108	0.0031	2.1230	2.2280	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.2204	0.4986	0.0108	0.0155	3.8378	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1085	0.4986	0.0031	0.0155	6.4071	2.2280	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.2204	0.2904	0.0108	0.0054	1.2307	2.2280	No
A2, s/c, 0.51 % - 45 mm	B5	0.1085	0.4404	0.0031	0.0142	5.6514	2.2280	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.4986	0.6104	0.0155	0.0075	1.6513	2.2280	No
B4	B5	0.2904	0.4404	0.0054	0.0142	2.3998	2.2280	Yes
B4	B6	0.2904	0.6104	0.0054	0.0075	6.3168	2.2280	Yes
B5	B6	0.4404	0.6104	0.0142	0.0075	2.5842	2.2280	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.3 *Summary of significance tests on sensitivity of the abrasion resistance test to mix variation and fibre inclusion for samples cured with curing compound (CC)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.1704	0.1538	0.0141	0.0118	0.2315	2.2280	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1704	0.5871	0.0141	0.0051	6.7300	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1538	0.5871	0.0118	0.0051	7.4447	2.2280	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.1704	0.3152	0.0141	0.0049	2.3493	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.1538	0.4585	0.0118	0.0064	5.0467	2.2280	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.5871	0.6355	0.0051	0.0172	0.7254	2.2280	No
B4	B5	0.3152	0.4585	0.0049	0.0064	3.0141	2.2280	Yes
B4	B6	0.3152	0.6355	0.0049	0.0172	4.8194	2.2280	Yes
B5	B6	0.4585	0.6355	0.0064	0.0172	2.5781	2.2280	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.4 *Summary of significance tests on sensitivity of the abrasion resistance test to mix variation and fibre inclusion for samples cured in air (AC)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.3160	0.1651	0.0020	0.0050	4.0322	2.2280	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.3160	0.7754	0.0020	0.0541	4.3360	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1651	0.7754	0.0050	0.0541	5.6098	2.2280	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.3160	0.7263	0.0020	0.0309	5.0576	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.1651	0.7927	0.0050	0.0057	13.5358	2.2280	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.7754	0.9458	0.0541	0.0235	1.3671	2.2280	No
B4	B5	0.7263	0.7927	0.0309	0.0057	0.7764	2.2280	No
B4	B6	0.7263	0.9458	0.0309	0.0235	2.1038	2.2280	No
B5	B6	0.7927	0.9458	0.0057	0.0235	2.0016	2.2280	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E 5 *Summary of significance tests on sensitivity of the abrasion resistance test to different curing regimes of selected mixes*

Specimen ID*	Curing		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
	1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	PS	AC	0.2204	0.3160	0.0108	0.0020	1.8911	2.2280	No
A1, s/c, 0.51 % - 45 mm	PS	CC	0.2204	0.1704	0.0108	0.0141	0.7087	2.2280	No
A1, s/c, 0.51 % - 45 mm	AC	CC	0.3160	0.1704	0.0020	0.0141	2.5707	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	PS	AC	0.1085	0.1651	0.0031	0.0050	1.4033	2.2280	No
A2, s/c, 0.51 % - 45 mm	PS	CC	0.1085	0.1538	0.0031	0.0118	0.8276	2.2280	No
A2, s/c, 0.51 % - 45 mm	AC	CC	0.1651	0.1538	0.0050	0.0118	0.1947	2.2280	No
A3, s/c, 0.51 % - 45 mm	PS	AC	0.4986	0.7754	0.0155	0.0541	2.3461	2.2280	Yes
A3, s/c, 0.51 % - 45 mm	PS	CC	0.4986	0.5871	0.0155	0.0051	1.3801	2.2280	No
A3, s/c, 0.51 % - 45 mm	AC	CC	0.7754	0.5871	0.0541	0.0051	1.7302	2.2280	No
B4	PS	AC	0.2904	0.7263	0.0054	0.0309	5.1162	2.2280	Yes
B4	PS	CC	0.2904	0.3152	0.0054	0.0049	0.5467	2.2280	No
B4	AC	CC	0.7263	0.3152	0.0309	0.0049	4.8551	2.2280	Yes
B5	PS	AC	0.4404	0.7927	0.0142	0.0057	5.5867	2.2280	Yes
B5	PS	CC	0.4404	0.4585	0.0142	0.0064	0.2827	2.2280	Yes
B5	AC	CC	0.7927	0.4585	0.0057	0.0064	6.7928	2.2280	Yes
B6	PS	AC	0.6104	0.9458	0.0075	0.0235	4.2586	2.2280	Yes
B6	PS	CC	0.6104	0.6355	0.0075	0.0172	0.3571	2.2280	No
B6	AC	CC	0.9458	0.6355	0.0235	0.0172	3.4394	2.2280	Yes
A2, s/c, 1.0 % - 45 mm	PS	AC	0.2890	0.4828	0.0018	0.0062	6.1299	2.1200	Yes
A2, s/c, 1.5 % - 45 mm	PS	AC	0.3464	0.5004	0.0053	0.0144	3.1098	2.1200	Yes
A2, s/c, 2.0 % - 45 mm	PS	AC	0.3949	0.6974	0.0220	0.0106	4.7423	2.1200	Yes
A2, s/c, 3.0 % - 45 mm	PS	AC	0.4428	0.9351	0.0050	0.0627	5.3512	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	PS	AC	0.1221	0.2452	0.0020	0.0088	3.3639	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	PS	AC	0.2040	0.3583	0.0071	0.0052	3.9357	2.1200	Yes
A2, s/t, 1.5 % - 32 mm	PS	AC	0.2524	0.7039	0.0063	0.0600	4.9589	2.1200	Yes
A2, s/t, 2.0 % - 32 mm	PS	AC	0.4225	0.7158	0.0171	0.0069	5.3615	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	PS	AC	0.1243	0.3732	0.0038	0.0112	5.7355	2.1200	Yes
A2, s/fe, 1.0 % - 30 mm	PS	AC	0.2004	0.4576	0.0047	0.0313	3.8374	2.1200	Yes
A2, s/fe, 1.5 % - 30 mm	PS	AC	0.2504	0.4774	0.0036	0.0131	4.9646	2.1200	Yes
A2, s/fe, 2.0 % - 30 mm	PS	AC	0.3058	0.5790	0.0428	0.0126	3.2816	2.1200	Yes
A2, s/s, 0.51 % - 35 mm	PS	AC	0.1222	0.4664	0.0023	0.0027	13.6978	2.1200	Yes
A2, s/s, 2.0 % - 35 mm	PS	AC	0.3608	0.4851	0.0027	0.0292	1.9689	2.1200	No
A2, p, 0.1 % - 12 mm	PS	AC	0.0646	0.2500	0.0002	0.0036	8.5001	2.1200	Yes
A2, p, 0.51 % - 12 mm	PS	AC	0.1551	0.2600	0.0077	0.0083	2.3413	2.1200	Yes
A2, sp, 0.1 % - 12.5, 60 mm	PS	AC	0.1222	0.2760	0.0023	0.0156	3.2520	2.1200	Yes
A2, sp, 0.51 % - 12.5, 60 mm	PS	AC	0.3744	0.5817	0.0067	0.0164	3.8557	2.1200	Yes
A2, s/c, 0.51 % - 60 mm	PS	AC	0.4436	0.6614	0.0091	0.0119	4.2529	2.1200	Yes
A2, s/c, 0.64 % - 60 mm	PS	AC	0.3621	0.6513	0.0165	0.0881	2.5290	2.1200	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.6 *Summary of significance tests on sensitivity of the abrasion resistance test to steel fibre shape and volume for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.1085	0.2890	0.0031	0.0018	6.6066	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.1085	0.3464	0.0031	0.0053	6.3486	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.1085	0.3949	0.0031	0.0220	4.2118	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1085	0.4428	0.0031	0.0050	9.0691	2.1600	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.2890	0.3464	0.0018	0.0053	1.9278	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.2890	0.3949	0.0018	0.0220	1.9397	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.2890	0.4428	0.0018	0.0050	5.2554	2.1200	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.3464	0.3949	0.0053	0.0220	0.8308	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.3464	0.4428	0.0053	0.0050	2.6909	2.1200	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.3949	0.4428	0.0220	0.0050	0.8248	2.1200	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.1221	0.2040	0.0020	0.0071	2.4413	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.1221	0.2524	0.0020	0.0063	4.0480	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.1221	0.4225	0.0020	0.0171	6.1628	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.2040	0.2524	0.0071	0.0063	1.1816	2.1200	No
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.2040	0.4225	0.0071	0.0171	3.9797	2.1200	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.2524	0.4225	0.0063	0.0171	3.1470	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.1243	0.2004	0.0038	0.0047	2.3314	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.1243	0.2504	0.0038	0.0036	4.1280	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1243	0.3058	0.0038	0.0428	2.3770	2.1200	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.2004	0.2504	0.0047	0.0036	1.5523	2.1200	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.2004	0.3058	0.0047	0.0428	1.3682	2.1200	No
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.2504	0.3058	0.0036	0.0428	0.7274	2.1200	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.1222	0.3608	0.0023	0.0027	9.5089	2.1200	Yes
B5	A2, s/c, 0.51 % - 45 mm	0.4404	0.1085	0.0142	0.0031	5.6514	2.2280	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.4404	0.2890	0.0142	0.0018	3.2505	2.1600	Yes
B5	A2, s/c, 1.5 % - 45 mm	0.4404	0.3464	0.0142	0.0053	1.7687	2.1600	No
B5	A2, s/c, 2.0 % - 45 mm	0.4404	0.3949	0.0142	0.0220	0.5860	2.1600	No
B5	A2, s/c, 3.0 % - 45 mm	0.4404	0.4428	0.0142	0.0050	0.0448	2.1600	No
B5	A2, s/t, 0.51 % - 32 mm	0.4404	0.1221	0.0142	0.0020	6.7977	2.1600	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.4404	0.2040	0.0142	0.0071	4.1961	2.1600	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.4404	0.2524	0.0142	0.0063	3.4142	2.1600	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.4404	0.4225	0.0142	0.0171	0.2510	2.1600	No
B5	A2, s/fe, 0.51 % - 30 mm	0.4404	0.1243	0.0142	0.0038	6.2522	2.1600	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.4404	0.2004	0.0142	0.0047	4.6046	2.1600	Yes
B5	A2, s/fe, 1.5 % - 30 mm	0.4404	0.2504	0.0142	0.0036	3.7903	2.1600	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.4404	0.3058	0.0142	0.0428	1.3425	2.1600	No
B5	A2, s/s, 0.51 % - 35 mm	0.4404	0.1222	0.0142	0.0023	6.6931	2.1600	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.4404	0.3608	0.0142	0.0027	1.6445	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.1085	0.1221	0.0031	0.0020	0.4879	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.1085	0.1243	0.0031	0.0038	0.4682	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.1085	0.1222	0.0031	0.0023	0.4728	2.1600	No
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.1221	0.1243	0.0020	0.0038	0.0825	2.1200	No
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.1221	0.1222	0.0020	0.0023	0.0060	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.1243	0.1222	0.0038	0.0023	0.0751	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.2890	0.2040	0.0018	0.0071	2.5500	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.2890	0.2004	0.0018	0.0047	3.1056	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.2040	0.2004	0.0071	0.0047	0.0943	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.3464	0.2524	0.0053	0.0063	2.4715	2.1200	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.3464	0.2504	0.0053	0.0036	2.8822	2.1200	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.2524	0.2504	0.0063	0.0036	0.0551	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.3949	0.4225	0.0220	0.0171	0.3957	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.3949	0.3058	0.0220	0.0428	0.9893	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.3949	0.3608	0.0220	0.0027	0.6122	2.1200	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.4225	0.3058	0.0171	0.0428	1.3487	2.1200	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.4225	0.3608	0.0171	0.0027	1.2400	2.1200	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.3058	0.3608	0.0428	0.0027	0.7290	2.1200	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.7 *Summary of significance tests on sensitivity of the abrasion resistance test to steel fibre shape and volume for samples cured in air*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.1651	0.4828	0.0050	0.0062	7.4256	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.1651	0.5004	0.0050	0.0144	5.7425	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.1651	0.6974	0.0050	0.0106	10.2829	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1651	0.9351	0.0050	0.0627	6.8317	2.1600	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.4828	0.5004	0.0062	0.0144	0.3473	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.4828	0.6974	0.0062	0.0106	4.6909	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.4828	0.9351	0.0062	0.0627	4.8748	2.1200	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.5004	0.6974	0.0144	0.0106	3.5272	2.1200	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.5004	0.9351	0.0144	0.0627	4.4286	2.1200	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.6974	0.9351	0.0106	0.0627	2.4838	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.2452	0.3583	0.0088	0.0052	2.7029	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.2452	0.7039	0.0088	0.0600	4.9471	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.2452	0.7158	0.0088	0.0069	10.6371	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.3583	0.7039	0.0052	0.0600	3.8266	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.3583	0.7158	0.0052	0.0069	9.1795	2.1200	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.7039	0.7158	0.0600	0.0069	0.1306	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.3732	0.4576	0.0112	0.0313	1.1581	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.3732	0.4774	0.0112	0.0131	1.8885	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.3732	0.5790	0.0112	0.0126	3.7683	2.1200	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.4576	0.4774	0.0313	0.0131	0.2648	2.1200	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.4576	0.5790	0.0313	0.0126	1.6387	2.1200	No
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.4774	0.5790	0.0131	0.0126	1.7926	2.1200	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.4664	0.4851	0.0027	0.0292	0.2969	2.1200	No
B5	A2, s/c, 0.51 % - 45 mm	0.7927	0.1651	0.0057	0.0050	13.5358	2.2280	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.7927	0.4828	0.0057	0.0062	7.0767	2.1600	Yes
B5	A2, s/c, 1.5 % - 45 mm	0.7927	0.5004	0.0057	0.0144	4.9429	2.1600	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.7927	0.6974	0.0057	0.0106	1.8120	2.1600	No
B5	A2, s/c, 3.0 % - 45 mm	0.7927	0.9351	0.0057	0.0627	1.2593	2.1600	No
B5	A2, s/t, 0.51 % - 32 mm	0.7927	0.2452	0.0057	0.0088	11.1337	2.1600	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.7927	0.3583	0.0057	0.0052	10.4127	2.1600	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.7927	0.7039	0.0057	0.0600	0.8018	2.1600	No
B5	A2, s/t, 2.0 % - 32 mm	0.7927	0.7158	0.0057	0.0069	1.6946	2.1600	No
B5	A2, s/fe, 0.51 % - 30 mm	0.7927	0.3732	0.0057	0.0112	7.8019	2.1600	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.7927	0.4576	0.0057	0.0313	4.0799	2.1600	Yes
B5	A2, s/fe, 1.5 % - 30 mm	0.7927	0.4774	0.0057	0.0131	5.5308	2.1600	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.7927	0.5790	0.0057	0.0126	3.7999	2.1600	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.7927	0.4664	0.0057	0.0027	9.1925	2.1600	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.7927	0.4851	0.0057	0.0292	3.8630	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.1651	0.2452	0.0050	0.0088	1.6604	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.1651	0.3732	0.0050	0.0112	3.9311	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.1651	0.4664	0.0050	0.0027	8.7953	2.1600	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.2452	0.3732	0.0088	0.0112	2.5607	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.2452	0.4664	0.0088	0.0027	5.8305	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.3732	0.4664	0.0112	0.0027	2.2293	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.4828	0.3583	0.0062	0.0052	3.2971	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.4828	0.4576	0.0062	0.0313	0.3681	2.1200	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.3583	0.4576	0.0052	0.0313	1.4701	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.5004	0.7039	0.0144	0.0600	2.1103	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.5004	0.4774	0.0144	0.0131	0.3934	2.1200	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.7039	0.4774	0.0600	0.0131	2.3699	2.1200	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.6974	0.7158	0.0106	0.0069	0.3944	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.6974	0.5790	0.0106	0.0126	2.1976	2.1200	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.6974	0.4851	0.0106	0.0292	3.0119	2.1200	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.7158	0.5790	0.0069	0.0126	2.7690	2.1200	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.7158	0.4851	0.0069	0.0292	3.4367	2.1200	Yes
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.5790	0.4851	0.0126	0.0292	1.2990	2.1200	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.8 *Summary of significance tests on sensitivity of the abrasion resistance test to fibre type and volume for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
B5	A2, p, 0.1 % - 12 mm	0.4404	0.0646	0.0142	0.0002	8.7058	2.1600	Yes
B5	A2, p, 0.51 % - 12 mm	0.4404	0.1551	0.0142	0.0077	4.9608	2.1600	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.4404	0.1222	0.0142	0.0023	6.7087	2.1600	Yes
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.4404	0.3744	0.0142	0.0067	1.1849	2.1600	No
B5	A2, HP, 0.04 % - 12 mm	0.4404	0.2517	0.0142	0.0012	4.1779	2.1600	Yes
B5	A2, HP, 0.21 % - 12 mm	0.4404	0.3043	0.0142	0.0008	3.0610	2.1600	Yes
B5	A2, HP, 0.41 % - 12 mm	0.4404	0.3732	0.0142	0.0025	1.4016	2.1600	No
B5	A2, HP, 0.83 % - 12 mm	0.4404	0.4032	0.0142	0.0055	0.6943	2.1600	No
B5	A2, HD, 0.02 % - 12 mm	0.4404	0.4544	0.0142	0.0059	0.2584	2.1600	No
B5	A2, GSF, 0.54 % - 50 mm	0.4404	0.4142	0.0142	0.0061	0.4798	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, p, 0.1 % - 12 mm	0.1085	0.0646	0.0031	0.0002	2.0934	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, p, 0.51 % - 12 mm	0.1085	0.1551	0.0031	0.0077	1.0735	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.1085	0.1222	0.0031	0.0023	0.4758	2.1600	No
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.1085	0.3744	0.0031	0.0067	6.4923	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.04 % - 12 mm	0.1085	0.2517	0.0031	0.0012	5.7617	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.21 % - 12 mm	0.1085	0.3043	0.0031	0.0008	8.3133	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.41 % - 12 mm	0.1085	0.3732	0.0031	0.0025	8.9439	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.83 % - 12 mm	0.1085	0.4032	0.0031	0.0055	7.7345	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, HD, 0.02 % - 12 mm	0.1085	0.4544	0.0031	0.0059	8.8619	2.1600	Yes
A2, s/c, 0.51 % - 45 mm	A2, GSF, 0.54 % - 50 mm	0.1085	0.4142	0.0031	0.0061	7.7113	2.1600	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.0646	0.1551	0.0002	0.0077	2.8646	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, GSF, 0.54 % - 50 mm	0.0646	0.4142	0.0002	0.0061	12.3943	2.1200	Yes
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.1222	0.3744	0.0023	0.0067	7.5511	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.21 % - 12 mm	0.2517	0.3043	0.0012	0.0008	3.3288	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.2517	0.3732	0.0012	0.0025	5.6750	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.2517	0.4032	0.0012	0.0055	5.2501	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.2517	0.4544	0.0012	0.0059	6.8361	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.3043	0.3732	0.0008	0.0025	3.3725	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.3043	0.4032	0.0008	0.0055	3.5146	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.3043	0.4544	0.0008	0.0059	5.1845	2.1200	Yes
A2, HP, 0.41 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.3732	0.4032	0.0025	0.0055	0.9476	2.1200	No
A2, HP, 0.41 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.3732	0.4544	0.0025	0.0059	2.5096	2.1200	Yes
A2, HP, 0.83 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.4032	0.4544	0.0055	0.0059	1.3593	2.1200	No
A2, p, 0.1 % - 12 mm	A2, HP, 0.04 % - 12 mm	0.0646	0.2517	0.0002	0.0012	14.1119	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.21 % - 12 mm	0.0646	0.3043	0.0002	0.0008	20.6363	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.0646	0.3732	0.0002	0.0025	16.6467	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.0646	0.4032	0.0002	0.0055	12.6382	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.0646	0.4544	0.0002	0.0059	14.0973	2.1200	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.9 Summary of significance tests on sensitivity of the abrasion resistance test to steel fibre length and volume for samples cured in polythene sheeting

Specimen ID* 1	Specimen ID* 2	Mean m_2	Mean m_2	Variance s_1^2	Variance s_2^2	t_{actual}	$t_{critical}$	Significant difference
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.51 % - 45 mm (a)	0.3032	0.1085	0.0019	0.0031	7.0677	2.1600	Yes
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.51 % - 45 mm (b)	0.3032	0.1814	0.0019	0.0015	5.8834	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 45 mm (b)	0.1085	0.1814	0.0031	0.0015	2.7757	2.1600	Yes
A2, s/c, 0.26 % - 50 mm	A2, s/c, 0.51 % - 50 mm	0.4000	0.3727	0.0062	0.0036	0.7801	2.1200	No
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.51 % - 60 mm (a)	0.5234	0.4436	0.0044	0.0091	1.9464	2.1200	No
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.51 % - 60 mm (b)	0.5234	0.4518	0.0044	0.0108	1.6421	2.1200	No
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.64 % - 60 mm	0.5234	0.3621	0.0044	0.0165	3.1594	2.1200	Yes
A2, s/c, 0.51 % - 60 mm (a)	A2, s/c, 0.51 % - 60 mm (b)	0.4436	0.4518	0.0091	0.0108	0.1644	2.1200	No
A2, s/c, 0.51 % - 60 mm (a)	A2, s/c, 0.64 % - 60 mm	0.4436	0.3621	0.0091	0.0165	1.4433	2.1200	No
A2, s/c, 0.51 % - 60 mm (b)	A2, s/c, 0.64 % - 60 mm	0.4518	0.3621	0.0108	0.0165	1.5363	2.1200	No
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.26 % - 50 mm	0.3032	0.4000	0.0019	0.0062	3.0439	2.1200	Yes
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.26 % - 60 mm	0.3032	0.5234	0.0019	0.0044	7.8610	2.1200	Yes
A2, s/c, 0.26 % - 50 mm	A2, s/c, 0.26 % - 60 mm	0.4000	0.5234	0.0062	0.0044	3.3932	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 50 mm	0.1085	0.3727	0.0031	0.0036	8.0027	2.1600	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 60 mm (a)	0.1085	0.4436	0.0031	0.0091	7.2511	2.1600	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 60 mm (b)	0.1085	0.4518	0.0031	0.0108	6.9014	2.1600	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 50 mm	0.1814	0.3727	0.0138	0.0036	4.1007	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 60 mm (a)	0.1814	0.4436	0.0138	0.0091	4.9068	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 60 mm (b)	0.1814	0.4518	0.0138	0.0108	4.8757	2.1200	Yes
A2, s/c, 0.51 % - 50 mm	A2, s/c, 0.51 % - 60 mm (a)	0.3727	0.4436	0.0234	0.0091	1.1135	2.1200	No
A2, s/c, 0.51 % - 50 mm	A2, s/c, 0.51 % - 60 mm (b)	0.3727	0.4518	0.0234	0.0108	1.2098	2.1200	No
B5	A2, s/c, 0.26 % - 45 mm	0.4404	0.3032	0.0142	0.0019	2.9381	2.1600	Yes
B5	A2, s/c, 0.51 % - 45 mm (a)	0.4404	0.1085	0.0142	0.0031	5.6514	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm (b)	0.4404	0.1814	0.0142	0.0015	5.6370	2.1600	Yes
B5	A2, s/c, 0.26 % - 50 mm	0.4404	0.4000	0.0142	0.0062	0.7369	2.1600	No
B5	A2, s/c, 0.51 % - 50 mm	0.4404	0.3727	0.0142	0.0036	1.3514	2.1600	No
B5	A2, s/c, 0.26 % - 60 mm	0.4404	0.5234	0.0142	0.0044	1.6088	2.1600	No
B5	A2, s/c, 0.51 % - 60 mm (a)	0.4404	0.4518	0.0142	0.0091	0.0536	2.1600	No
B5	A2, s/c, 0.51 % - 60 mm (b)	0.4404	0.4518	0.0142	0.0108	0.1824	2.1600	No
B5	A2, s/c, 0.64 % - 60 mm	0.4404	0.3621	0.0142	0.0165	1.1096	2.1600	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table E.10 Summary of significance tests on sensitivity of the abrasion resistance test to different curing regimes for samples containing superplasticizing agents

Specimen ID*	Curing		Mean m_2	Mean m_2	Variance s_1^2	Variance s_2^2	t_{actual}	$t_{critical}$	Significant difference
B5	PS	AC	0.440417	0.792708	0.01417	0.00571	5.5867	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	PS	AC	0.108542	0.165063	0.00307	0.30703	0.2270	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	PS	AC	0.115625	0.201250	0.00011	0.00004	11.4910	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	PS	AC	0.104792	0.250000	0.00008	0.00006	20.8922	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	PS	AC	0.090625	0.341667	0.00003	0.00010	43.6648	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	PS	AC	0.080208	0.403333	0.00005	0.00083	22.9543	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 1.0 %	PS	AC	0.452708	0.637500	0.00053	0.00403	5.5948	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	PS	AC	0.394861	0.697403	0.02198	0.01058	4.7423	2.1200	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	PS	AC	0.246042	0.506250	0.00052	0.00003	17.2161	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	PS	AC	0.203125	0.418750	0.00008	0.00082	14.8799	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	PS	AC	0.152833	0.301667	0.00027	0.00014	12.3599	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	PS	AC	0.074583	0.200833	0.00010	0.00001	18.9906	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 1.0 %	PS	AC	0.448396	0.770833	0.00113	0.00008	14.4199	2.3650	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table E.11 *Summary of significance tests on sensitivity of the abrasion resistance tests to superplasticizing agents and steel fibre volume for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_1	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.108542	0.115625	0.00307	0.00011	0.2809	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.108542	0.104792	0.00307	0.00008	0.1493	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.108542	0.090625	0.00307	0.00003	0.7194	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.108542	0.080208	0.00307	0.00005	1.1338	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.108542	0.452708	0.00307	0.00053	12.8228	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.115625	0.104792	0.00011	0.00008	1.7565	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.115625	0.090625	0.00011	0.00003	4.7900	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.115625	0.080208	0.00011	0.00005	6.3232	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.115625	0.452708	0.00011	0.00053	29.8750	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.104792	0.090625	0.00008	0.00003	2.9924	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.104792	0.080208	0.00008	0.00005	4.7714	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.104792	0.452708	0.00008	0.00053	31.4368	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.090625	0.080208	0.00003	0.00005	2.6250	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.090625	0.452708	0.00003	0.00053	34.2620	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.080208	0.452708	0.00005	0.00053	34.6132	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.0 %	0.440417	0.108542	0.01417	0.00307	5.6514	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.440417	0.115625	0.01417	0.00011	6.0781	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.440417	0.104792	0.01417	0.00008	6.2861	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.440417	0.090625	0.01417	0.00003	6.5639	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.440417	0.080208	0.01417	0.00005	6.7545	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.440417	0.452708	0.01417	0.00053	0.2267	2.2280	No
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.394861	0.246042	0.02198	0.00052	2.2711	2.1600	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.394861	0.203125	0.02198	0.00008	2.9453	2.1600	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.394861	0.152833	0.02198	0.00027	3.7074	2.1600	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.394861	0.074583	0.02198	0.00010	4.9186	2.1600	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.394861	0.448396	0.02198	0.00113	0.8096	2.1600	No
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.246042	0.203125	0.00052	0.00008	3.9175	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.246042	0.152833	0.00052	0.00027	7.4303	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.246042	0.074583	0.00052	0.00010	15.4319	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.246042	0.448396	0.00052	0.00113	11.1479	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.203125	0.152833	0.00008	0.00027	6.0109	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.203125	0.074583	0.00008	0.00010	21.3983	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.203125	0.448396	0.00008	0.00113	15.7626	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.152833	0.074583	0.00027	0.00010	9.1316	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.152833	0.448396	0.00027	0.00113	17.6800	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.074583	0.448396	0.00010	0.00113	23.8551	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.440417	0.394861	0.01417	0.02198	0.5860	2.1600	No
B5	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.440417	0.246042	0.01417	0.00052	3.5862	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.440417	0.203125	0.01417	0.00008	4.4446	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.440417	0.152833	0.01417	0.00027	5.3516	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.440417	0.074583	0.01417	0.00010	6.8481	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.440417	0.448396	0.01417	0.00113	0.1442	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.108542	0.394861	0.00307	0.02198	4.2118	2.1600	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.115625	0.246042	0.00011	0.00052	11.6592	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.104792	0.203125	0.00008	0.00008	17.1348	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.090625	0.152833	0.00003	0.00027	8.0660	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.080208	0.074583	0.00005	0.00010	1.0322	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 1.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.452708	0.448396	0.00053	0.00113	0.2368	2.2280	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table E.12 *Summary of significance tests on sensitivity of the abrasion resistance tests to superplasticizing agents and steel fibre volume for samples cured in air*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.165063	0.201250	0.30703	0.00004	0.0998	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.165063	0.250000	0.30703	0.00006	0.2341	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.165063	0.341667	0.30703	0.00010	0.4868	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.165063	0.403333	0.30703	0.00083	0.6564	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.165063	0.637500	0.30703	0.00403	1.2981	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.201250	0.250000	0.00004	0.00006	6.7550	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.201250	0.341667	0.00004	0.00010	16.7250	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.201250	0.403333	0.00004	0.00083	9.6884	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.201250	0.637500	0.00004	0.00403	9.6622	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.250000	0.341667	0.00006	0.00010	10.3940	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.250000	0.403333	0.00006	0.00083	7.2903	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.250000	0.637500	0.00006	0.00403	8.5672	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.341667	0.403333	0.00010	0.00083	2.8728	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.341667	0.637500	0.00010	0.00403	6.5113	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.403333	0.637500	0.00083	0.00403	4.7515	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.0 %	0.792708	0.165063	0.00571	0.30703	2.5096	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.792708	0.201250	0.00571	0.00004	11.9306	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.792708	0.250000	0.00571	0.00006	10.9403	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.792708	0.341667	0.00571	0.00010	9.0779	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.792708	0.403333	0.00571	0.00083	7.5999	2.3650	Yes
B5	A2, s/c, 0 51 % - 45 mm - SP 1.0 %	0.792708	0.637500	0.00571	0.00403	2.6969	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.697403	0.506250	0.01058	0.00003	2.9374	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.697403	0.418750	0.01058	0.00082	4.2299	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.697403	0.301667	0.01058	0.00014	6.0706	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.697403	0.200833	0.01058	0.00001	7.6331	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.697403	0.770833	0.01058	0.00008	1.1276	2.2280	No
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.506250	0.418750	0.00003	0.00082	4.2548	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.506250	0.301667	0.00003	0.00014	22.2493	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.506250	0.200833	0.00003	0.00001	70.2087	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.506250	0.770833	0.00003	0.00008	36.6008	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.418750	0.301667	0.00082	0.00014	5.3536	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.418750	0.200833	0.00082	0.00001	10.7272	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.418750	0.770833	0.00082	0.00008	16.6715	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.301667	0.200833	0.00014	0.00001	11.6975	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.301667	0.770833	0.00014	0.00008	45.2212	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.200833	0.770833	0.00001	0.00008	87.9384	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.792708	0.697403	0.00571	0.01058	1.8120	2.1600	No
B5	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.792708	0.506250	0.00571	0.00003	5.7822	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.792708	0.418750	0.00571	0.00082	7.3016	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.792708	0.301667	0.00571	0.00014	9.8642	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.792708	0.200833	0.00571	0.00001	11.9578	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.792708	0.770833	0.00571	0.00008	0.4407	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.165063	0.697403	0.30703	0.01058	2.6164	2.1600	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.201250	0.506250	0.00004	0.00003	50.1558	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.250000	0.418750	0.00006	0.00082	8.0630	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.341667	0.301667	0.00010	0.00014	3.6814	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.403333	0.200833	0.00083	0.00001	9.9163	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 1.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.637500	0.770833	0.00403	0.00008	2.9421	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Appendix F: Microhardness profiles

Figure F.1 *Left side and front view of MICROMET 4*

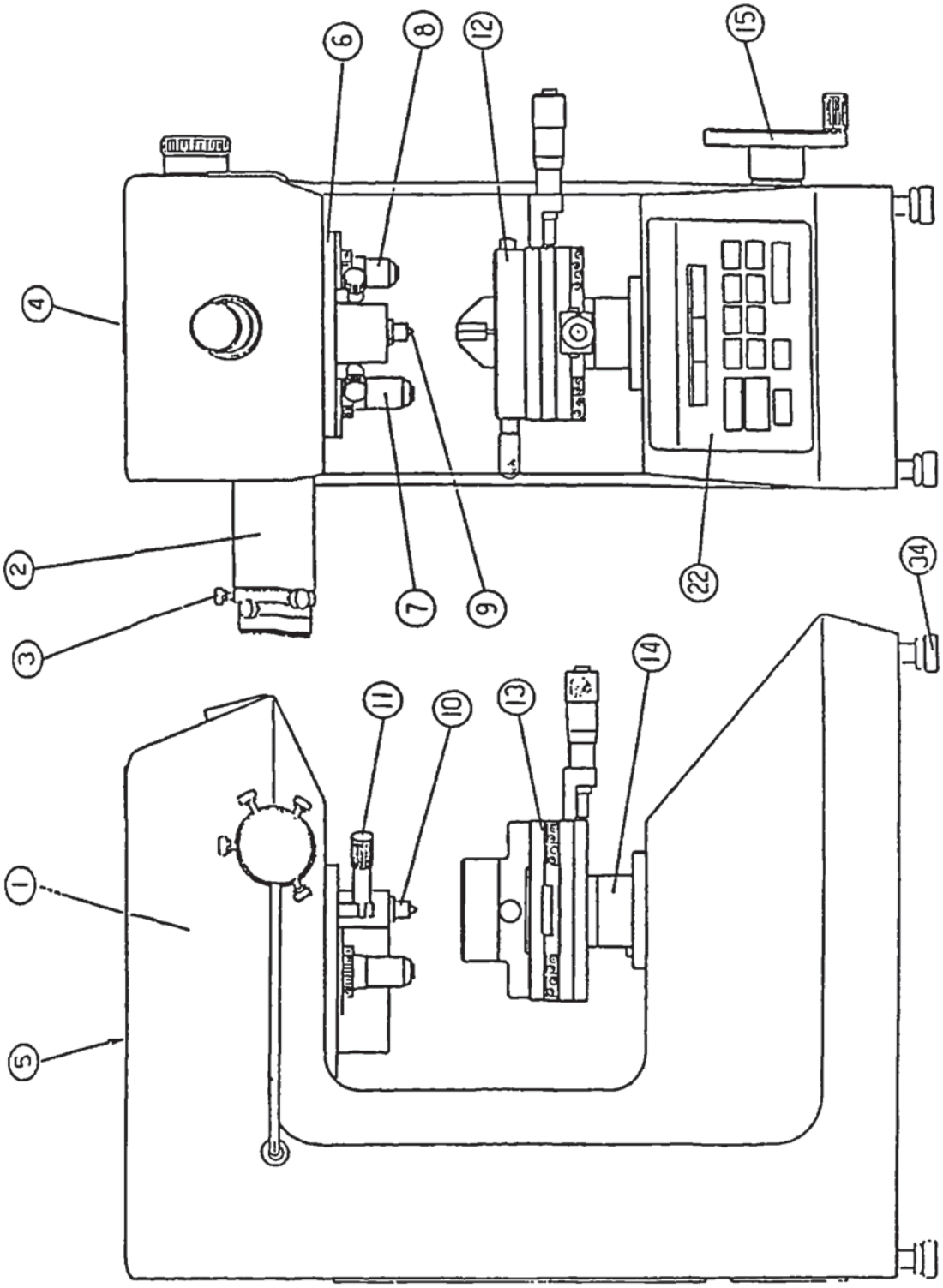


Figure F.2 Right side and back view of MICROMET 4

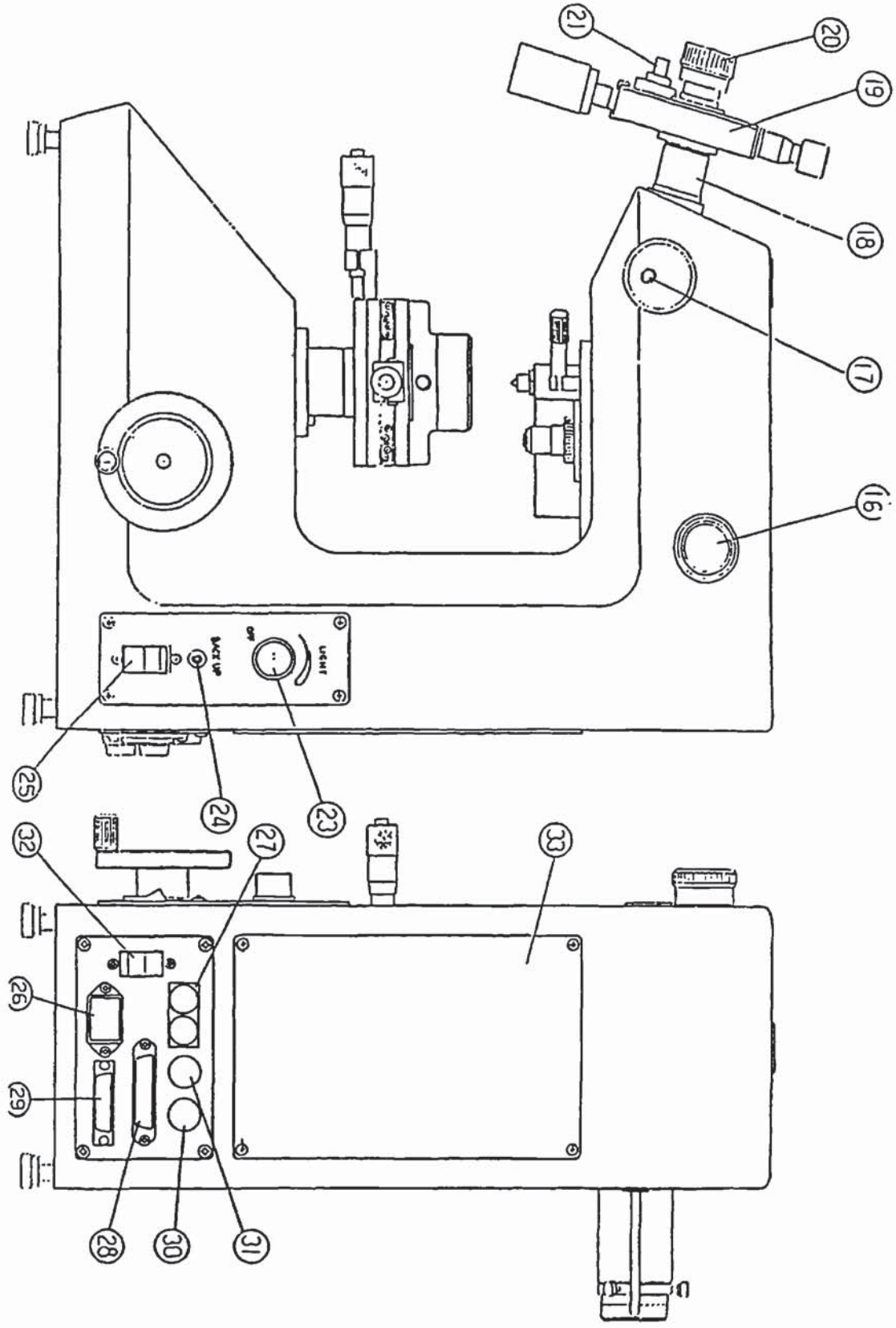


Table F.1 Components for Appearance Drawings of Micromet 4

No.	Component	No.	Component
1	Tester body	29	RS-2320 connector
2	Lamp house	30	Data input connector
3	Visual field brightness center adjustment screw	31	Connector for external control (Option)
		32	Main power switch
4	Photographic optical path cover	33	Rear cover
5	Top cover	34	Level adjustment legs
6	Turret	35	Digital display
7	Objective lens x 40	36	START key (for activating load application)
8	Objective lens x 10	37	LOADING LED
9	Diamond indenter	38	SET key (for zero-resetting of measurement line)
10	Indenter shaft protector tube		
11	Turret lever	39	Dwell key
12	Precision vise	39A	ENTER key
13	X-Y stage	40	CL key (for clearing memory data, MICROMET 4 Tester only)
14	Table elevating device		
15	Table elevating handle	41	HV/HK selection key
16	Load selector dial	42	DEC key
17	Optical path selector knob	43	INC key
18	Measuring microscope mounting tube	44	Cursor control key
19	Electronic measuring microscope	45	F key (for mode selection, MICROMET® 4 Tester only)
20	Eyepiece		
21	READ switch	46	HV/HK indicator LED
22	Front panel	47	Mode indicator LED (MICROMET®Tester 4 only)
23	Brightness adjustment knob		
24	Main power indicator LED	48	CONV key (for conversion scale selection MICROME1S 4 Tester
25	Power switch		
26	Power connector	49	LCD (MICROMET® 4 Tester only)
27	Fuse holder	50	Hardness value judgment display (MICROMET® 4 Tester only)
28	Printer connector		

Figure F.3 Microhardness profile for concrete mix B4

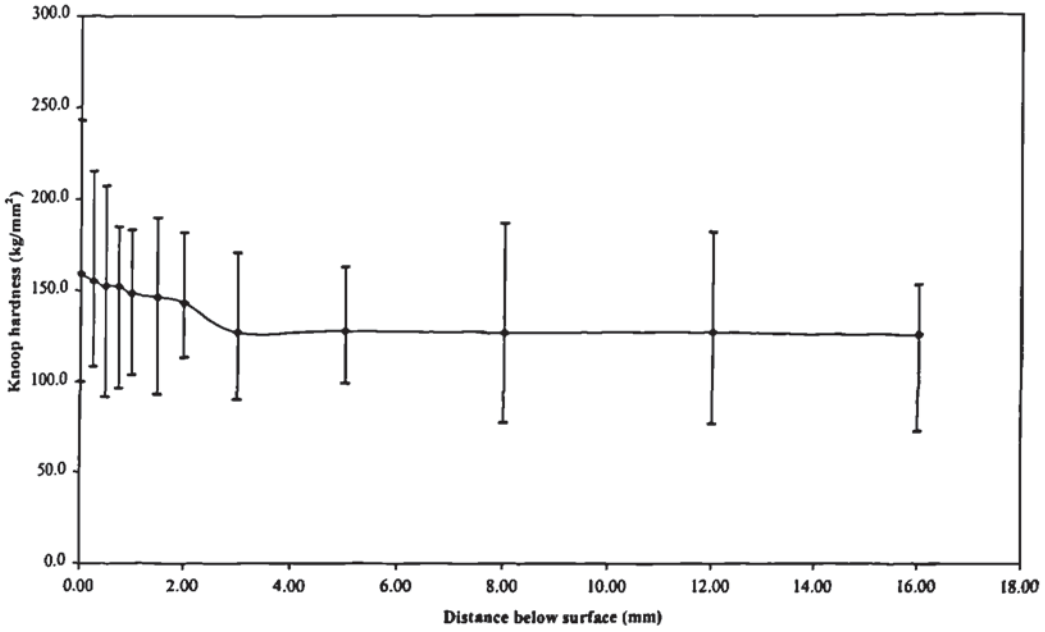


Figure F.4 *Microhardness profile for concrete mix B5*

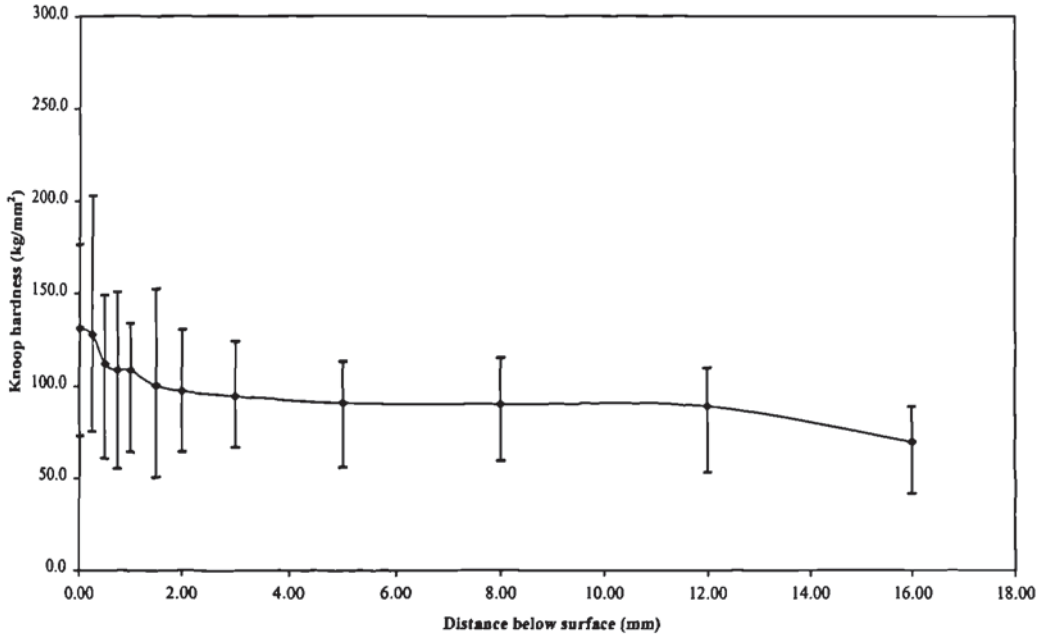


Figure F.5 *Microhardness profile for concrete mix B6*

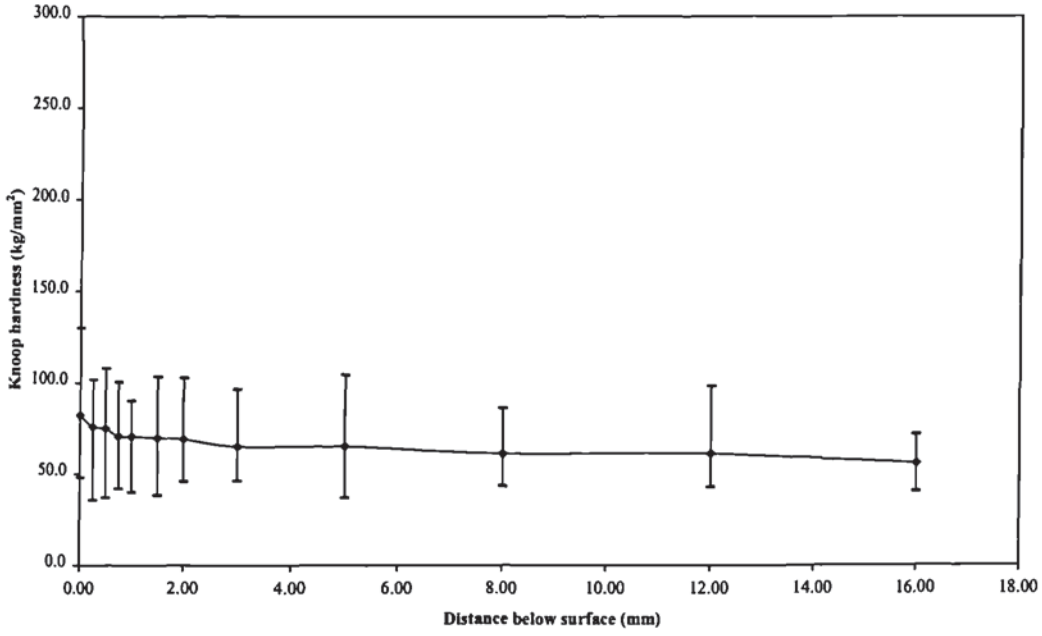


Figure F.6 *Microhardness profile for concrete mix A1, sc, 0.51 % - 45 mm*

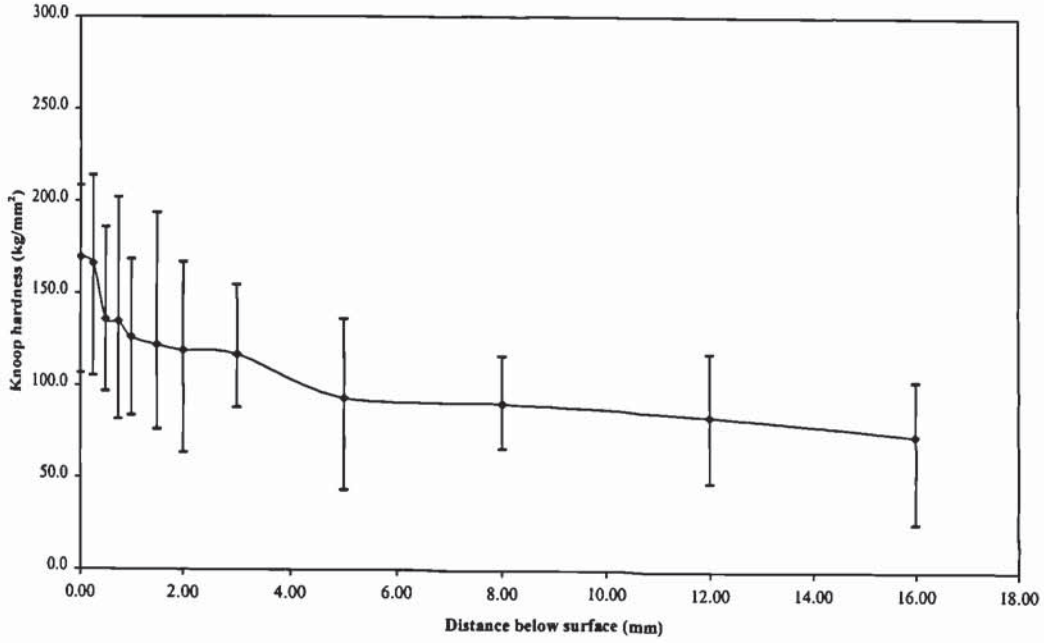


Figure F.7 *Microhardness profile for concrete mix A2, sc, 0.51 % - 45 mm*

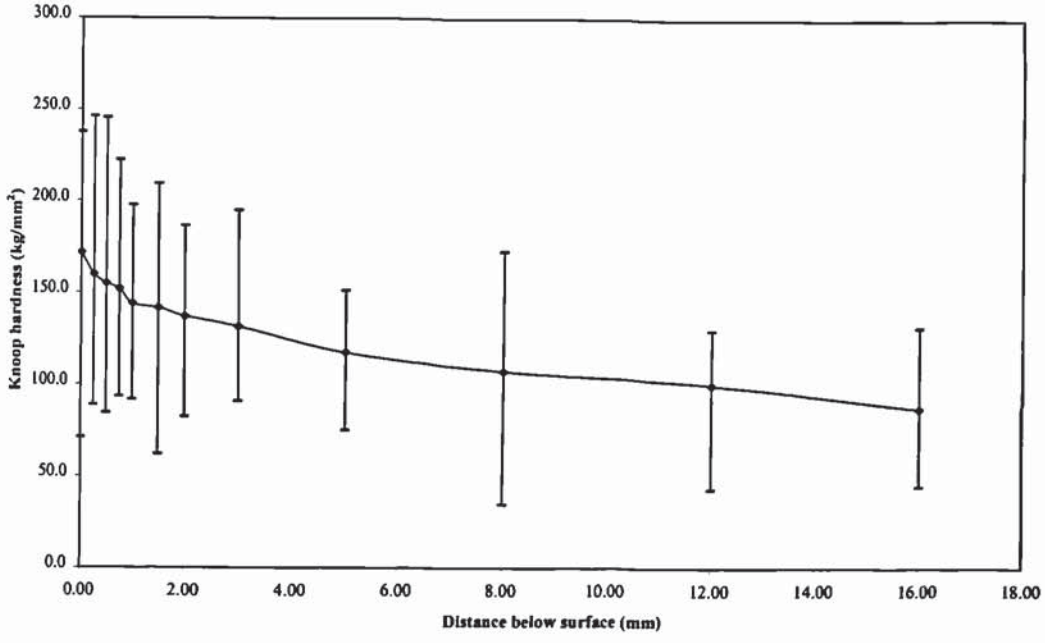


Figure F.8 *Microhardness profile for concrete mix A3, sc, 0.51 % - 45 mm*

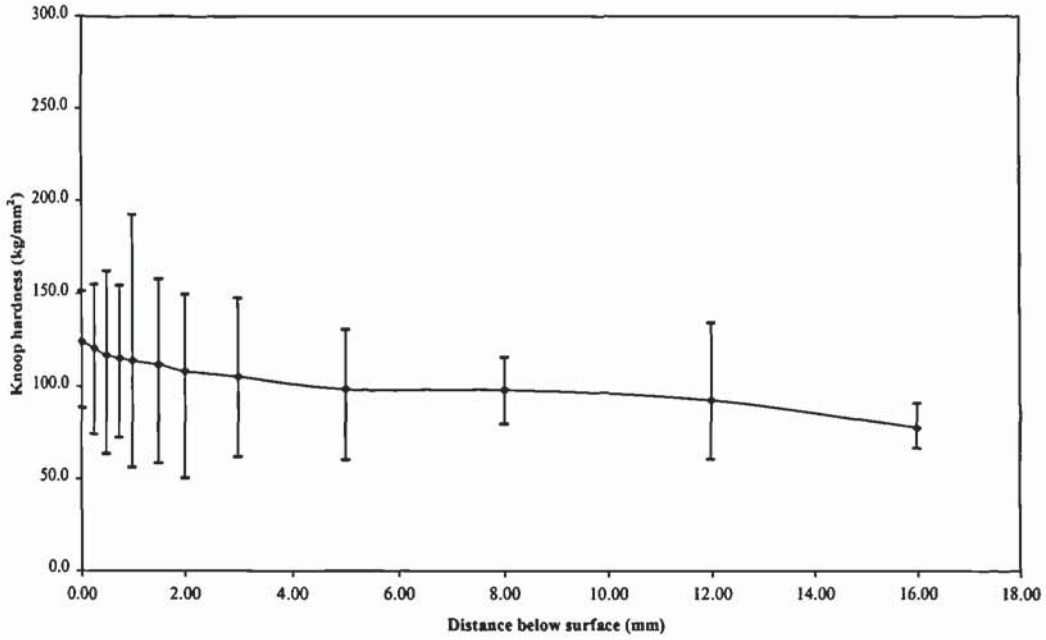


Figure F.9 *Microhardness profile for concrete mix A2, sc, 1.0 % - 45 mm*

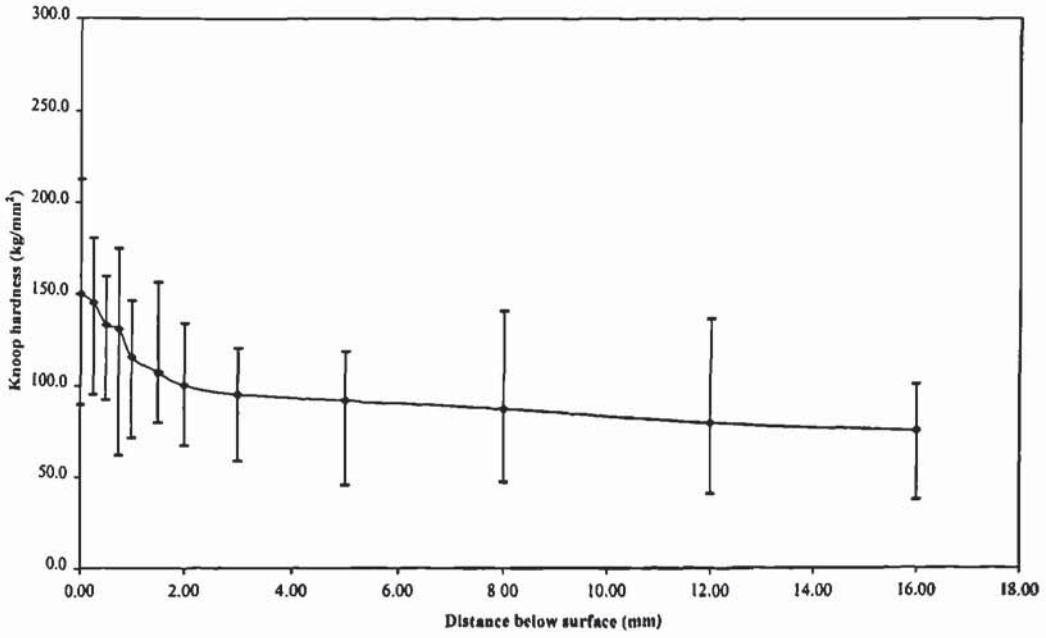


Figure F.10 Microhardness profile for concrete mix A2, sc, 1.5 % - 45 mm

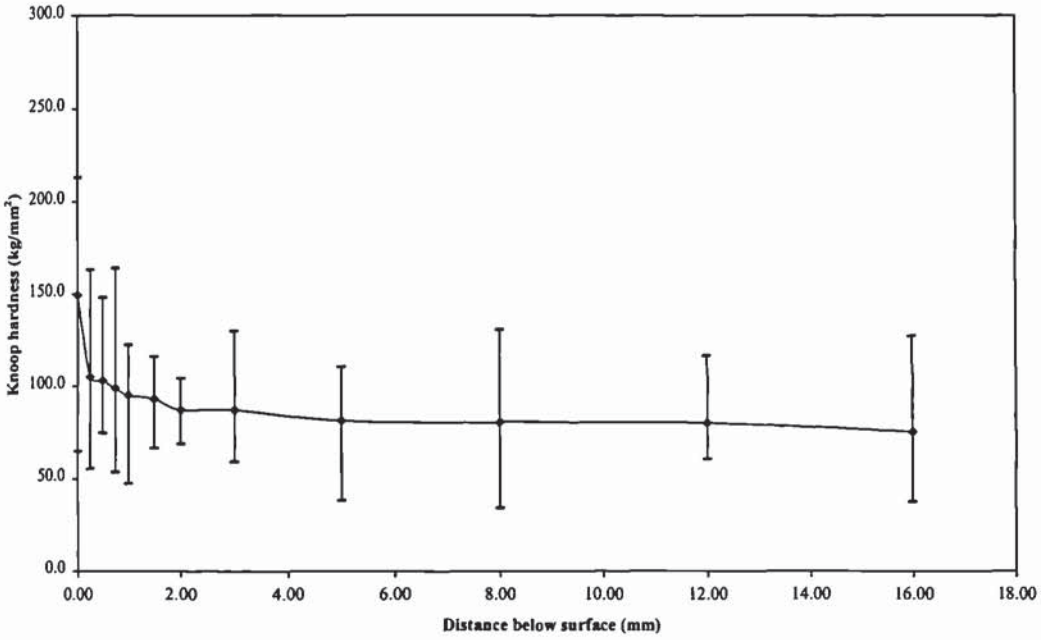


Figure F.11 Microhardness profile for concrete mix A2, sc, 2.0 % - 45 mm

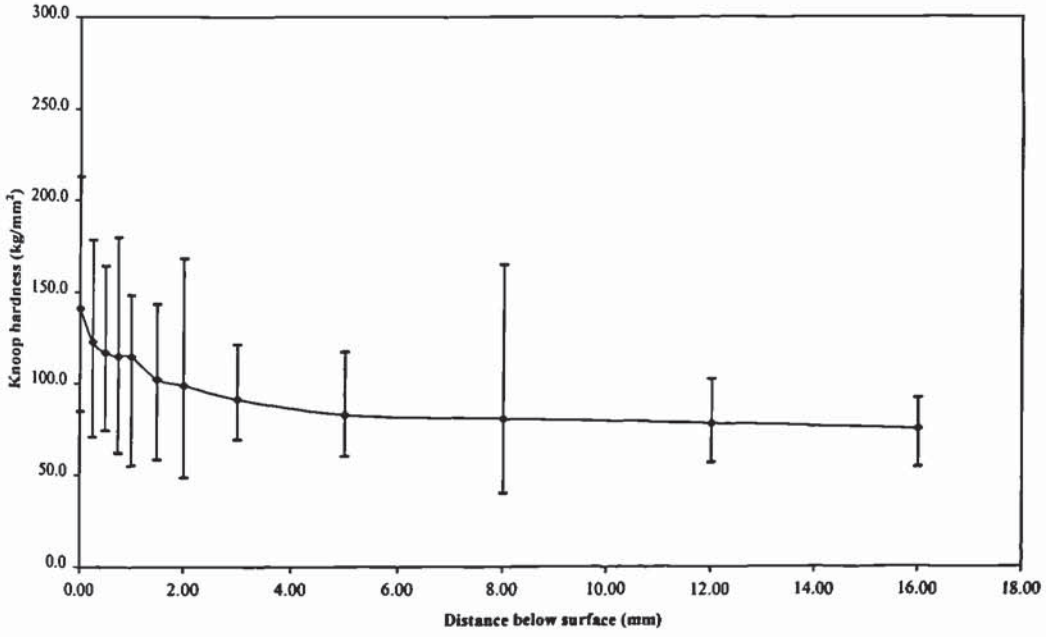


Figure F.12 Microhardness profile for concrete mix A2, sc, 3.0 % - 45 mm

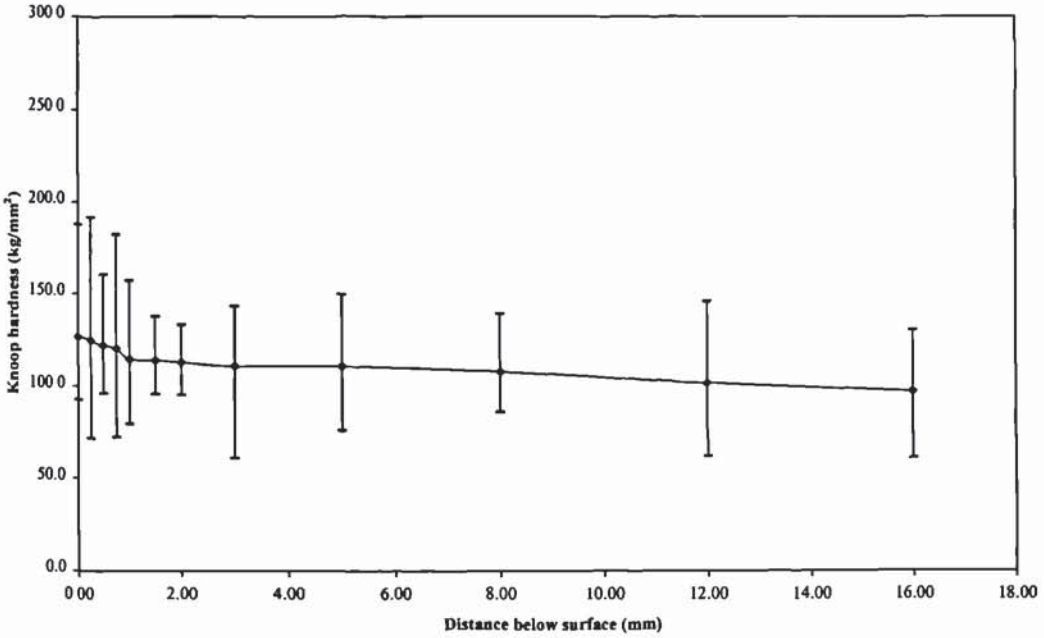


Figure F.13 Microhardness profile for concrete mix A2, p, 0.1% - 12 mm

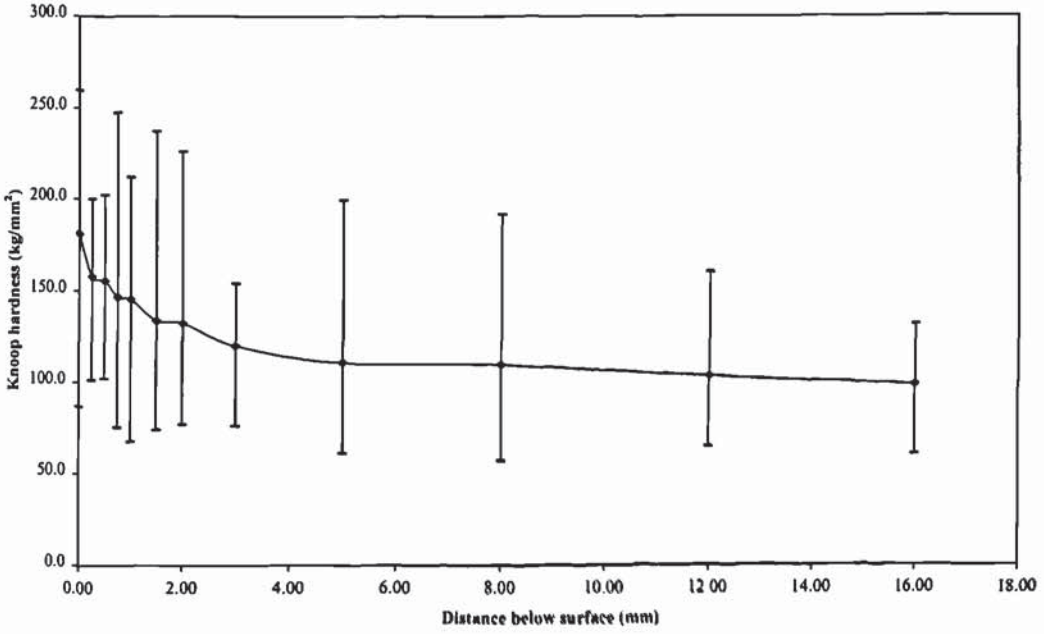


Figure F.14 *Microhardness profile around surface steel fibre, at 0.055 mm from the surface, for concrete mix A2, s/c, 0.51 % - 45 mm*

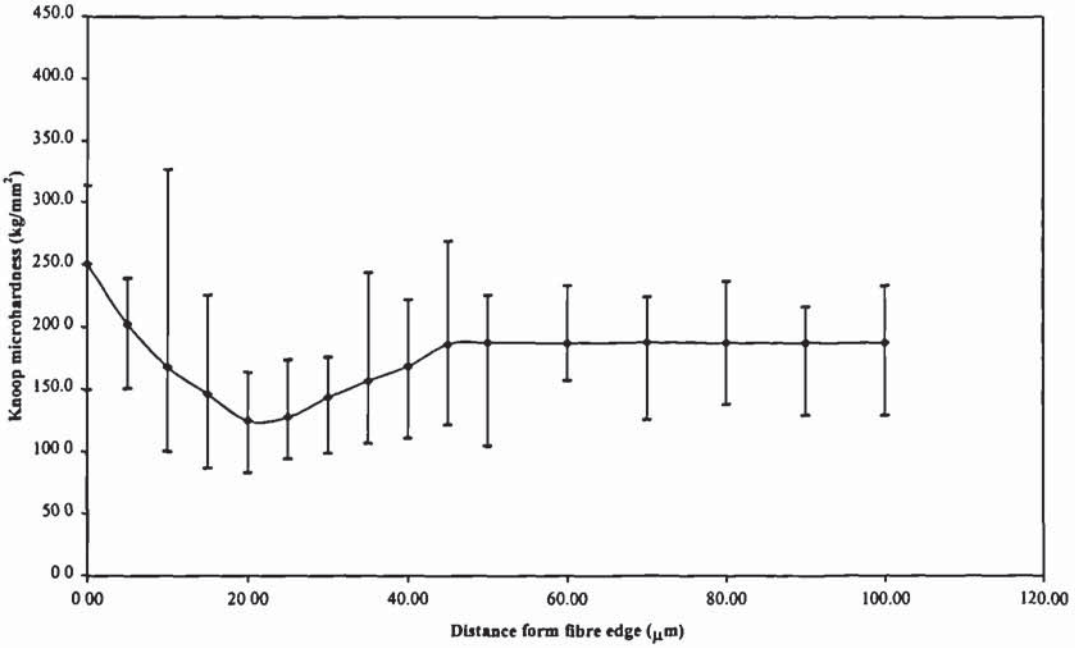
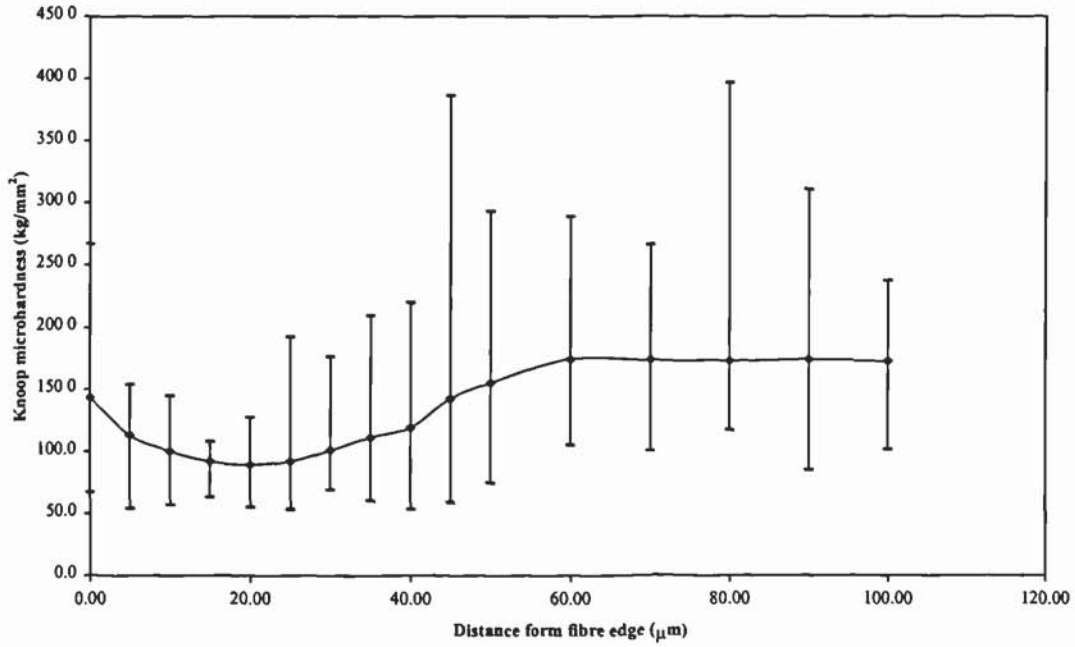


Figure F.15 *Microhardness profile around main body steel fibre, at 0.725 mm from the surface, Mix A2, s/c, 0.51 % - 45 mm*



Appendix G: Petrographic analysis

Table G.1 (a) General features of the samples

Sample reference	B4	B5	B6	A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm
Sample dimensions:						
Length (mm)	97	97	102	97	102	98
Diameter (mm)	98	98	98	100	100	100
Number of pieces	1	1	1	1	1	1
Macrocracking:	None	None	None	None	None	None
Fine cracking:	None	None	None	None	None	None
Carbonation:						
General depth (mm)	0.5	1	3	2	1.5	3
Maximum depth (mm)	4	4.5	6.5	10	6.5	5.5
Reinforcement:						
Diameter (mm)	10	10	10	1*	1*	1*
Depth (mm)	32	35	40	43	47	45
Corrosion	None	None	None	None	None	None
Voids:						
Maximum size (mm)	5	4	8	4	3	3
Typical size (mm)	1	1	2	1.5	1	1
Excess voidage (%)	0.5	0	0.5	0	0	0

* Sample contains wire reinforcement strand

Table G.1 (b) General features of the samples

Sample reference	B5	A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	A2, p, 0.1 % - 12 mm
Sample dimensions:							
Length (mm)	97	102	98	98	102	100	100
Diameter (mm)	98	100	100	100	100	100	100
Number of pieces	1	1	1	1	1	1	1
Macrocracking:	None	None	None	None	None	None	None
Fine cracking:	None	None	None	None	None	None	None
Carbonation:							
General depth (mm)	1	1.5	3	2	1	1	2
Maximum depth (mm)	4.5	6.5	4.5	5	4	5	4
Reinforcement:							
Diameter (mm)	10	1*	1*	1*	1*	1*	0.018**
Depth (mm)	35	47	45	43	40	42	47
Corrosion	None	None	None	None	None	None	None
Voids:							
Maximum size (mm)	4	3	3	3	2	8	3
Typical size (mm)	1	1	1	0.5	1	2	1
Excess voidage (%)	0	0	0	0	0	0.5	0

* Sample contains wire reinforcement strand
** Sample contains polypropylene fibres

Table G.2 (a) Summary description of the aggregate

Sample reference	B4	B5	B6	A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm
Coarse aggregate:						
Maximum size (mm)	17	16	21	16	19	17
Typical shape	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded
Major rock types	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone
Minor rock types	Chert Greywacke	Chert Greywacke	Chert Greywacke	Greywacke	Greywacke	Greywacke
Trace rock types	-	-	-	Chert	Chert	Chert
Fine aggregate:						
Grading	Fine-medium	Fine-medium	Fine-medium	Fine-medium	Fine-medium	Fine-medium
Maximum size (mm)	5	5	5	5	5	5
Typical shape	Sub-angular	Sub-angular	Sub-angular	Sub-angular	Sub-angular	Sub-angular
Major rock types	Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite
Minor rock types	Chert	Chert	Chert	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke
Trace rock types	Ironstone Mica	Ironstone Mica	Ironstone Mica	Ironstone	Ironstone	Ironstone
Alkali-aggregate reaction						
Gel on plate	Trace	Trace	Trace	None	None	None
Gel in voids	None	None	None	None	None	None
Gel in cracks	None	None	None	None	None	None

Table G.2 (b) Summary description of the aggregate

Sample reference	B5	A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	A2, p, 0.1 % - 12 mm
Coarse aggregate:							
Maximum size (mm)	16	19	16	18	18	20	16
Typical shape	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded	Sub-rounded
Major rock types	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone	Metaquartzite Recrystalized sandstone and siltstone
Minor rock types	Chert Greywacke	Greywacke	Greywacke	Greywacke	Greywacke	Greywacke	Greywacke
Trace rock types	-	Chert	Chert	Chert	Chert	Chert	Chert
Fine aggregate:							
Grading	Fine-medium	Fine-medium	Fine-medium	Fine-medium	Fine-medium	Fine-medium	Fine-medium
Maximum size (mm)	5	5	5	5	5	5	5
Typical shape	Sub-angular	Sub-angular	Sub-angular	Sub-angular	Sub-angular	Sub-angular	Sub-angular
Major rock types	Quartz Metaquartzite	Quartz Metaquartzite		Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite	Quartz Metaquartzite
Minor rock types	Chert	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke	Chert Recrystalized sandstone and siltstone Greywacke
Trace rock types	Ironstone Mica	Ironstone	Ironstone	Ironstone	Ironstone	Ironstone	Ironstone
Alkali-aggregate reaction							
Gel on plate	Trace	None	None	None	None	None	None
Gel in voids	None	None	None	None	None	None	None
Gel in cracks	None	None	None	None	None	None	None

Table G.3 (a) Summary description of the paste

Sample reference	B4	B5	B6	A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm
Cement type:	Portland	Portland	Portland	Portland	Portland	Portland
Cement replacement	None	None	None	None	None	None
Portlandite (Approx. vol. % of paste)	15	10	20	15	10-15	15
Cement grains:						
Unhydrated cement (Approx. vol. % of paste)	1	1	1-2	2	2	1-2
Pseudomorphically hydrated cement (Approx. vol. % of paste)	2-3	2-3	2-3	1	1	<1
Maximum size of unhydrated cement grains (mm)	0.08	0.14	0.17	0.12	0.18	0.12
Porosity						
General level	Moderate	Moderate-high	Moderate-high	Moderate	Moderate-high	Moderate
Porosity distribution	Very patchy	Very patchy	Patchy	Very patchy	Very patchy	Patchy
Microcracking:						
Microcracking level	Low	Very low	Very low	None	None	Very low
Typical length (μm)	1-1.5	<0.3	<0.3	-	-	<0.3
Fillings	None	None	None	-	-	None
Void fillings:						
Portlandite	None	None	None	None	None	None
Ettingite	Trace	Trace	Trace	None	None	None
Thaumasite	None	None	None	None	None	None
Others	None	None	None	None	None	None

Table G.3 (b) Summary description of the paste

Sample reference	B5	A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	A2, p, 0.1 % - 12 mm
Cement type:	Portland	Portland	Portland	Portland	Portland	Portland	Portland
Cement replacement	None	None	None	None	None	None	None
Portlandite (Approx. vol. % of paste)	10	10-15	20	15-20	20	15	10-15
Cement grains:							
Unhydrated cement (Approx. vol. % of paste)	1	2	1-2	2-3	1-2	1-2	1-2
Pseudomorphically hydrated cement (Approx. vol. % of paste)	2-3	1	<1	1	1-2	1	1
Maximum size of unhydrated cement grains (mm)	0.14	0.18	0.14	0.14	0.22	0.18	0.16
Porosity							
General level	Moderate-high	Moderate-high	Moderate	Moderate	Moderate	Moderate	Moderate
Porosity distribution	Very patchy	Very patchy	Patchy	Patchy	Patchy	Slightly patchy	Patchy
Microcracking:							
Microcracking level	Very low	None	Very low	None	None	None	Very low
Typical length (μm)	<0.3	-	<0.3	-	-	-	<0 3
Fillings	None	-	None	-	-	-	None
Void fillings:							
Portlandite	None	None	None	None	None	None	None
Ettingite	Trace	None	None	None	None	None	None
Thaumasite	None	None	None	None	None	None	None
Others	None	None	None	None	None	None	None

Table G.4 (a) Summary of compositional data

Sample reference	B4	B5	B6	A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm
Volume proportions:						
Paste (%)	28.0	30.4	34.2	25.4	29.8	27.2
Aggregate (%)	71.0	69.2	64.4	72.4	68.2	69.4
Void (%)	1.0	0.4	1.4	2.2	2.0	3.4
w/c ratio (measured petrographically)	0.45	0.53	0.66	0.48	0.46	0.55
Normalised volume proportions (excluding void)						
Paste (%)	28.3	30.5	34.7	26.0	30.4	28.2
Aggregate (%)	71.7	69.5	65.3	74.0	69.3	71.8
Weight proportions:**						
Aggregate (kg/m^3)	1879	1820	1711	1940	1823	1882
Cement (kg/m^3)	368	345	320	324	390	300
Water (kg/m^3)	166	183	210	156	179	166
Total (kg/m^3)	2413	2348	2241	2420	2392	2348
Aggregate/cement ratio	5.1	5.3	5.3	6.0	4.7	6.3
Cement content (Wt. %)*	15.8	14.7	14.3	13.9	16.9	12.8

* Calculated as an equivalent % by mass of oven-dried sample

** Attention is drawn to the coarse size of the aggregate and the possibility that these compositions may not be representative of the concrete as a whole

Table G.4 (b) Summary of compositional data

Sample reference	B5	A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	A2, p, 0.1 % - 12 mm
Volume proportions:							
Paste (%)	30.4	29.8	30.0	27.2	25.2	30.0	28.2
Aggregate (%)	69.2	68.2	68.8	72.0	73.6	69.6	71.2
Void (%)	0.4	2.0	1.2	0.8	1.2	0.4	0.6
w/c ratio (measured petrographically)	0.53	0.46	0.49	0.51	0.51	0.52	0.45
Normalised volume proportions (excluding void)							
Paste (%)	30.5	30.4	30.4	27.4	25.5	30.1	28.4
Aggregate (%)	69.5	69.3	69.6	72.6	74.5	69.6	71.6
Weight proportions:**							
Aggregate (kg/m^3)	1820	1823	1824	1902	1952	1831	1877
Cement (kg/m^3)	345	390	376	330	308	358	369
Water (kg/m^3)	183	179	184	168	157	186	166
Total (kg/m^3)	2348	2392	2384	2400	2417	2376	2412
Aggregate/cement ratio	5.3	4.7	4.9	5.8	6.3	5.1	5.1
Cement content (Wt. %)*	14.7	16.9	16.4	14.3	13.2	15.8	15.8

* Calculated as an equivalent % by mass of oven-dried sample

** Attention is drawn to the coarse size of the aggregate and the possibility that these compositions may not be representative of the concrete as a whole

Plate G. 1 *A typical sample as extracted from the concrete slab*

Scale: The scale bar is divided into millimetres and centimetres.

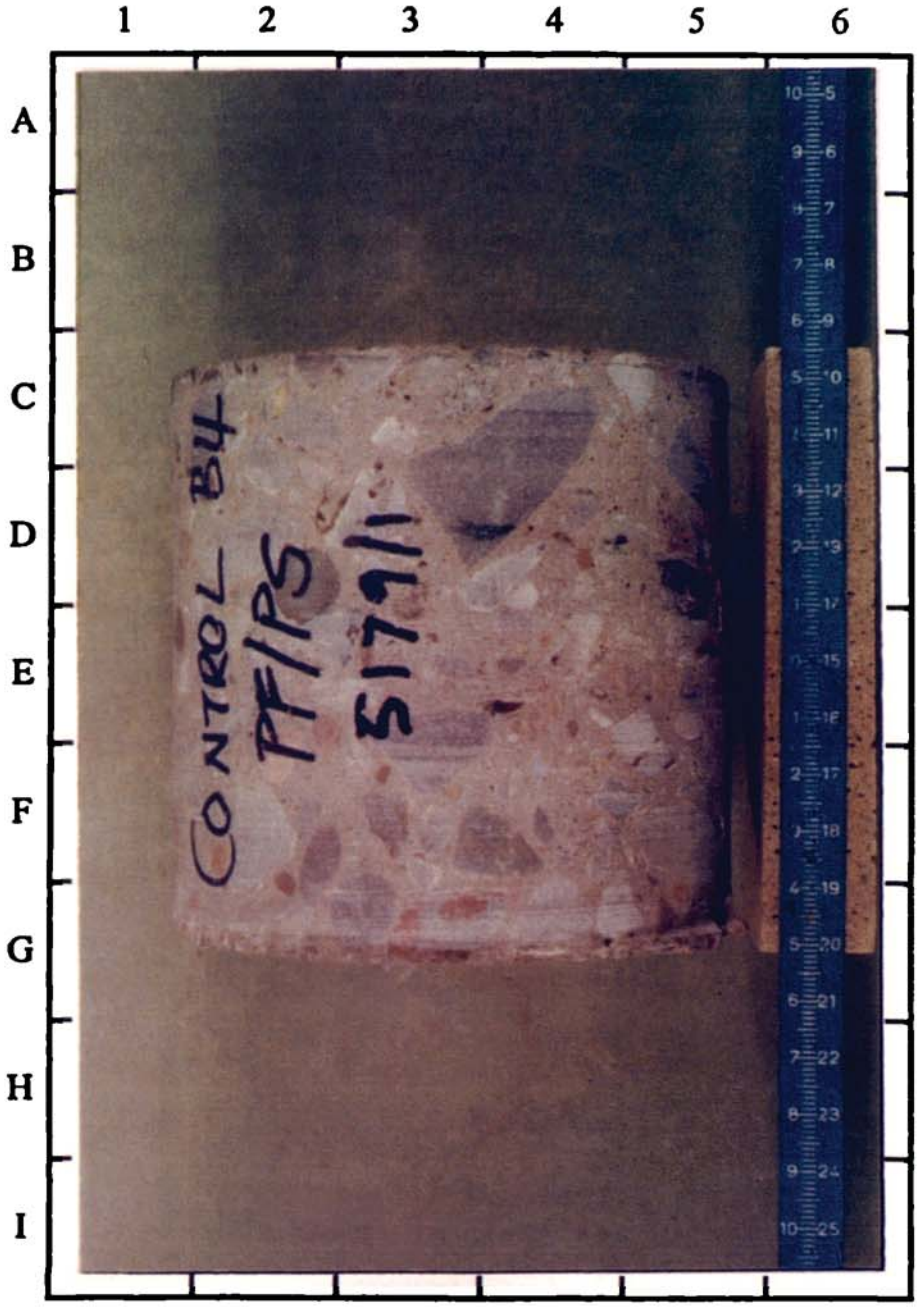


Plate G. 2 *A typical sample as extracted from the concrete slab, external surface*

Scale: The scale bar is divided into millimetres and centimetres.

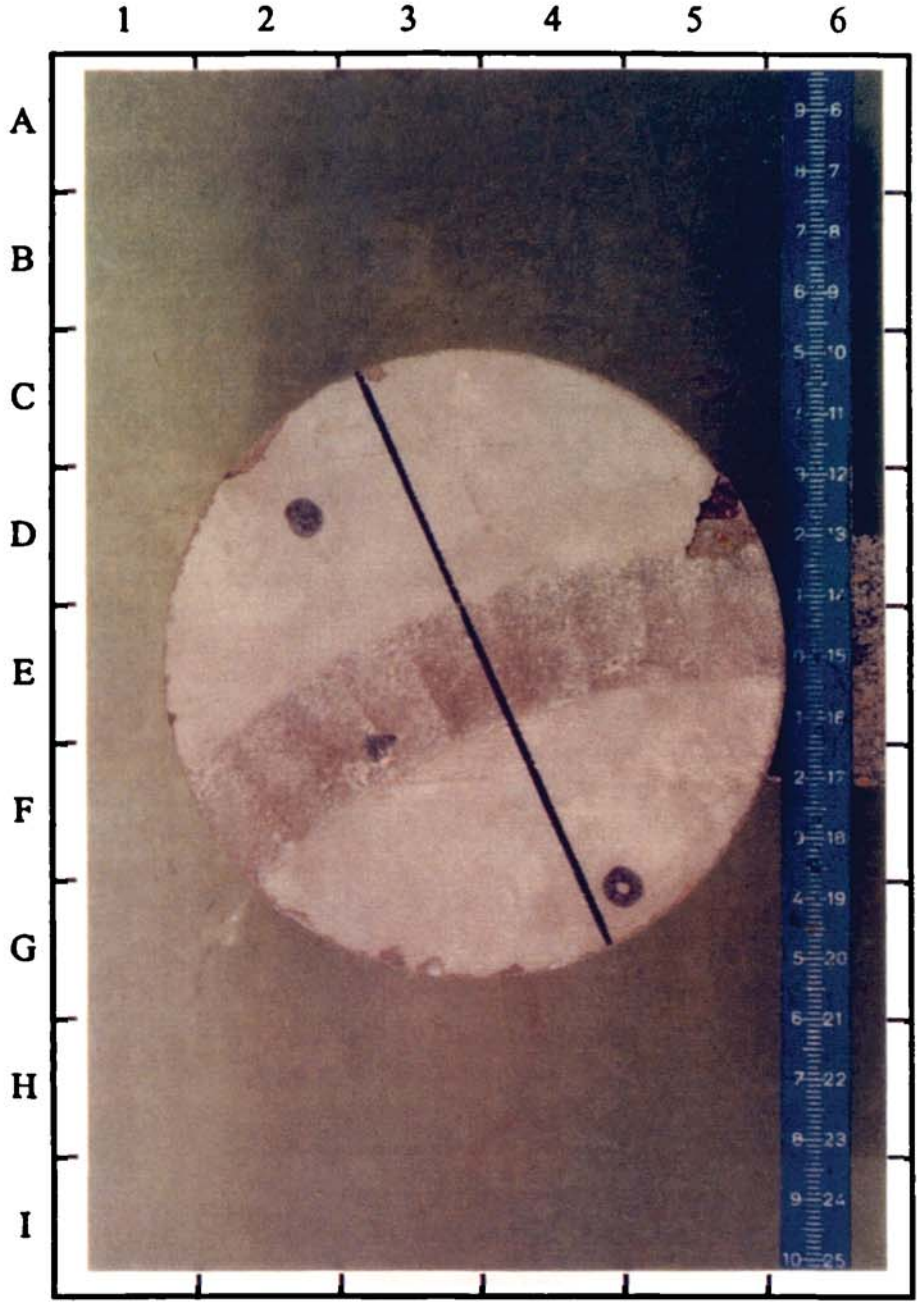


Plate G. 3 *Sample B4 – Thin section, oblique polars*

Scale: The width of the photograph represents 0.5 mm

This view shows the typical appearance of the paste below a worn part of the external surface. The external surface runs along the right side of the field view from A6 to I6. The aggregate particles are exposed at the external surface, for example C/D6. Particles of unhydrated cement are visible for example in E5/6 and C3 and angular particles of quartz occur for example in B1/2 and F5.

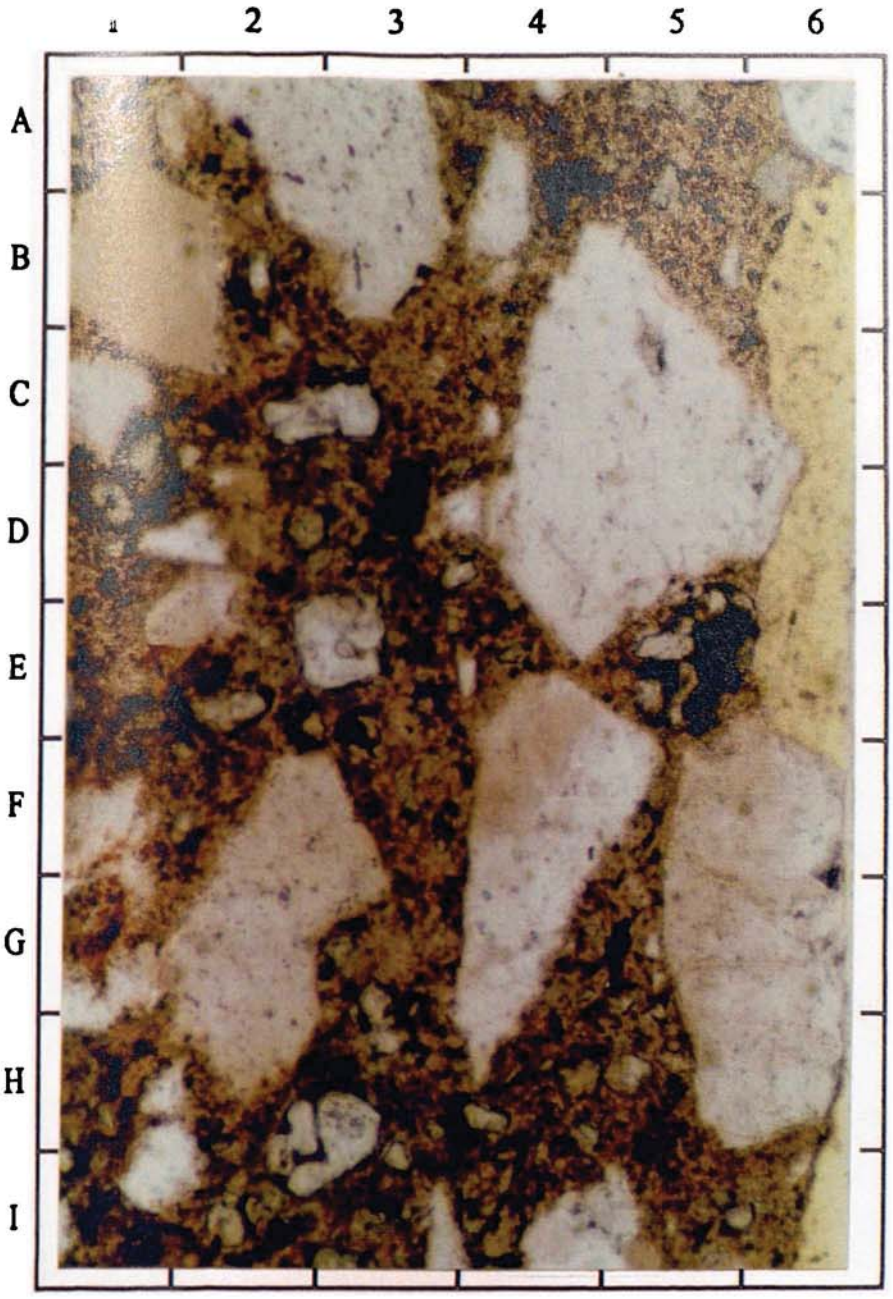


Plate G. 4 *Sample B4 – Thin section, fluorescent light*

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and microcracking below part of the external surface not subjected to abrasion resistance testing. Vertically orientated cracks intersected the external surface, for example from E1 to E6. The paste has a patchy but often low porosity and areas of high porosity paste appear in bright green occur for example in E3 and areas of much lower porosity paste appearing in dark green occur for example in H3. The external surface runs along the right side of the field of view from A6 to I6.

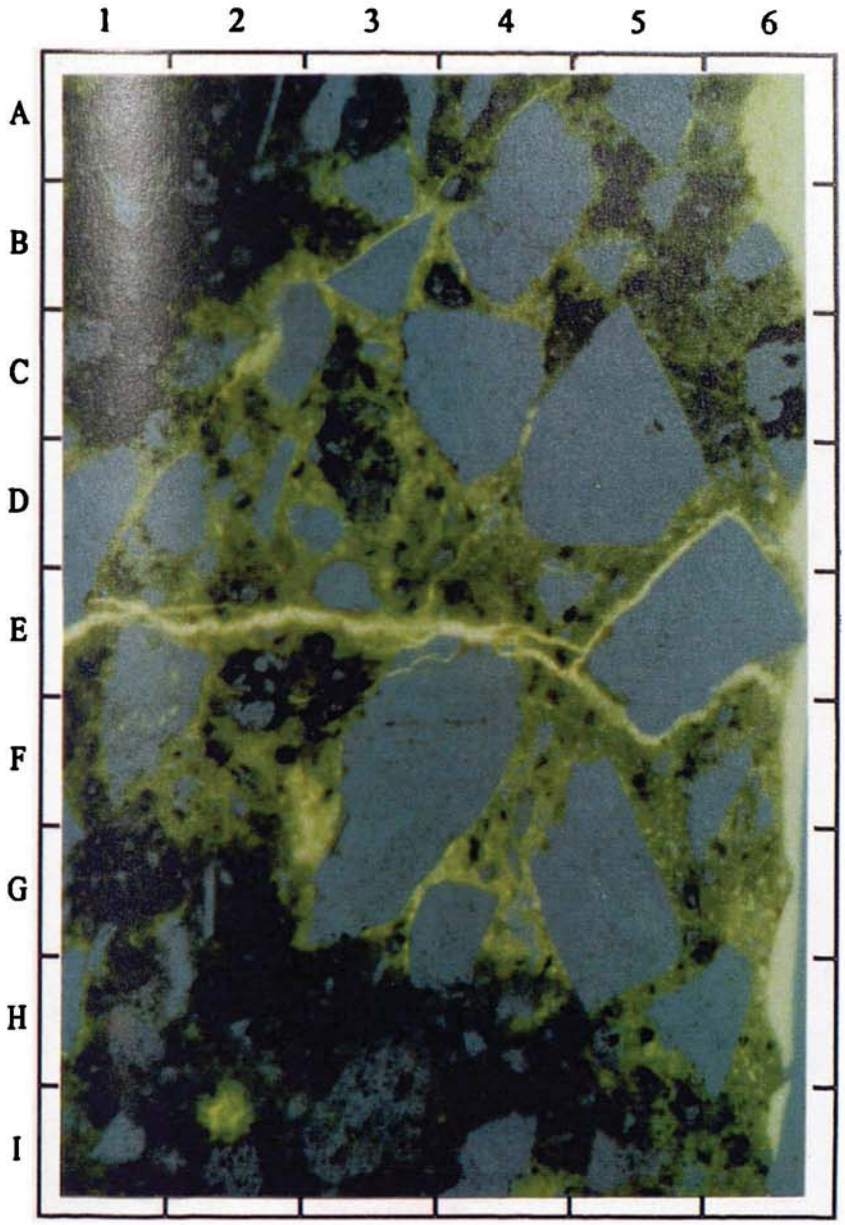


Plate G. 5 *Sample B4 – Thin section, fluorescent light*

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and cracking below part of the external surface subjected to abrasion resistance testing. The external surface runs along the right side of the field of view from A6 to I6. A vertically oriented microcrack runs from E/F1 to F6. Patchy paste porosity occurs for example in E5. Some very shallow cracking in aggregate particles exposed at the external surface can be seen for example in C6 and D6.

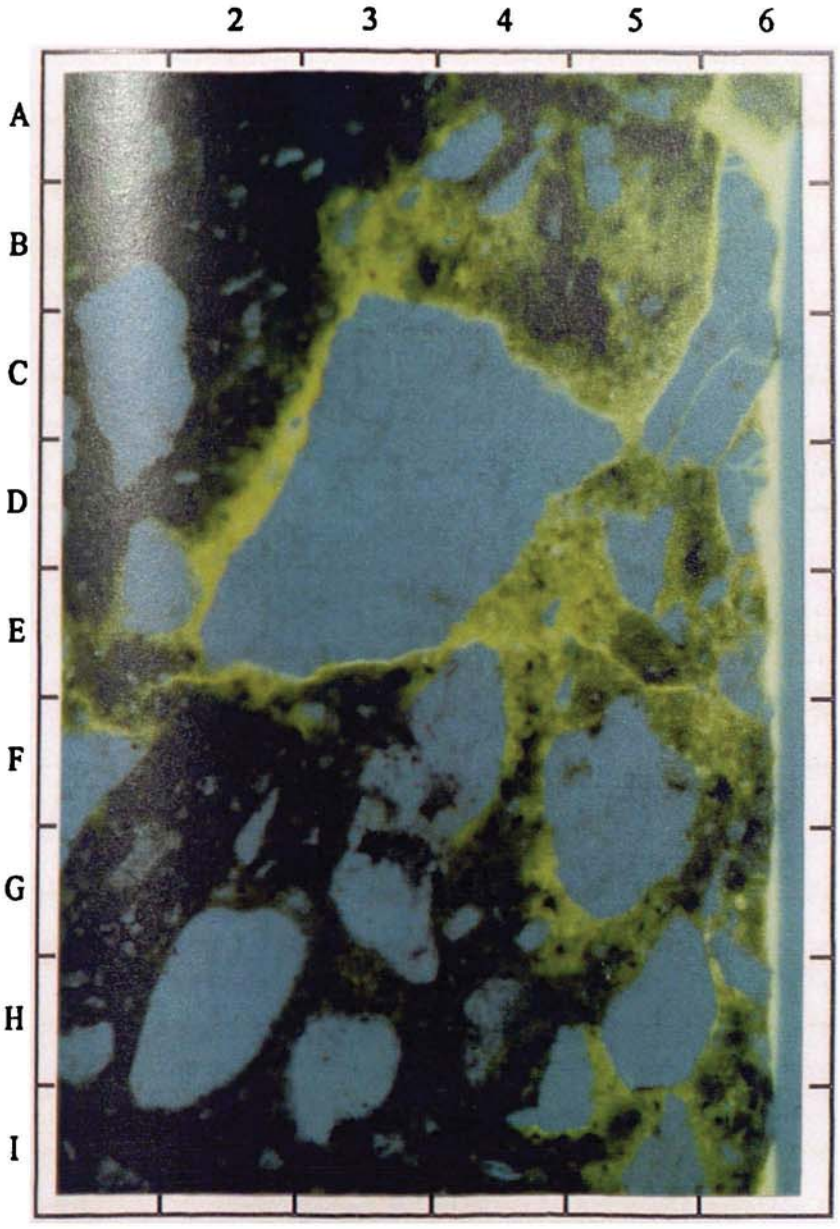


Plate G. 6 *Sample B5 – Thin section, oblique polars*

Scale: The width of the photograph represents 0.5 mm

This view shows the typical appearance of the paste at the external surface, where the surface has been subjected to abrasion resistance testing. The external surface is irregular and has exposed aggregate particles and tuns from A5 to I6. Particles of unhydrated cement are visible for example in F2 and H5. A quartz grain occurs in G4/5 and typical areas of carbonated cement paste occur for example around D2 and B4. Some shallow sub-parallel cracking in the cement paste at the external surface is visible for example around H5 and I4/5.

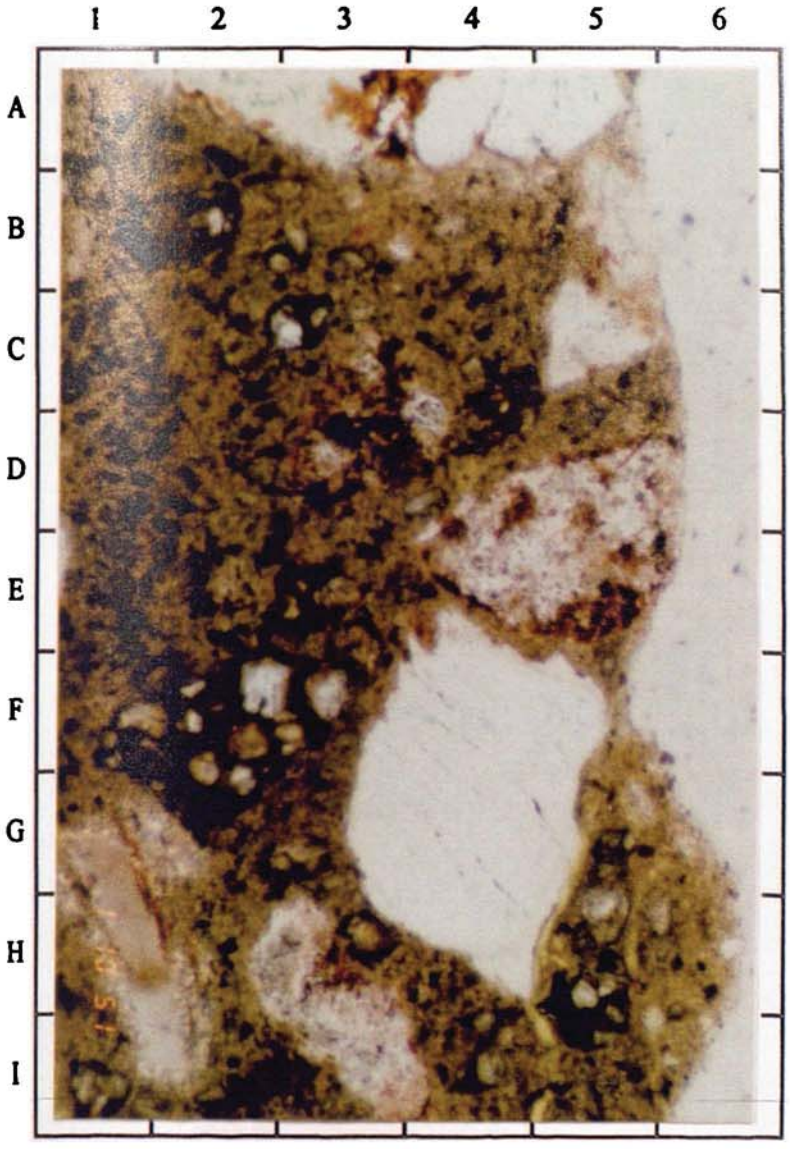


Plate G. 7 Sample B5 – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and microcracking below part of the external surface that has not been subjected to abrasion resistance testing. The external surface is visible on the right side of the field of view from A6 to E6. The porosity at the external surface is patchy and there are occasional microcracks within the paste, for example C3/4 and E1. Typical areas of low porosity paste at the external surface occur for example in B5 and G5/6 and areas of much higher porosity paste are visible for example in F3.

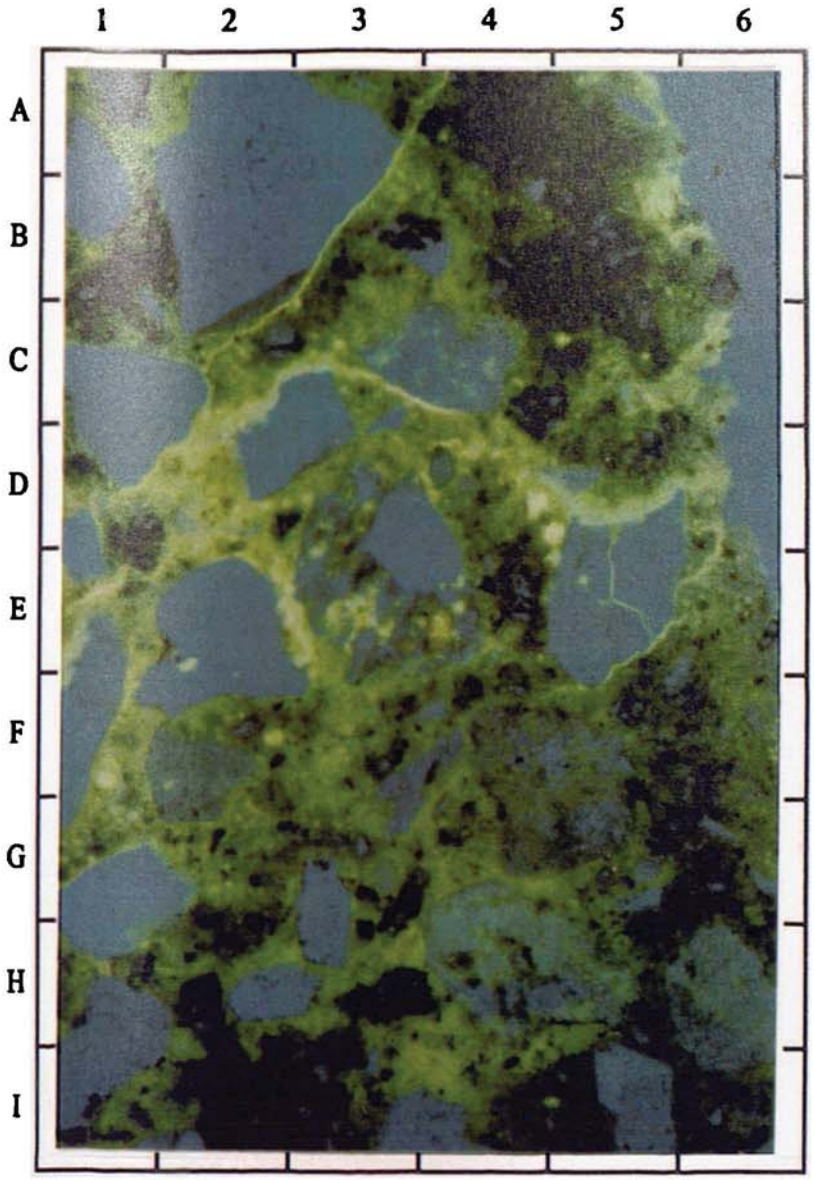


Plate G. 8 *Sample B5 – Thin section, fluorescent light*

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity below part of the external surface subjected to abrasion resistance testing. The paste in this view contains moderately abundant shallow, sub-parallel microcracks that are now infilled with the bright green resin used during the preparation of the thin section. Some of these cracks are visible for example in C4/5 and in E3/4. The external surface runs along the right side of the field of view from A5 to I5/6.

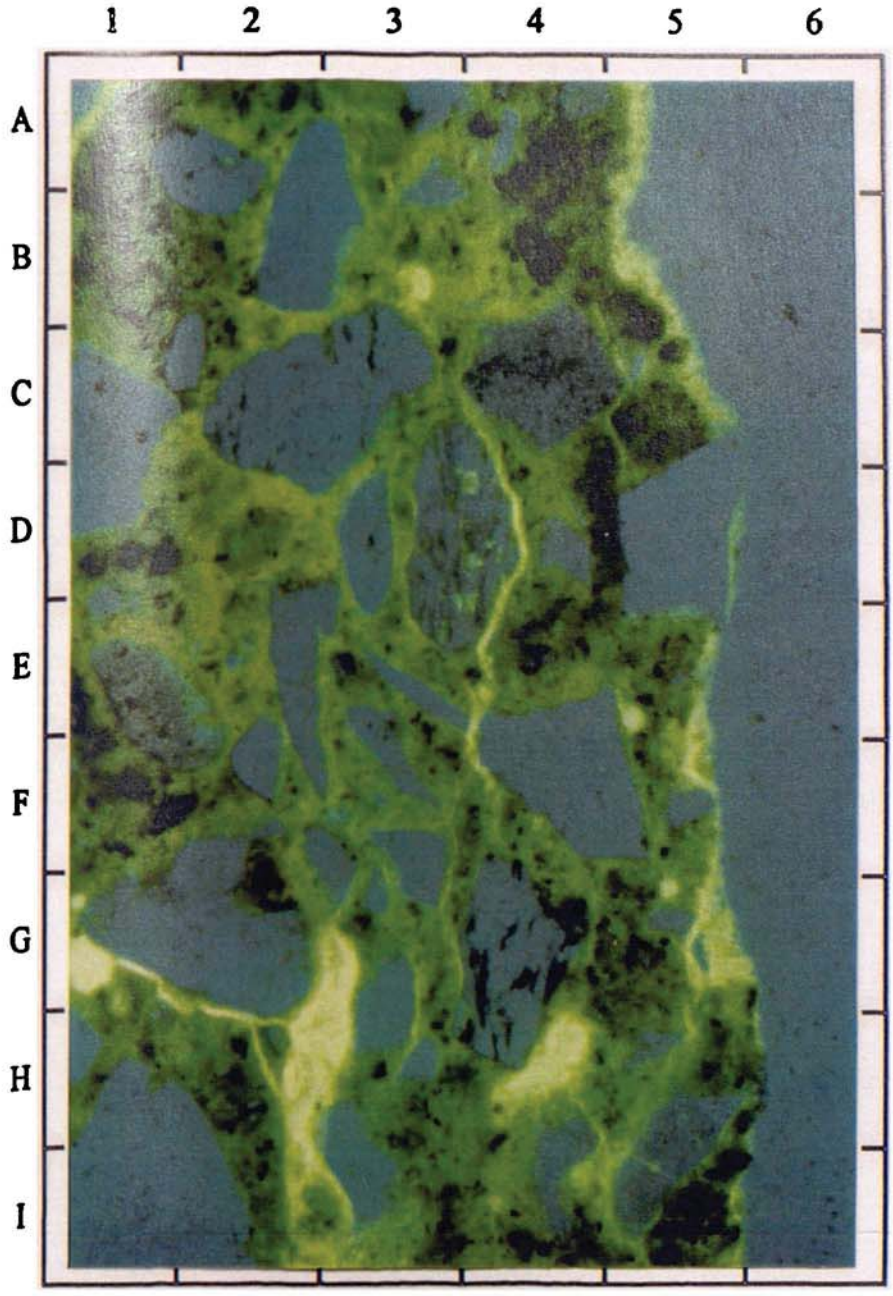


Plate G. 9 *Sample B6 – Thin section, oblique polars*

Scale: The width of the photograph represents 0.5 mm

This view shows the typical appearance of the paste below part of the external surface subjected to abrasion resistance testing. The external surface runs along the right side of the field of view from A6 to I6. Shallow microcracks occur just below the external surface of the paste, for example around D4 and H4/5. Quartz aggregate particles occur in E1 and F5.

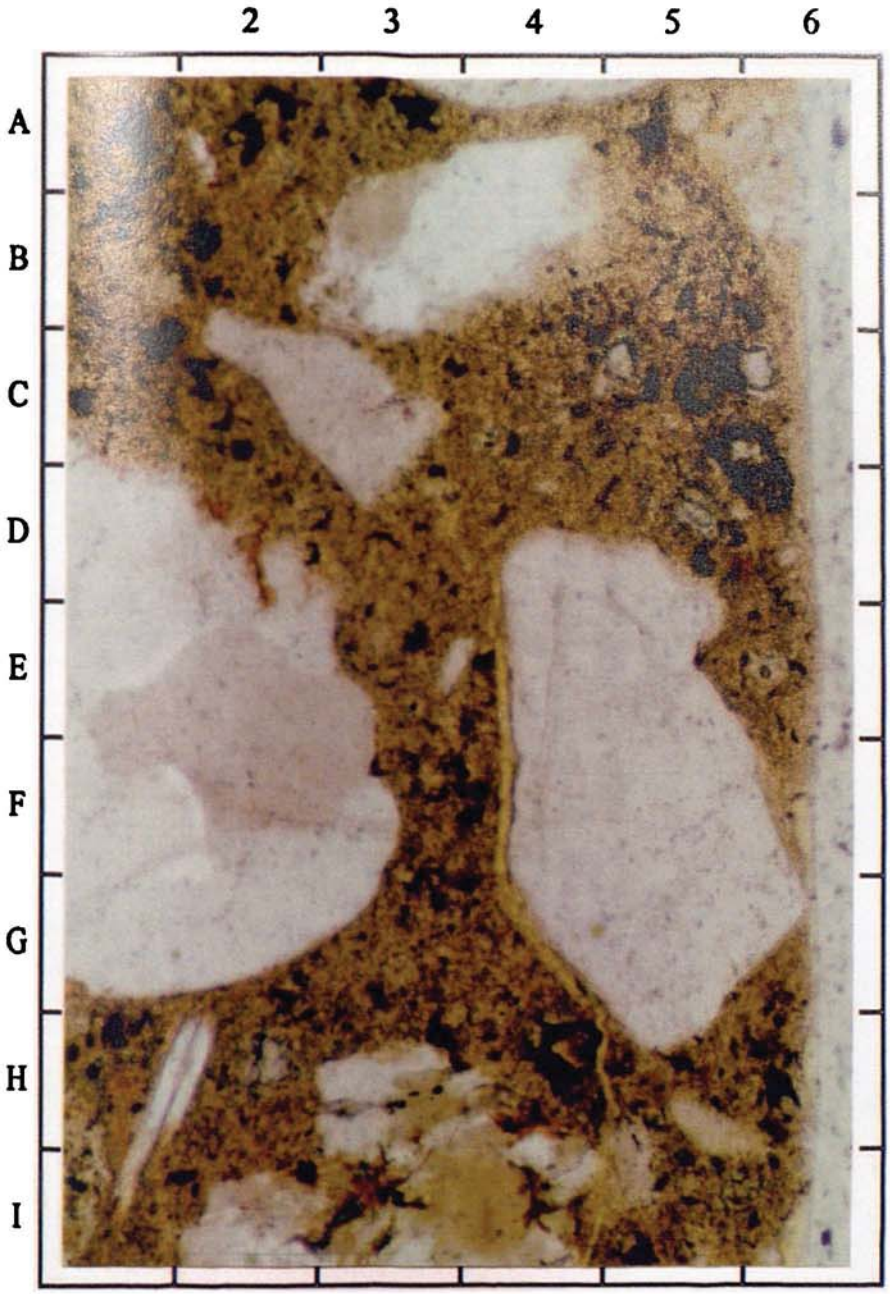


Plate G. 10 Sample B6 – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and microcracking below part of the external surface not subjected to abrasion resistance testing. The paste in this view has a generally high level of porosity and appears bright green, for example around C1 and D1. The external surface runs along the right side of the field of view from B6 to I6.

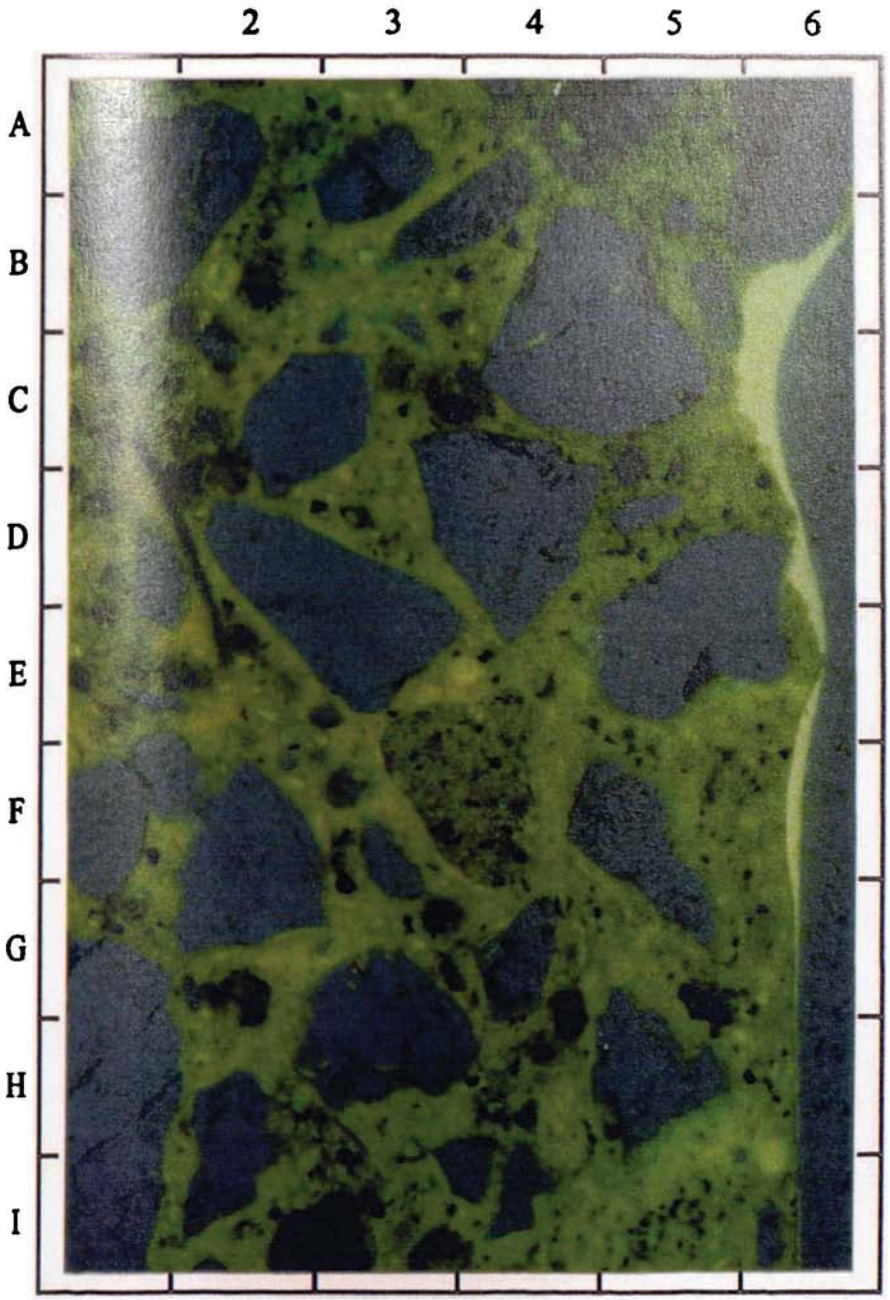


Plate G. 11 Sample B6 – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and microcracking below part of the external surface subjected to abrasion resistance testing. Abundant, shallow, surface parallel and sub-parallel cracks occur just below the external surface, for example around E5 and C4/5. Aggregate particles exhibiting microcracking can be seen for example in A5 and H5/6. The external surface runs from A6 to I5/6.

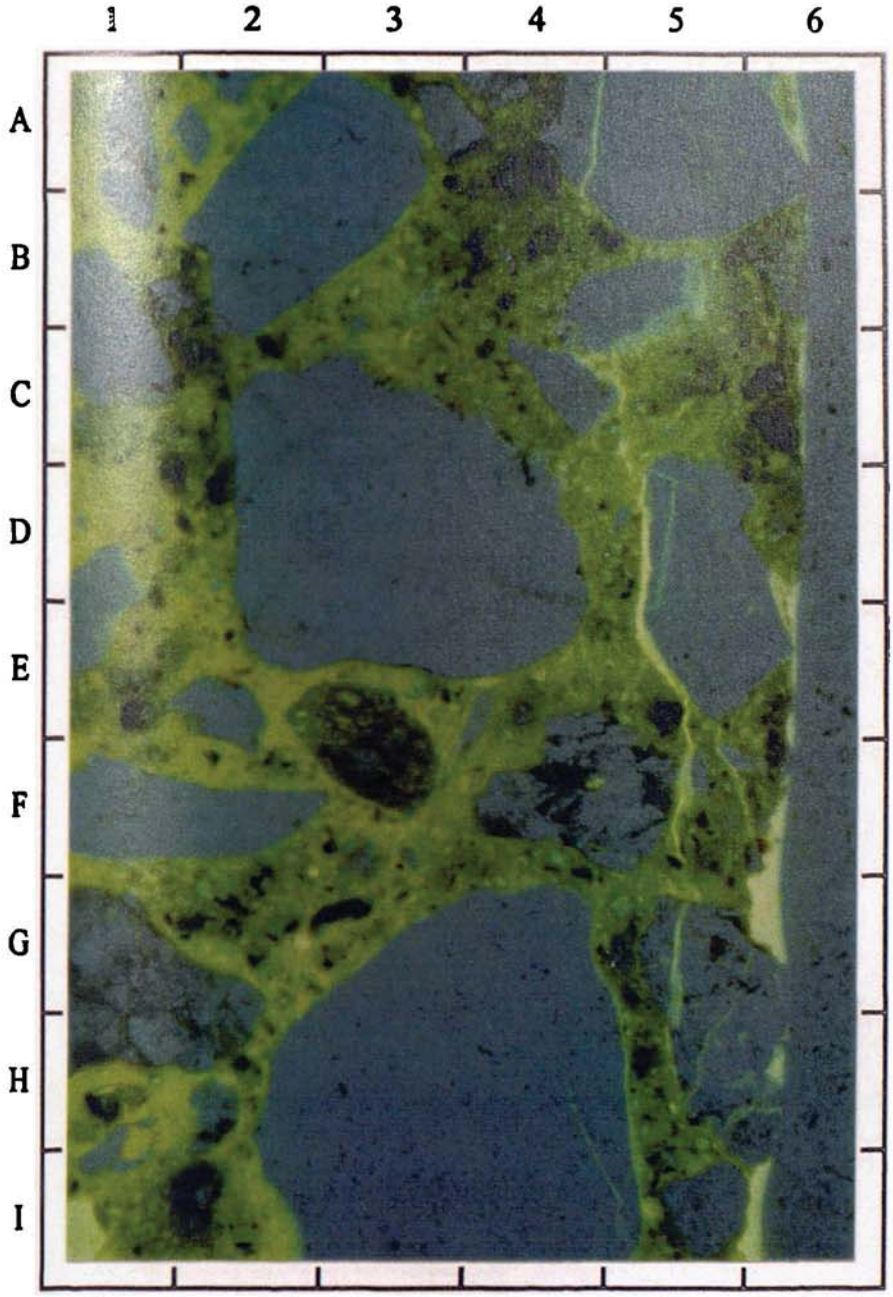


Plate G. 12 Sample A1, s/c, 0.51 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface runs along the right side of the field of view from A5 to I6. The red marker pen used to highlight the external surface has penetrated into the microcracks and aggregate particles at the external surface, for example in H5 and D5. Areas of cement containing abundant partially hydrated cement grains occur for example in B 2 and E1.

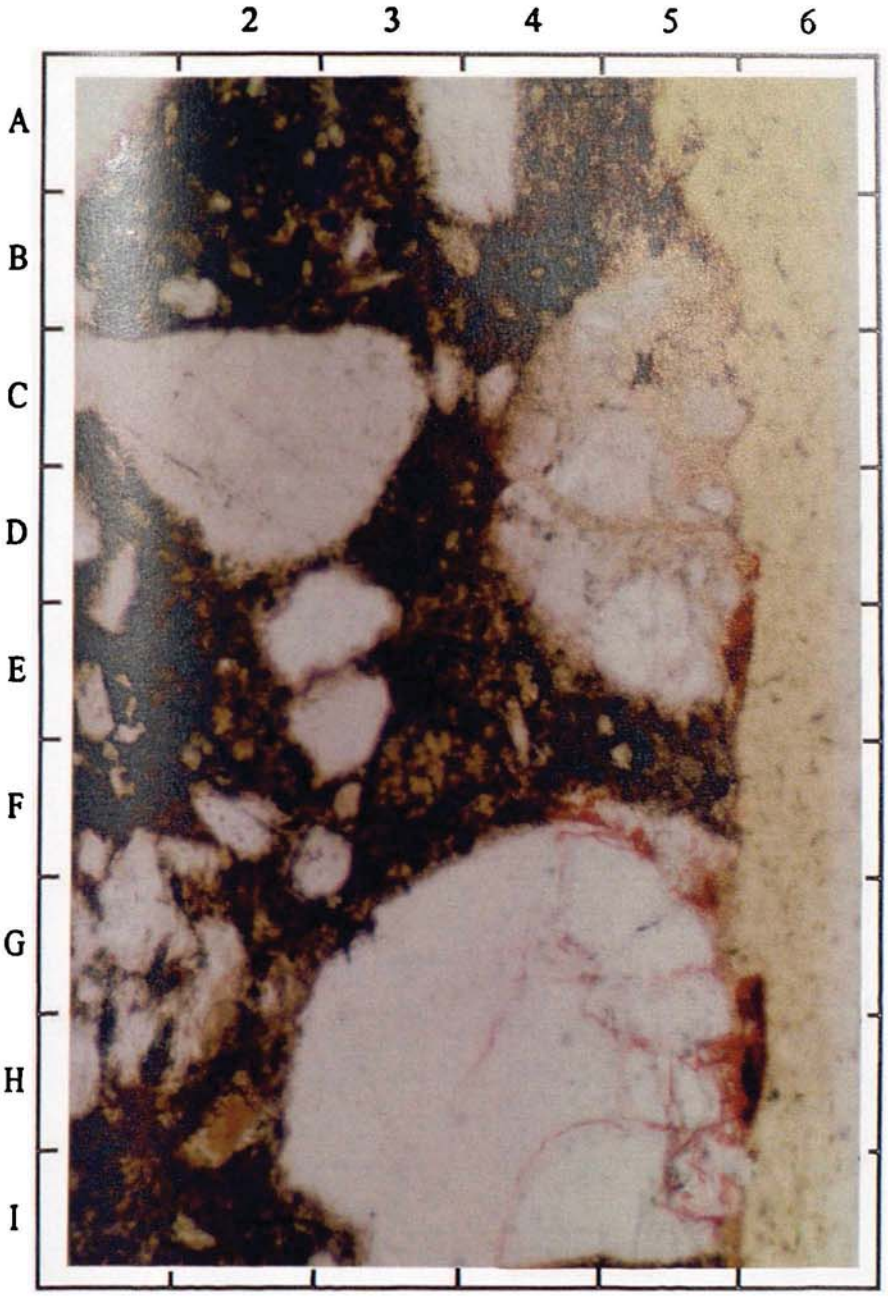


Plate G. 13 Sample A1, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

The external surface runs along the right side of the field of view from A6 to I6. This view shows the typical distribution of porosity and cracking below part of the surface not subjected to abrasion testing. A vertically orientated microcrack intersects the external surface at C/D6 and continues inwards towards C1. Much of the paste in this is of low porosity and is carbonated and appears medium to dark green.

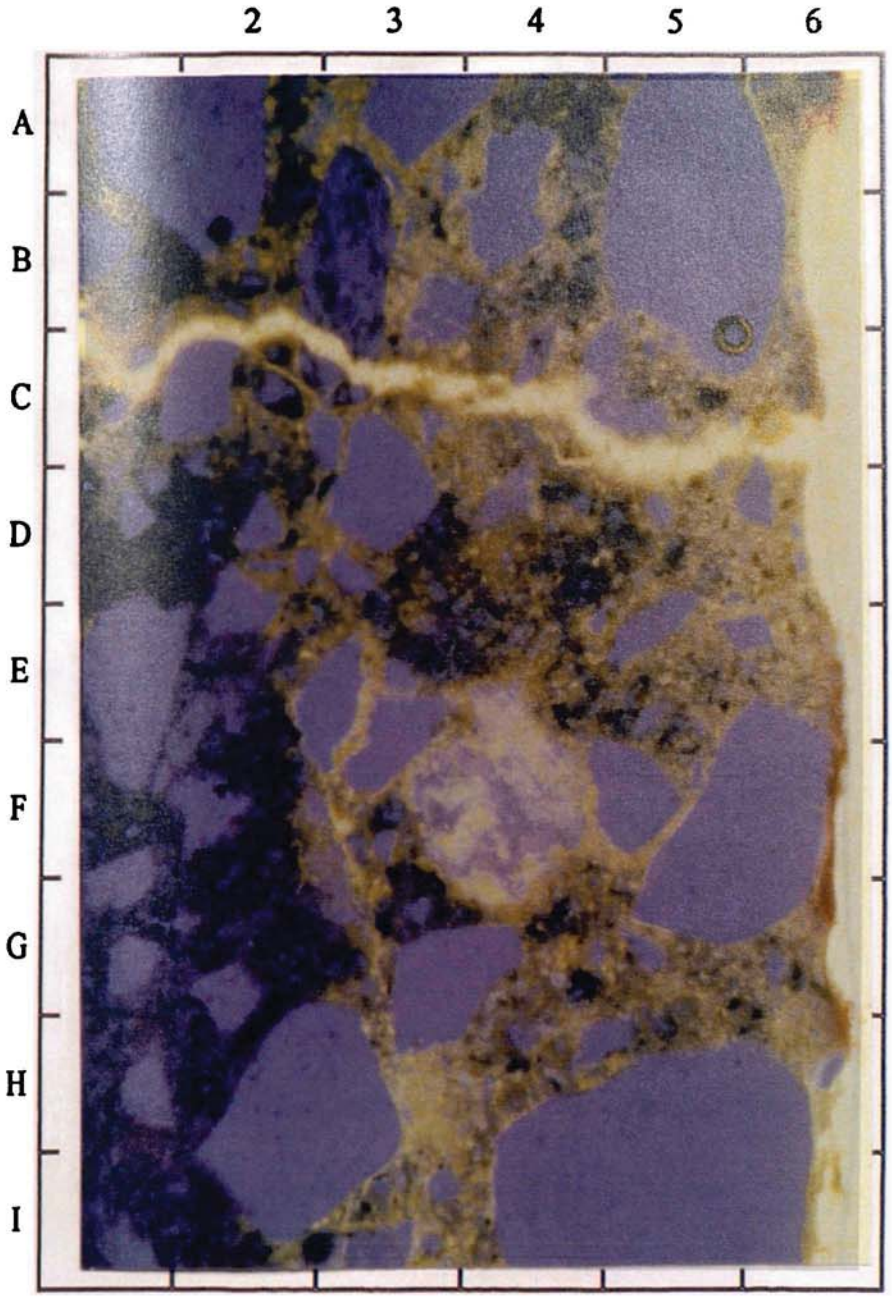


Plate G. 14 Sample A1, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows part of the surface subjected to abrasion testing. The external surface runs along the right side of the field of view from A4 to I5/6. Much of the field of view is occupied by a steel fibre, which appears black in this view. The paste surrounding the fibre has low levels of microcracking. However, the paste has plucked from the surface of steel fibre in A4 to C4.

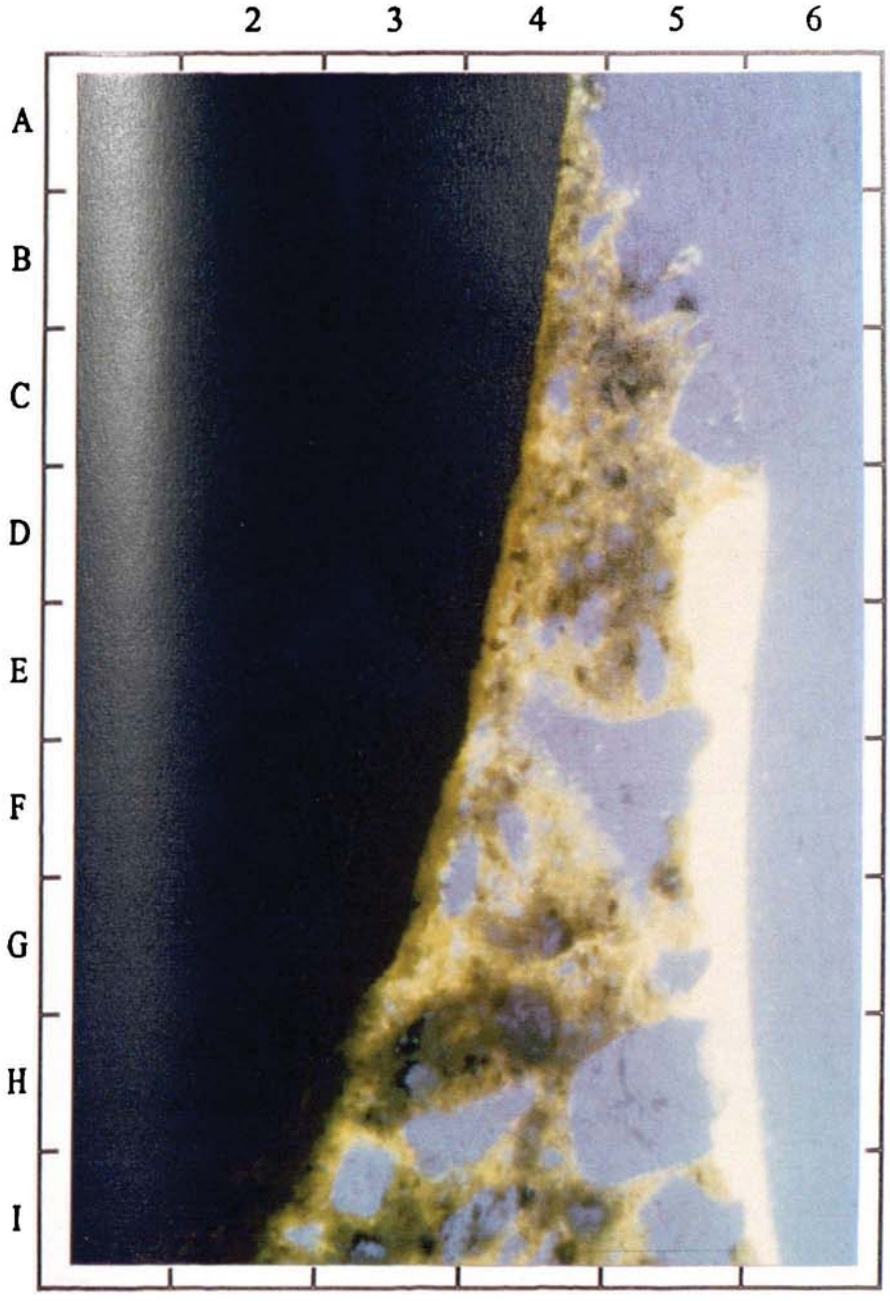


Plate G. 15 Sample A2, s/c, 0.51 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface runs along the right side of the field of view. Some extremely fine microcracks occur in an aggregate particle centred in F5. A particle of partially hydrated cement occurs just below the external surface in B/C5.

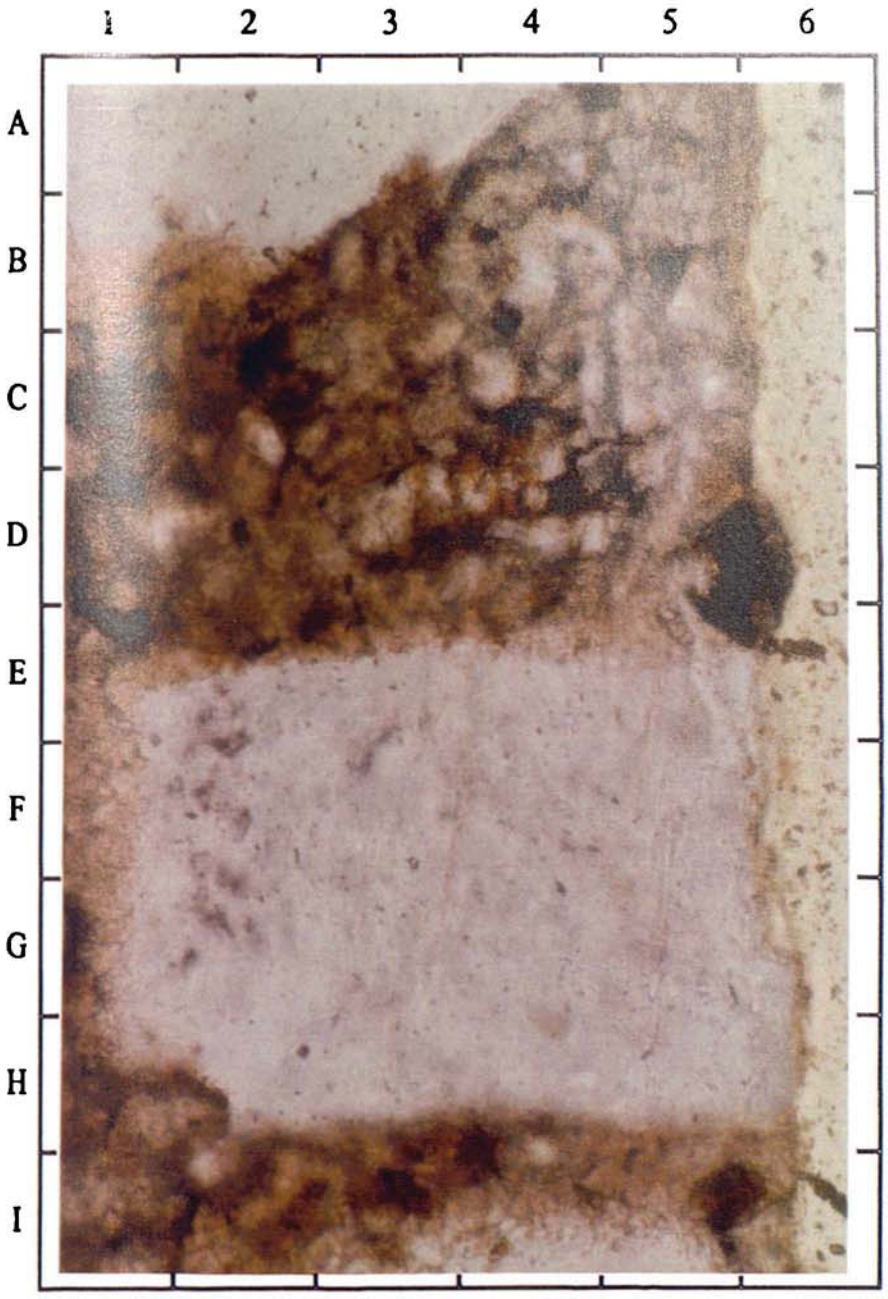


Plate G. 16 Sample A2, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the distribution of porosity below part of the surface of this sample that was not subjected to abrasion testing. The surface runs along the right side of the field of view from A6 to I6. There are some very shallow microcracks that are orientated vertically at the external surface, for example in D6. Much of the paste in this view is of low porosity.

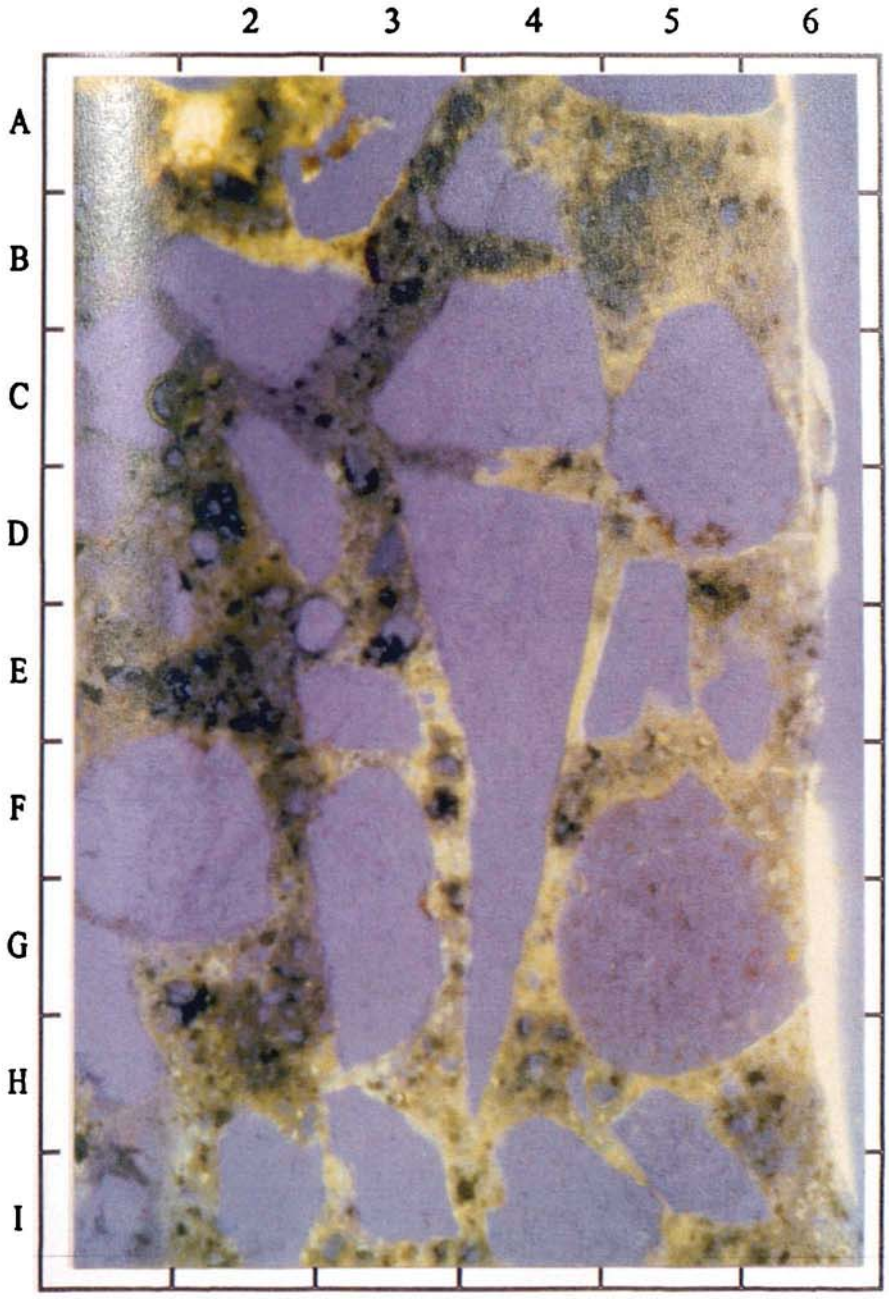


Plate G. 17 Sample A2, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity and microcracking below part of the external surface subjected to abrasion resistance testing. There are some very shallow microcracks in the paste just below the abraded external surface visible for example in D5 and G5. The paste in this view is carbonated and has patchy porosity.

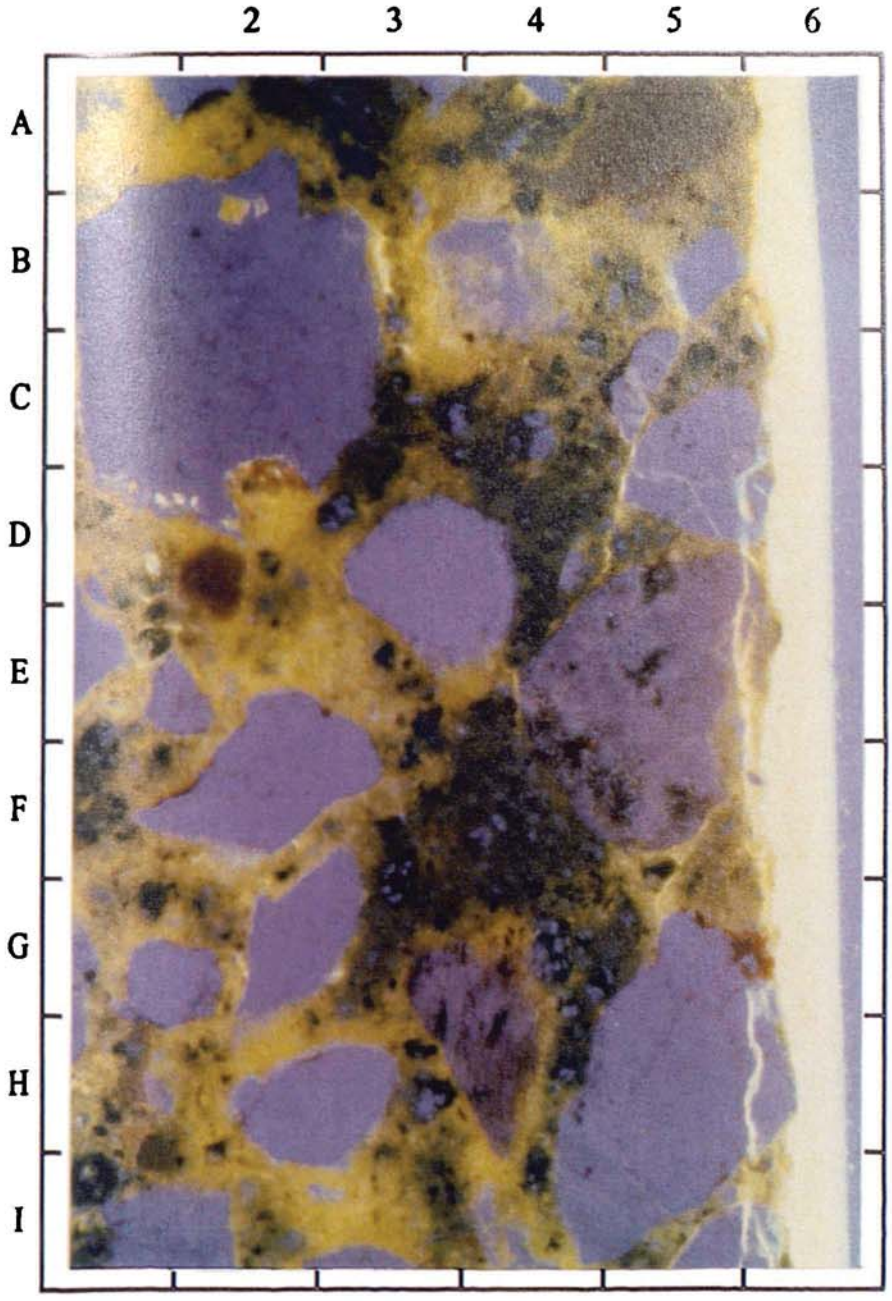


Plate G. 18 Sample A3, s/c, 0.51 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface runs along the top of the field of view from A1 to A6. The paste in this view has patchy carbonation and contains hydrated and partially carbonated cement grains.

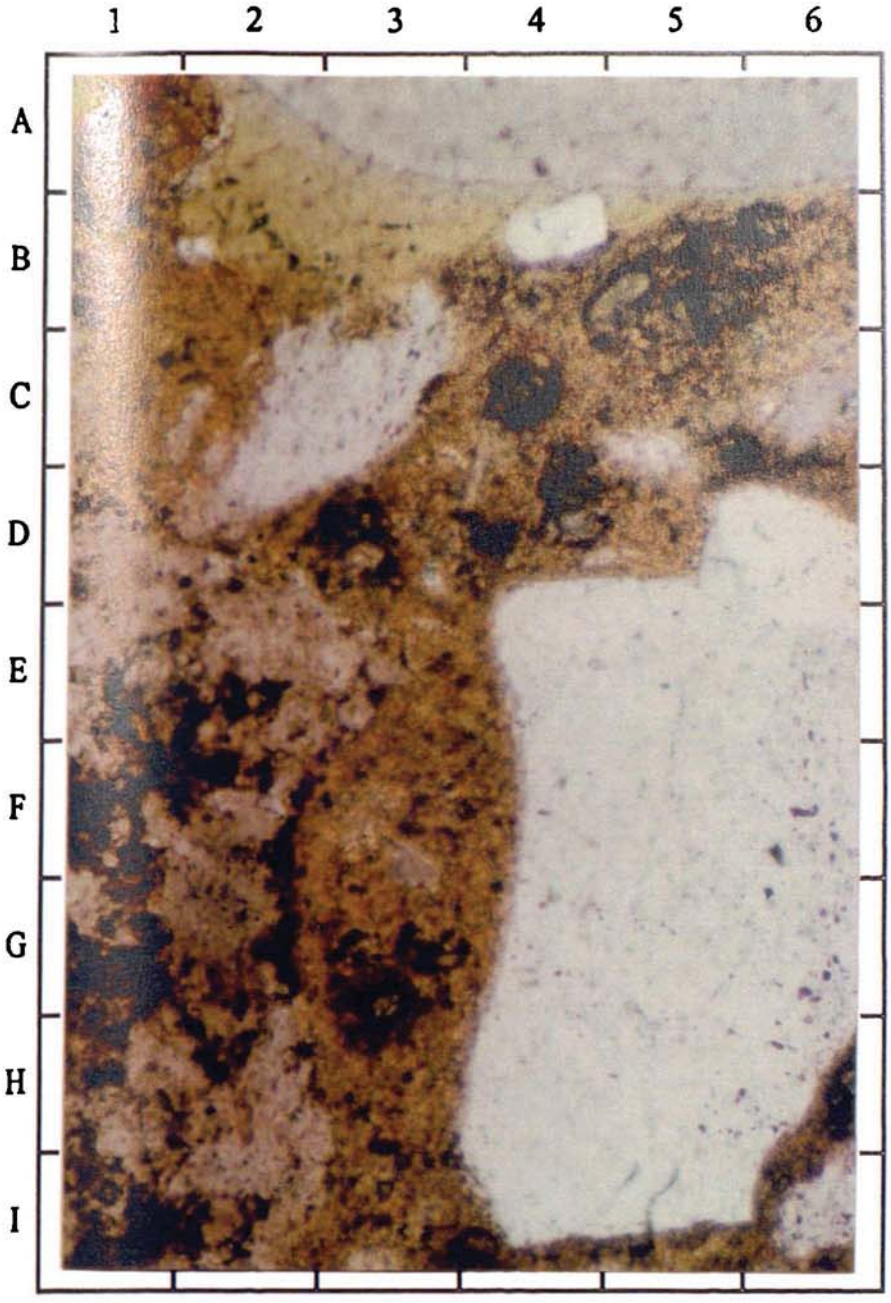


Plate G. 19 Sample A3, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of porosity below part of the surface not subjected to abrasion resistance testing. The external surface runs along the right side of the field of view from A5 to I6. The paste in this view has a moderate to high patchy porosity and appears bright green.

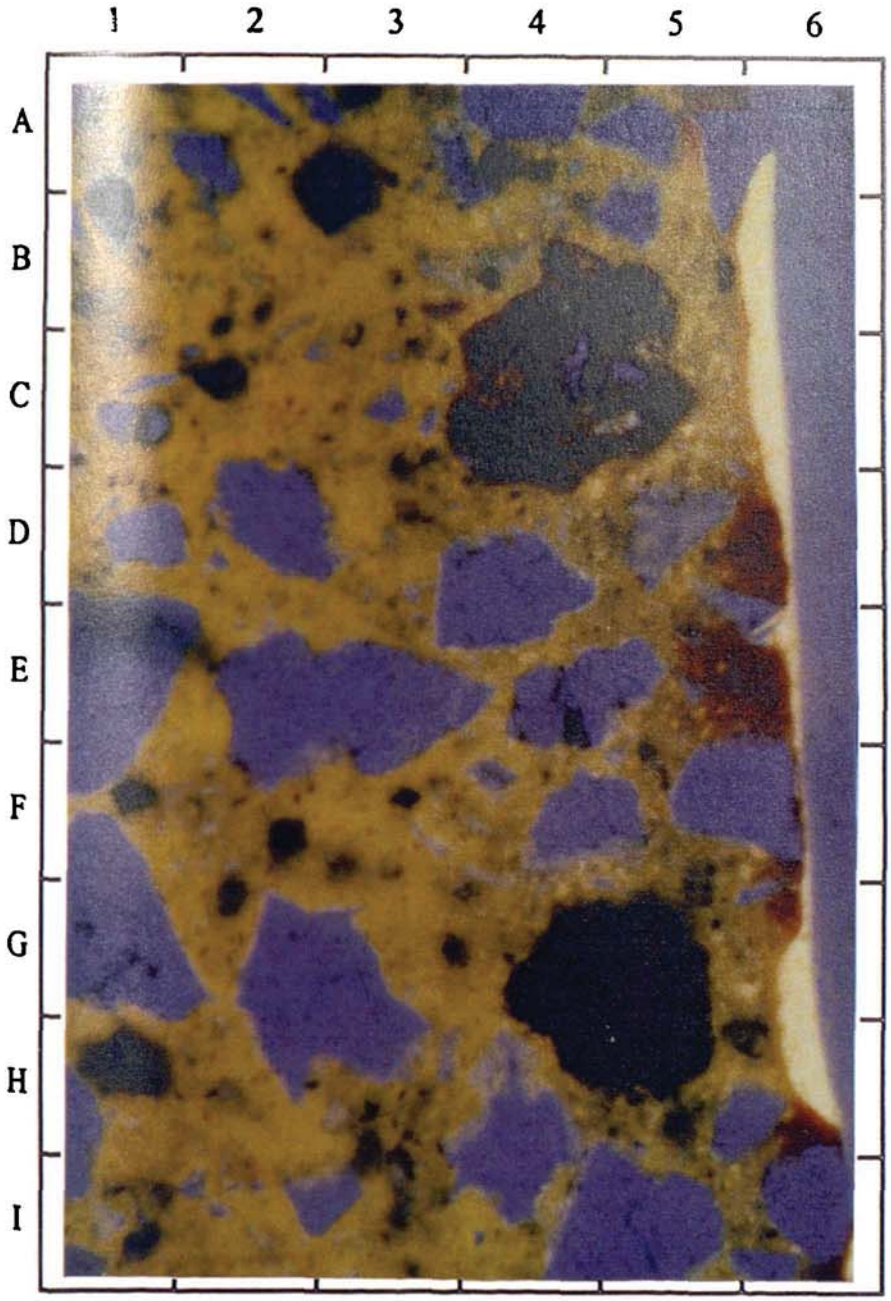


Plate G. 20 Sample A3, s/c, 0.51 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

The external surface runs along the right side of the field of view. This view shows part of the surface subjected to abrasion. A steel wire occupies much of the field of view and appears black. The paste close to the external surface and close to the contact with the steel wire contains locally abundant microcracks, for example around E5.

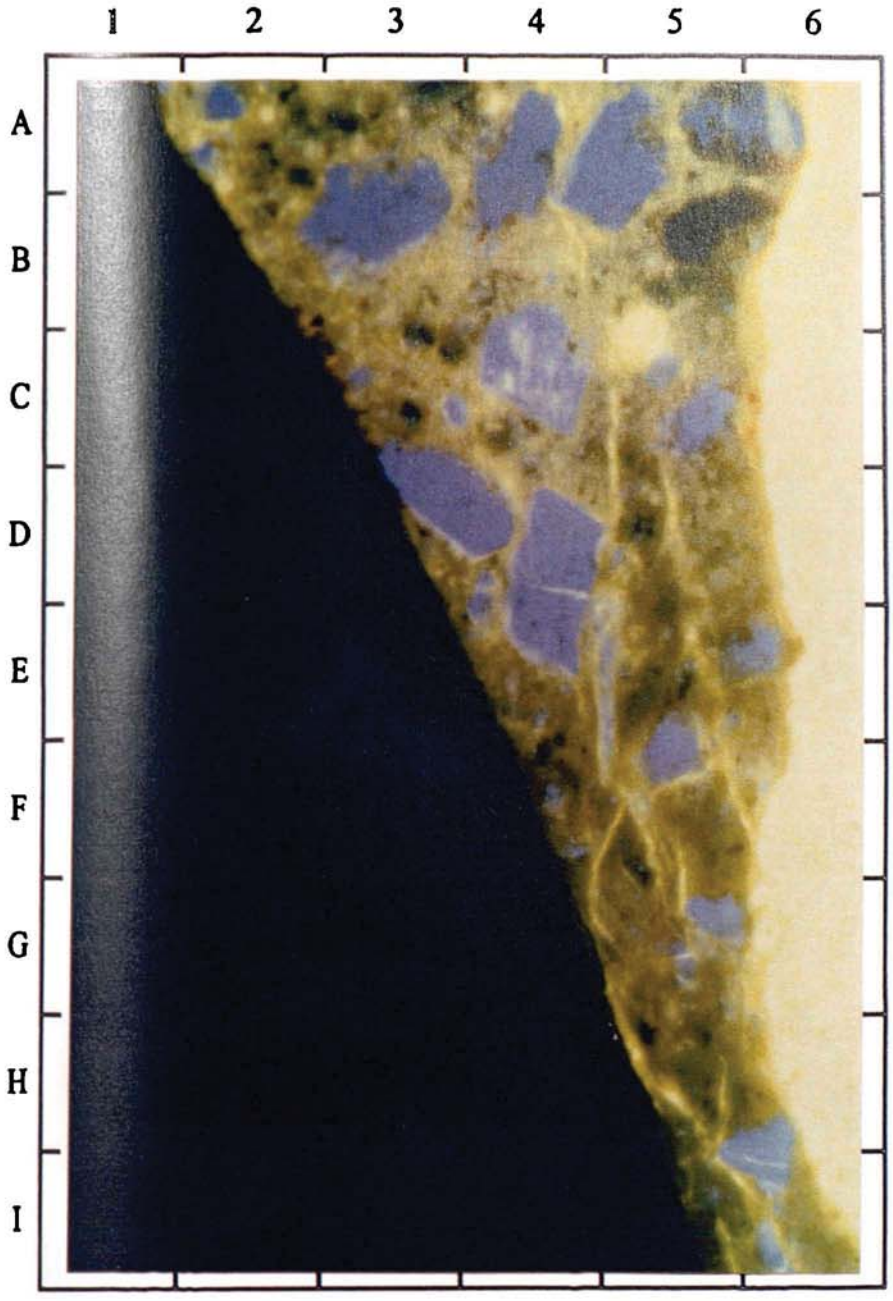


Plate G. 21 Sample A2, s/c, 1.0 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface occurs towards the top of the field of view. Microcracks are locally abundant around the broken aggregate particle that is exposed at the external surface (C2, C3). Much of the paste in this view has patchy carbonation. Quartz sand grains occur for example in E1 and F6.

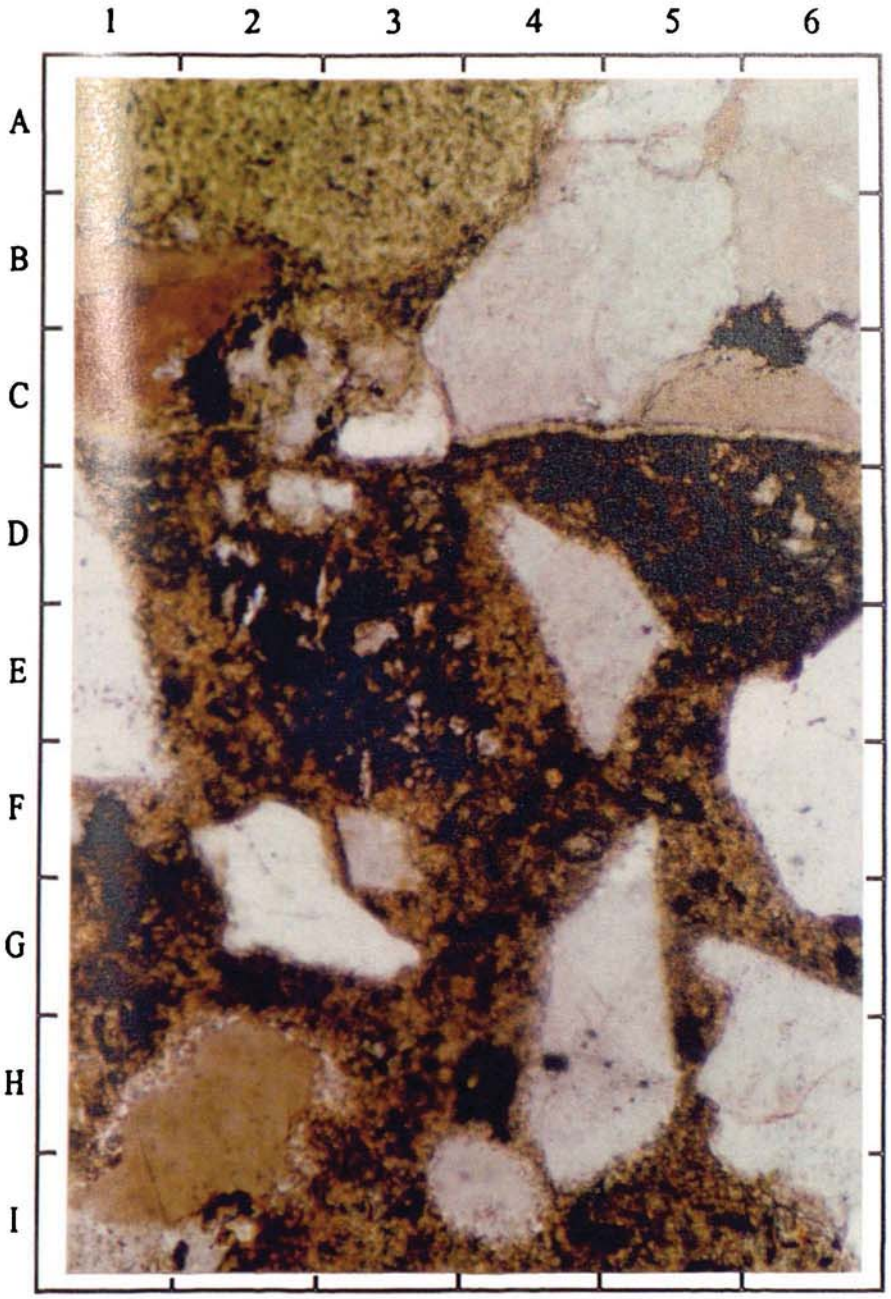


Plate G. 22 Sample A2, s/c, 1.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the distribution of porosity below part of the surface of this sample not subjected to abrasion testing. The surface is irregular and has patchy porosity and runs from A6 to I6.

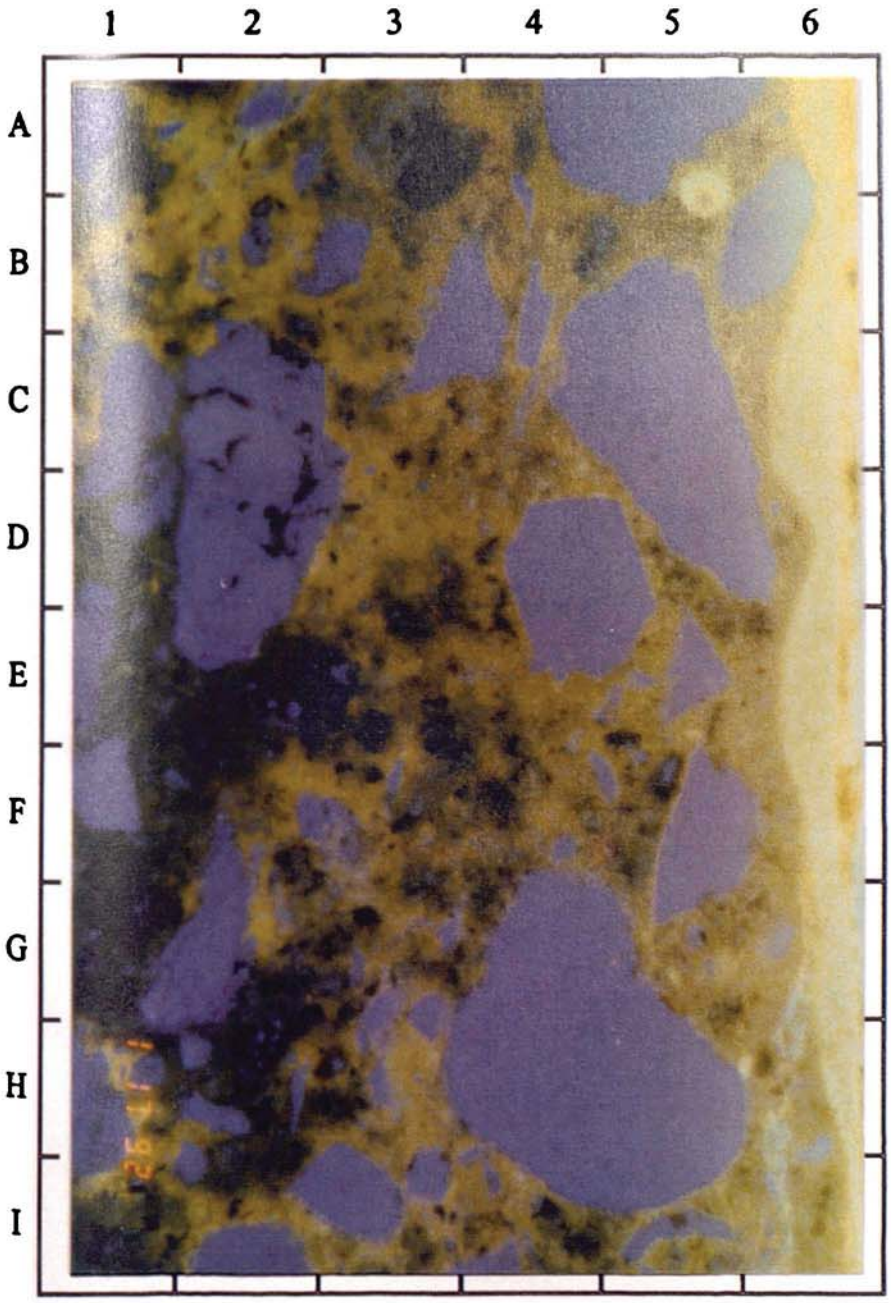


Plate G. 23 Sample A2, s/c, 1.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the paste below part of the surface subjected to abrasion testing. The paste contains locally abundant microcracks, for example around D4/5. The external surface runs from A6 to I6 and a particle of ironstone is centred on A1.

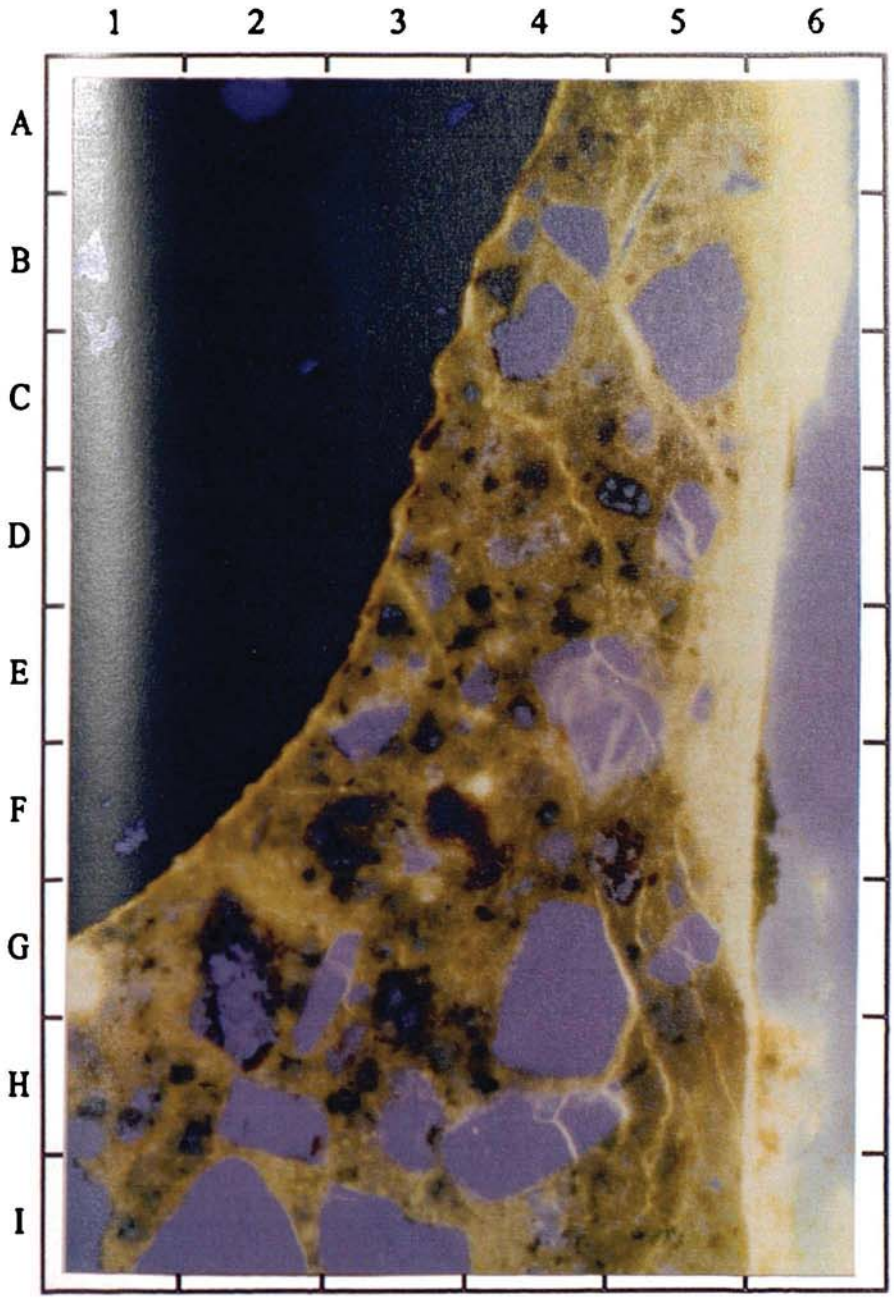


Plate G. 24 Sample A2, s/c, 1.5 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

A particle of steel wire is centred in B5. The paste surrounding the steel wire contains very few microcracks or partings and contains small quantities of portlandite.

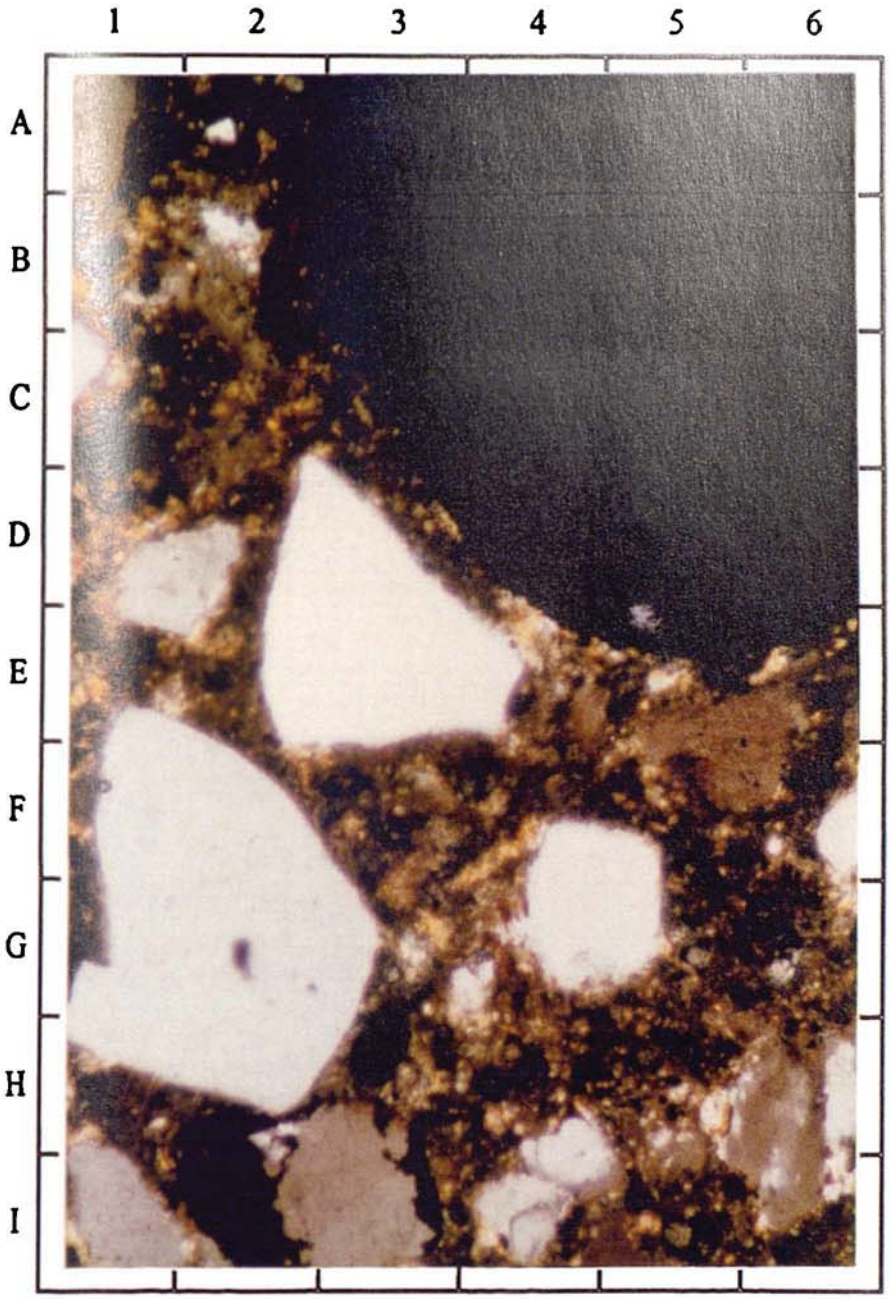


Plate G. 25 Sample A2, s/c, 1.5 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows an area of the external surface not subjected to abrasion resistance testing. The external surface runs along the right side of the field of view from A6 to I6 and a vertically orientated microcrack intersects the external surface in E6.

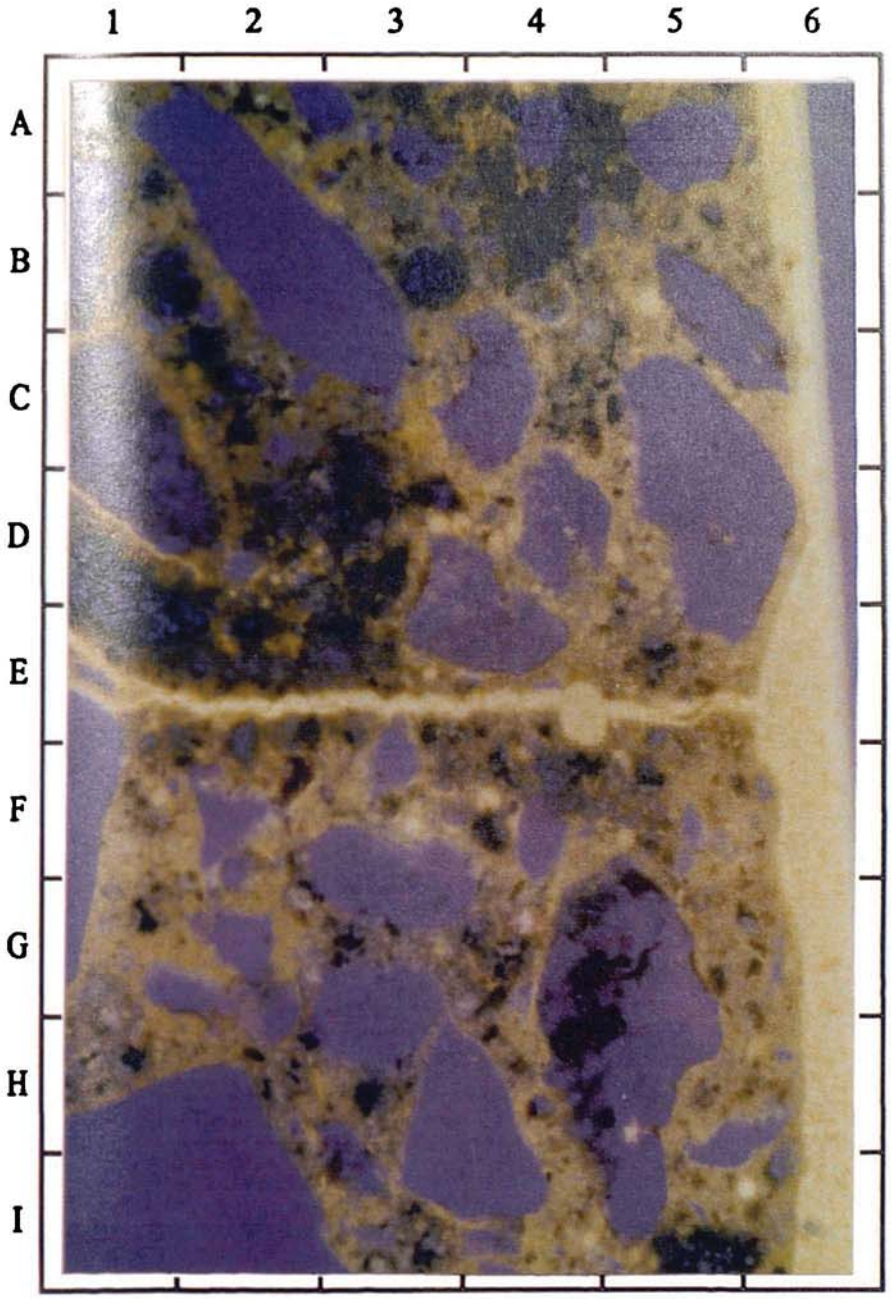


Plate G. 26 Sample A2, s/c, 1.5 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the paste in one of the parts of the surface that was subjected to abrasion testing. At the bottom of the field of view there is a steel wire that is centred in I3. The external surface that runs along the top of the field of view from A1 to A6 has locally abundant microcracks. However, there is very little microcracking between the surface of the steel wire and the concrete surface.

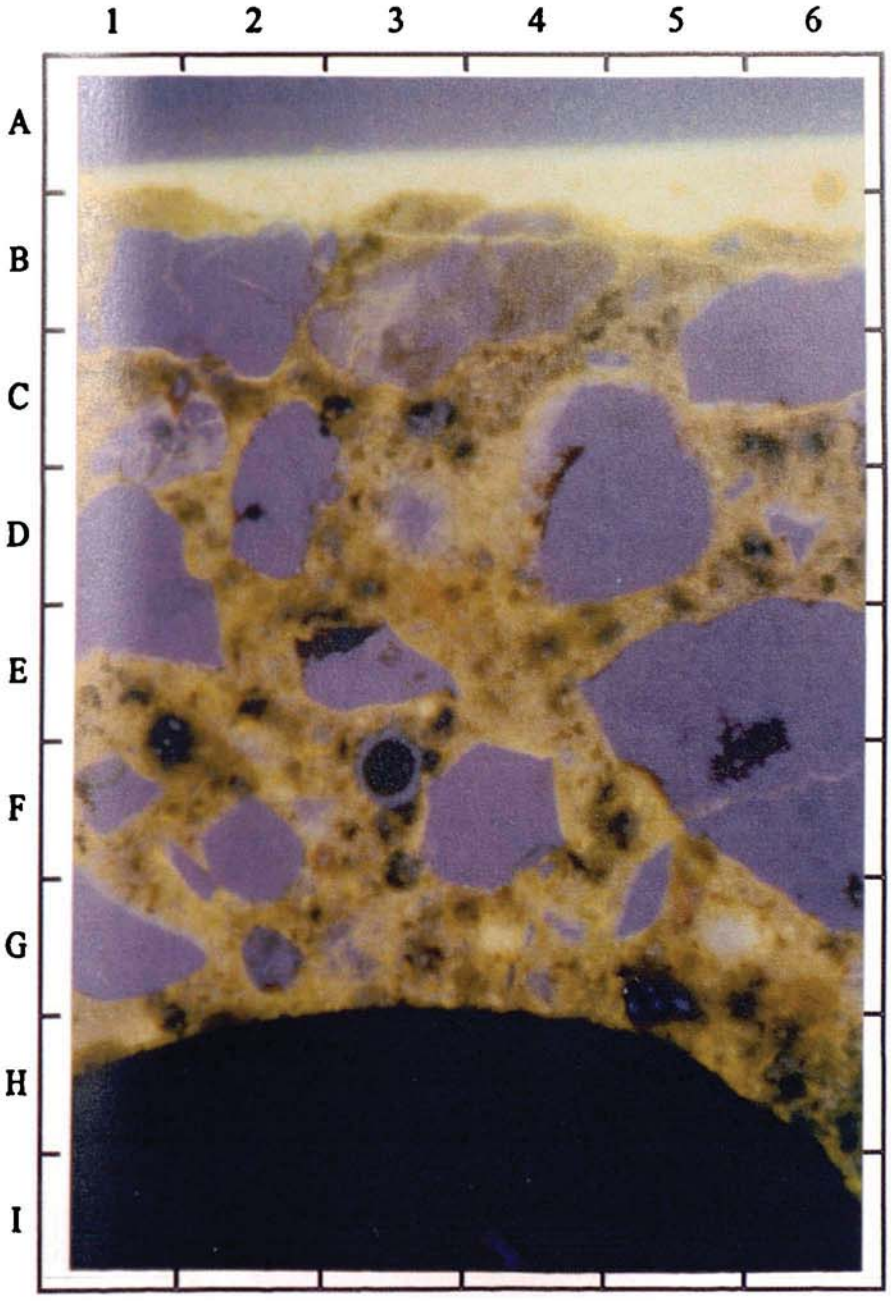


Plate G. 27 Sample A2, s/c, 2.0 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface runs along the top field of view. A vertically orientated microcrack connects voids centred in D/E3 and G/H4.

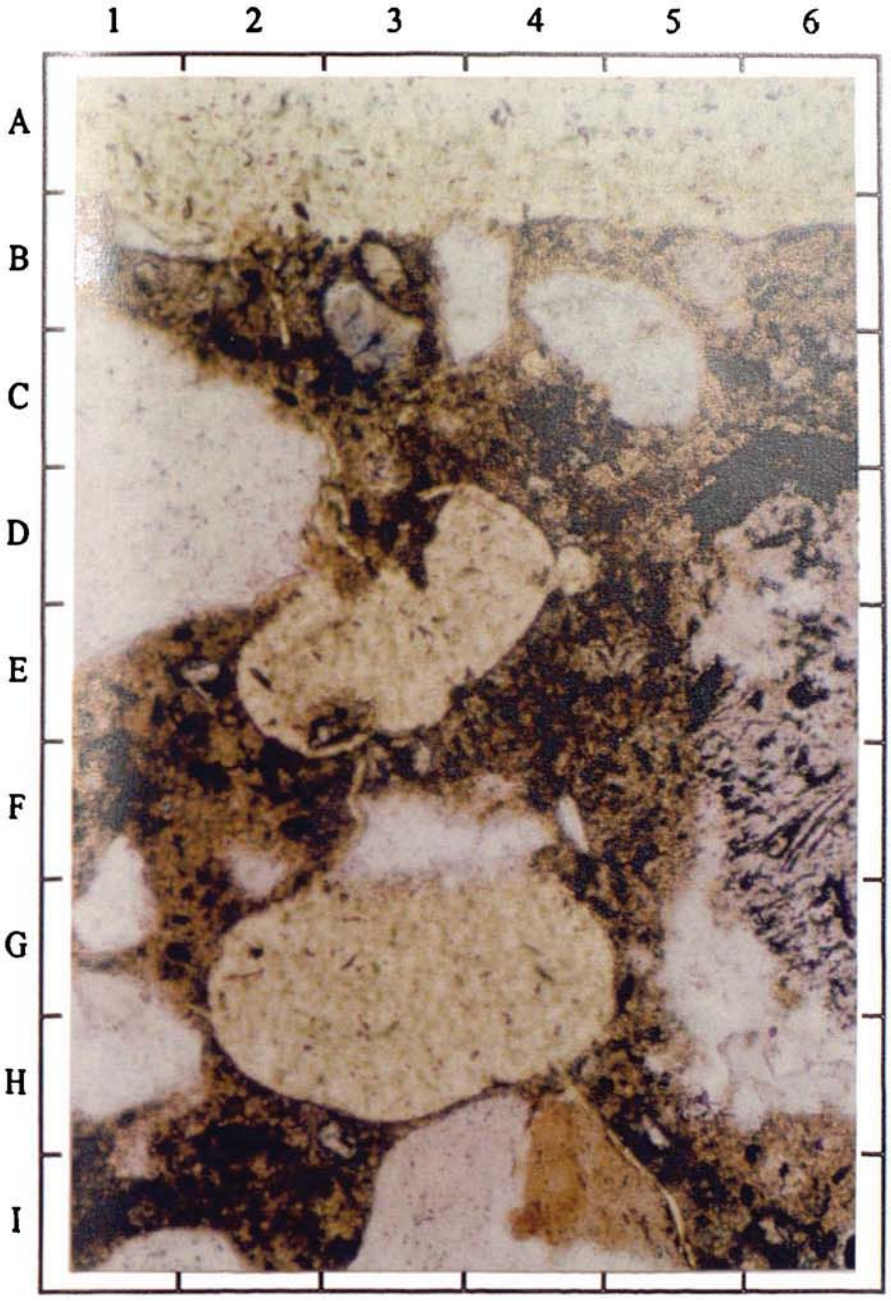


Plate G. 28 Sample A2, s/c, 2.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the surface not subjected to abrasion testing. The external surface runs along the right side of the field of view from A6 to I6 and is an irregular surface. a microcrack is centred on F5/6. The paste in this view has very patchy porosity.

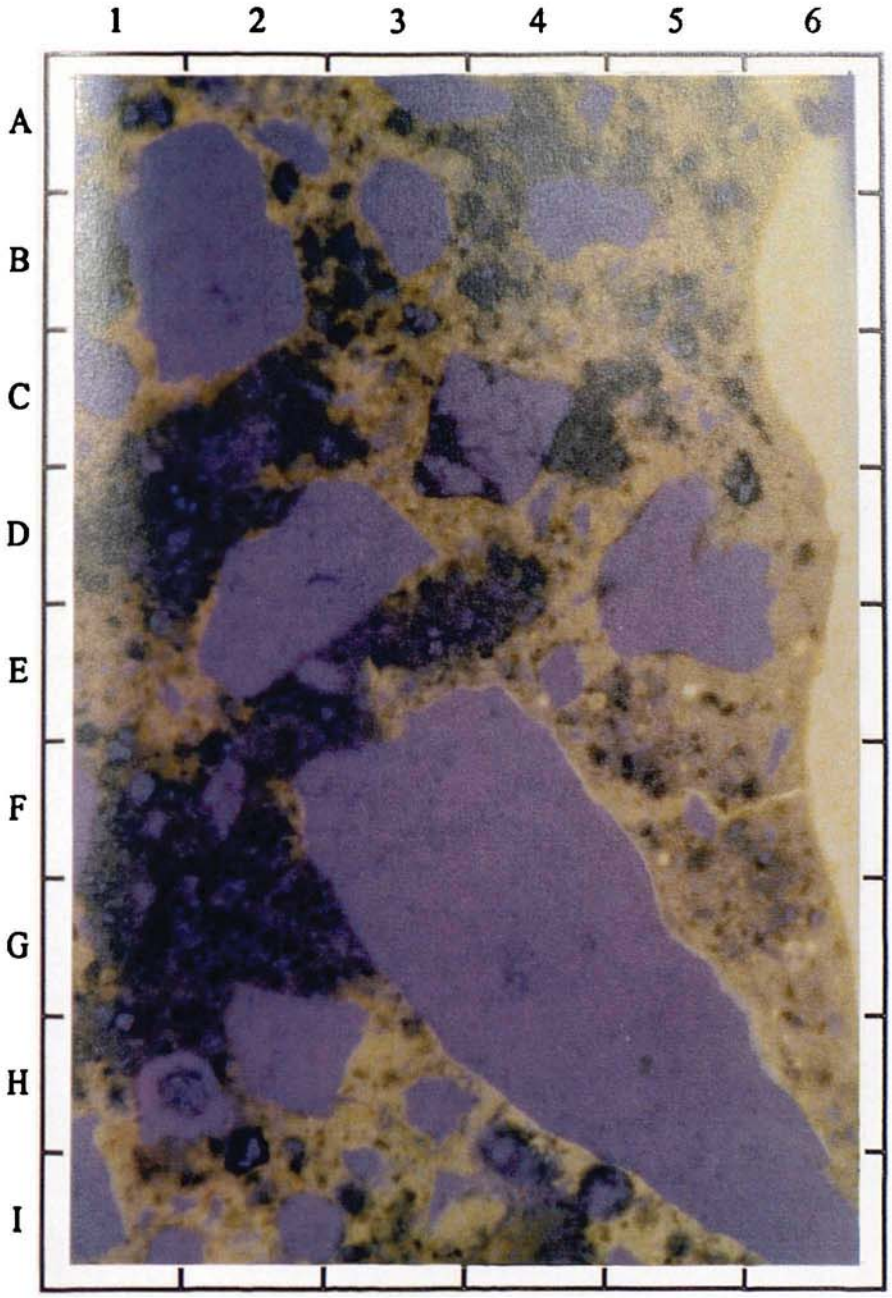


Plate G. 29 Sample A2, s/c, 2.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

The external surface runs along the right side of the field of view from A5/6 to I6. This view shows part of the surface subjected to abrasion testing. There are some very shallow microcracks in the paste just below the external surface. There are also some microcracks and locally abundant voids around the surface and an aggregate particle centred in C5.

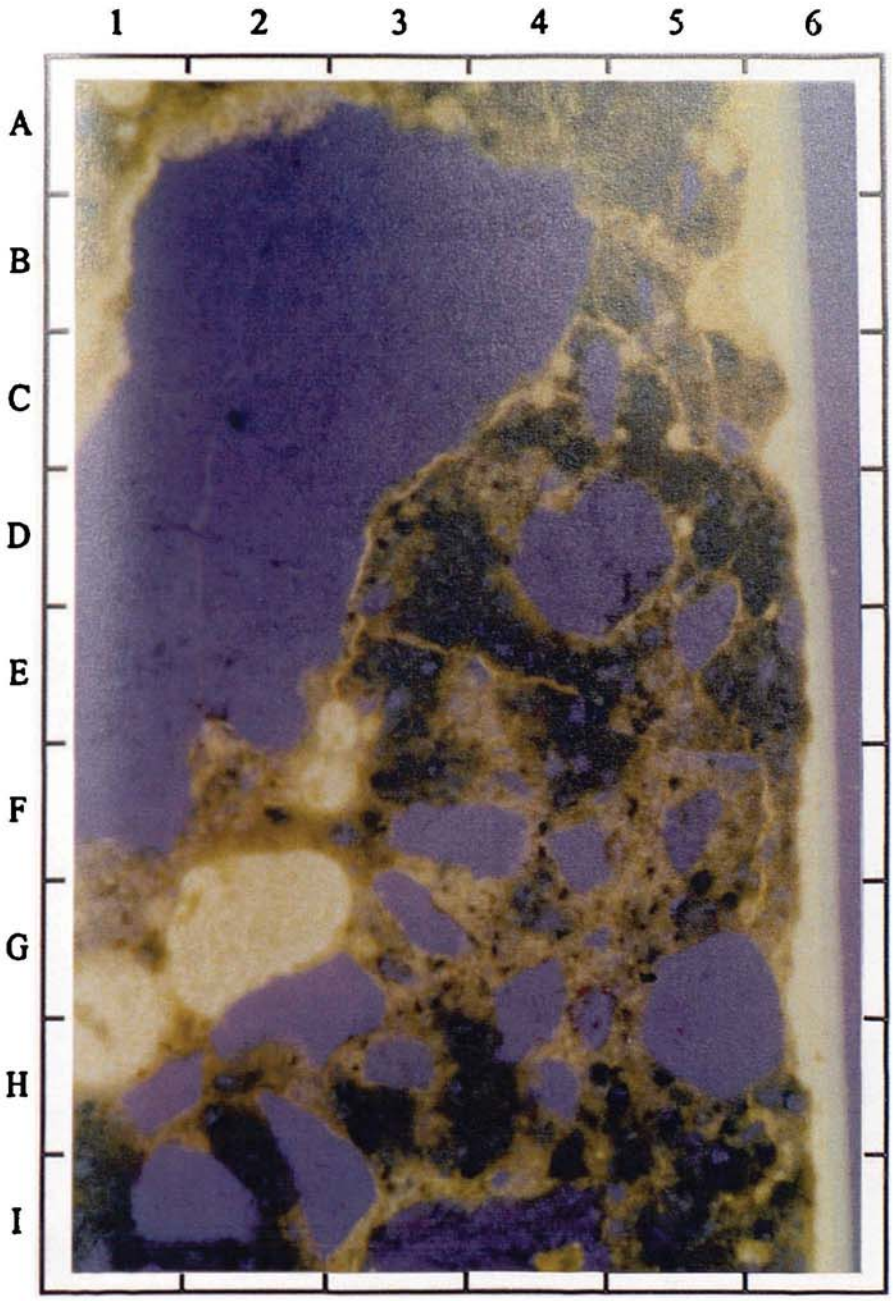


Plate G. 30 Sample A2, s/c, 3.0 % - 45 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface runs along the right side of the field of view. This view shows the paste surrounding one of the steel wires just below the external surface of this sample. Microcracks are abundant in the paste above the steel wire, for example around B6 and F5. The external surface runs along the left side of the field of view and the steel wire in this view appears black and is centred on E1.

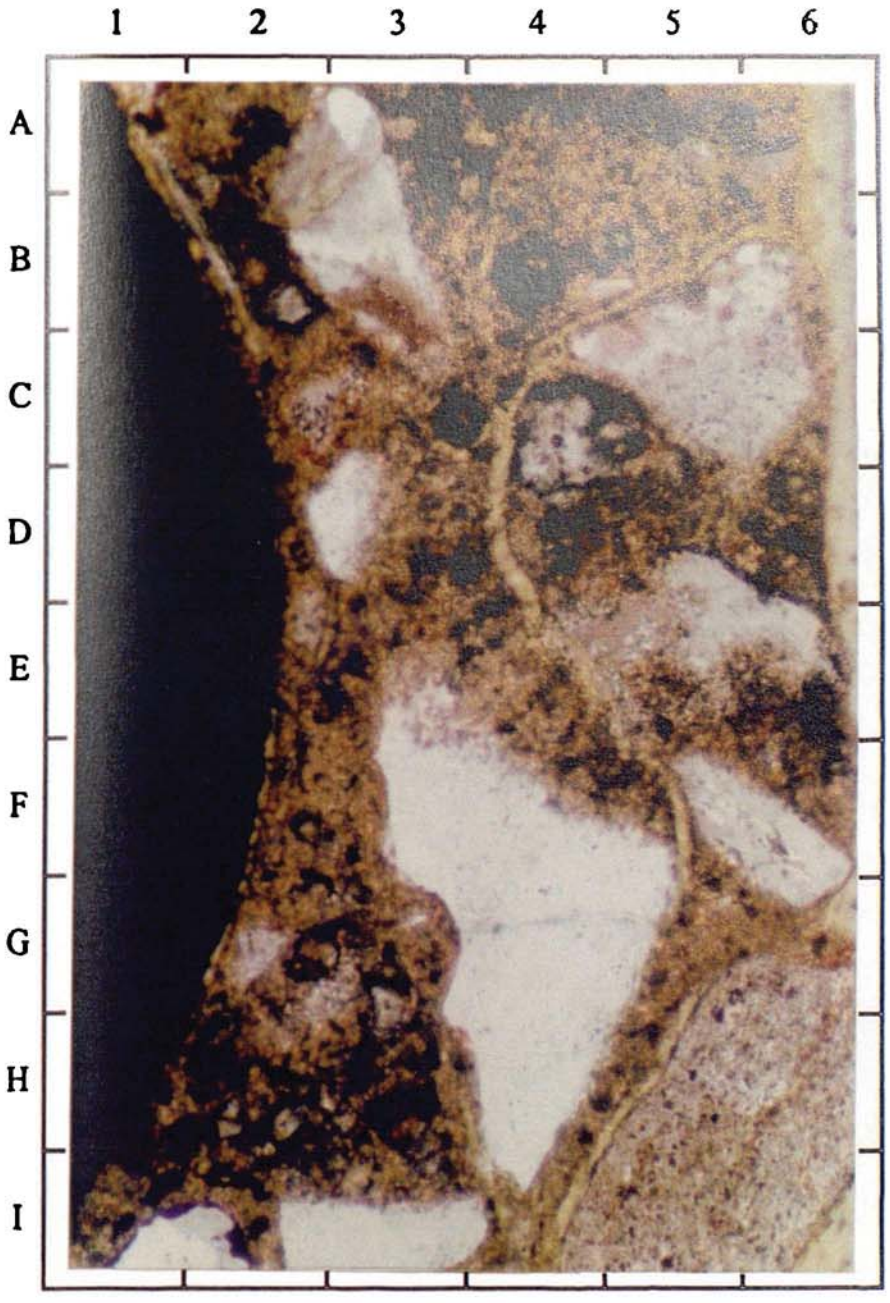


Plate G. 31 Sample A2, s/c, 3.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

The external surface runs along the right side of the field of view from A6 to I6. The paste below the external surface has patchy porosity.

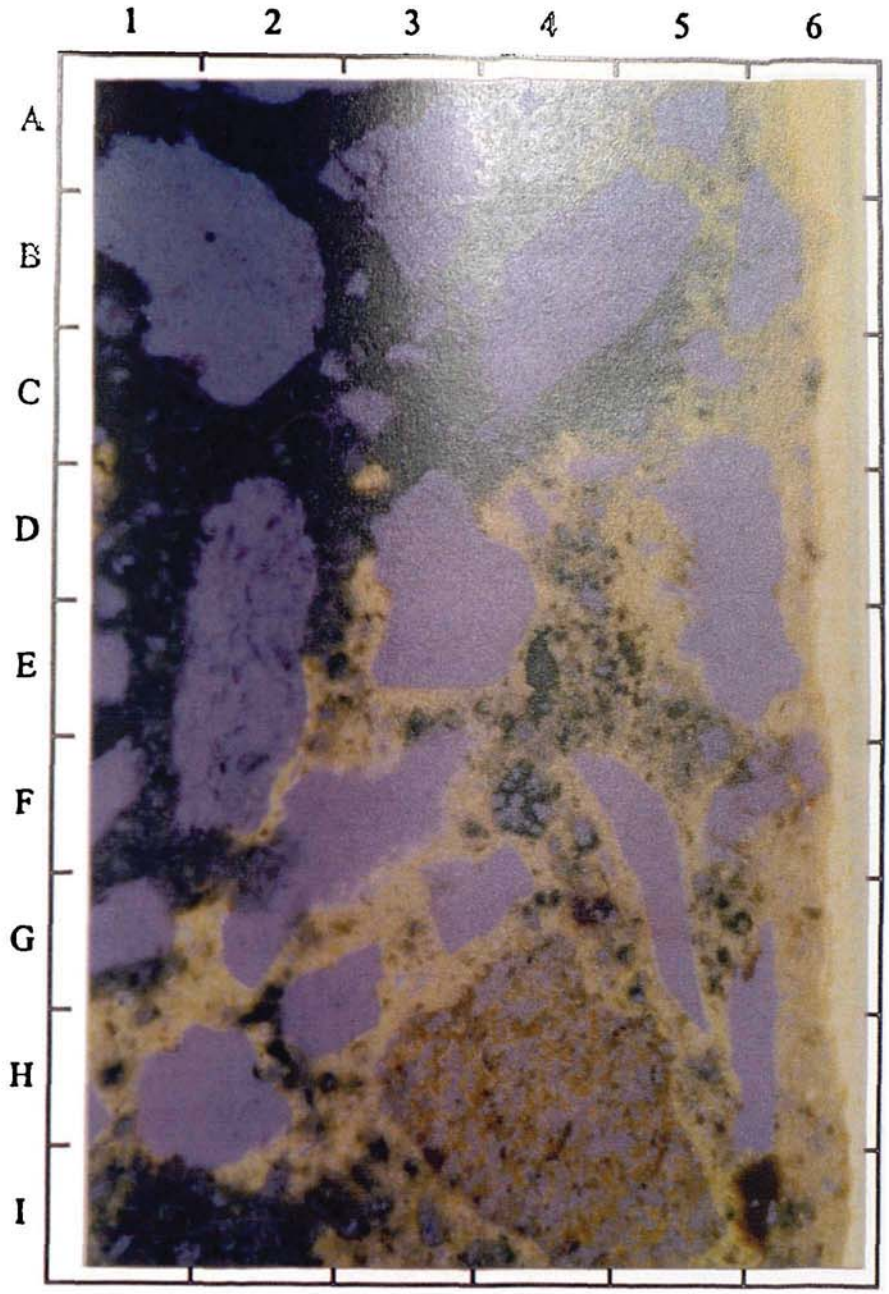


Plate G. 32 Sample A2, s/c, 3.0 % - 45 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

The external surface runs along the right side of the field of view from A6 to I6. The paste below the external surface contains some very shallow microcracks.

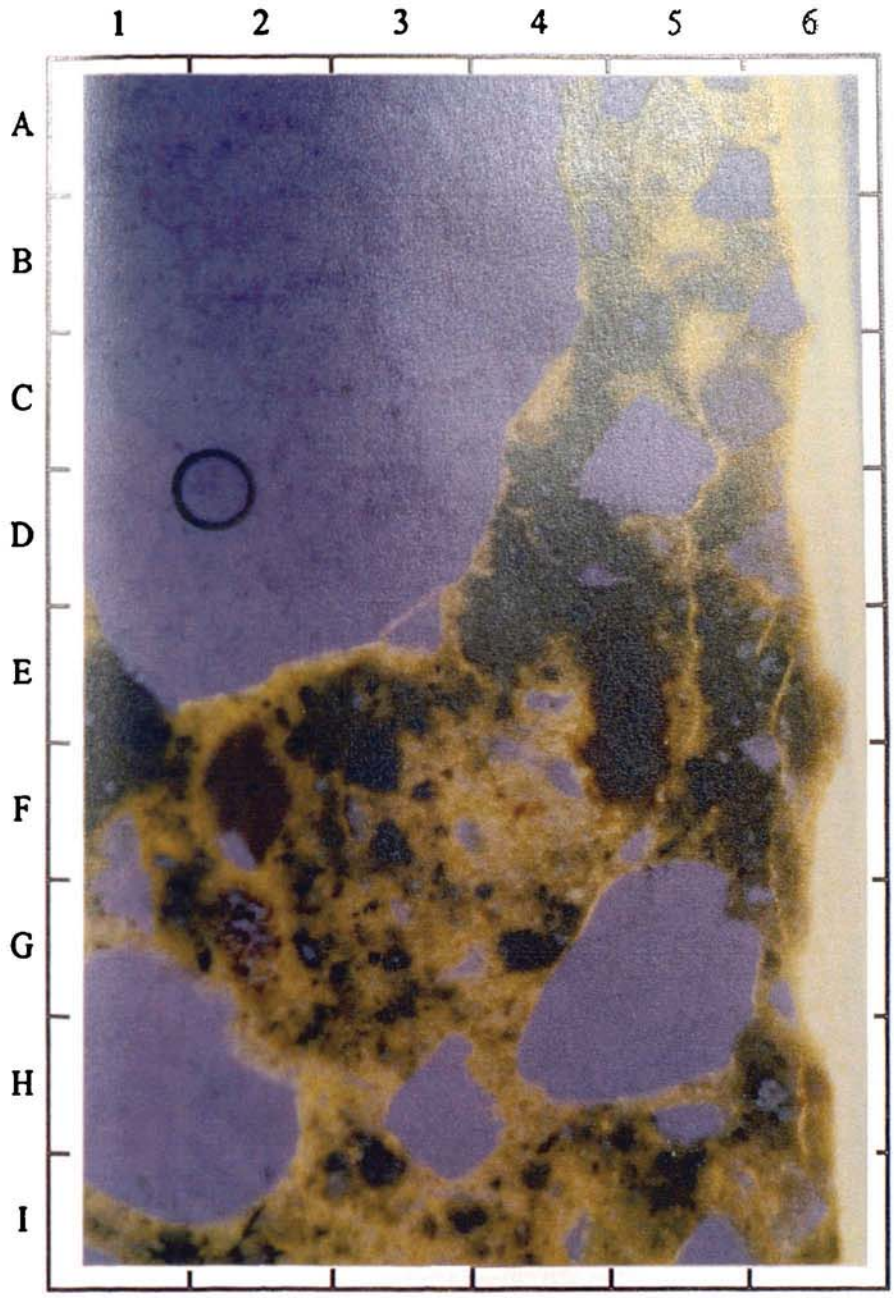


Plate G. 33 Sample A2, p, 0.1 % - 12 mm – Thin section, oblique polars

Scale: The width of the photograph represents 0.5 mm

The external surface occurs towards the top of the field of view. A polypropylene fibre bridges a microcrack and runs from D1 to C4. Typical areas of paste containing abundant particles of unhydrated and partially hydrated cement occur for example around G6 and C1.

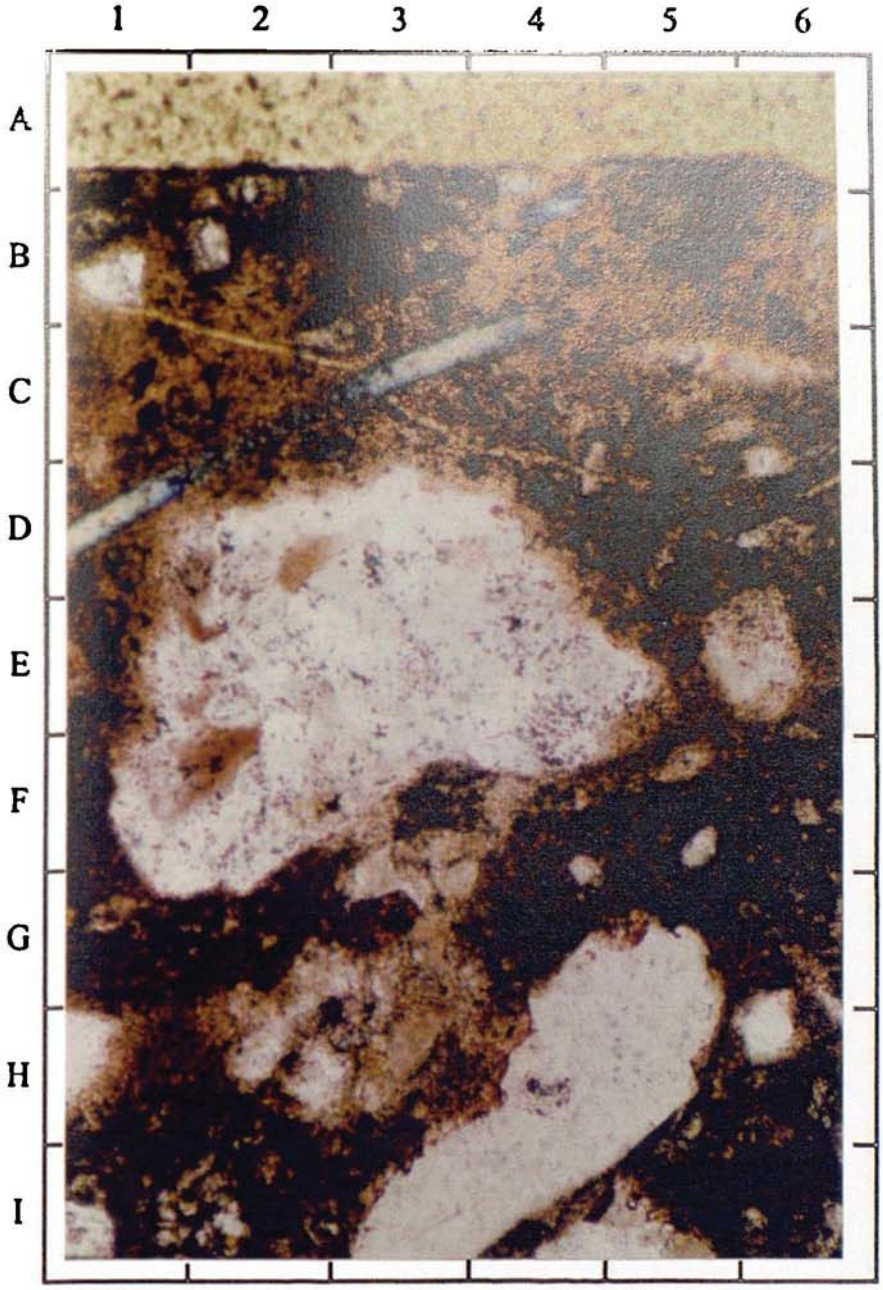


Plate G. 34 *Sample A2, p, 0.1 % - 12 mm – Thin section, fluorescent light*

Scale: The width of the photograph represents 1 mm

This view shows part of the external surface that was not subjected to abrasion resistance testing. The paste has patchy porosity and the external surface runs from A6 to I6.

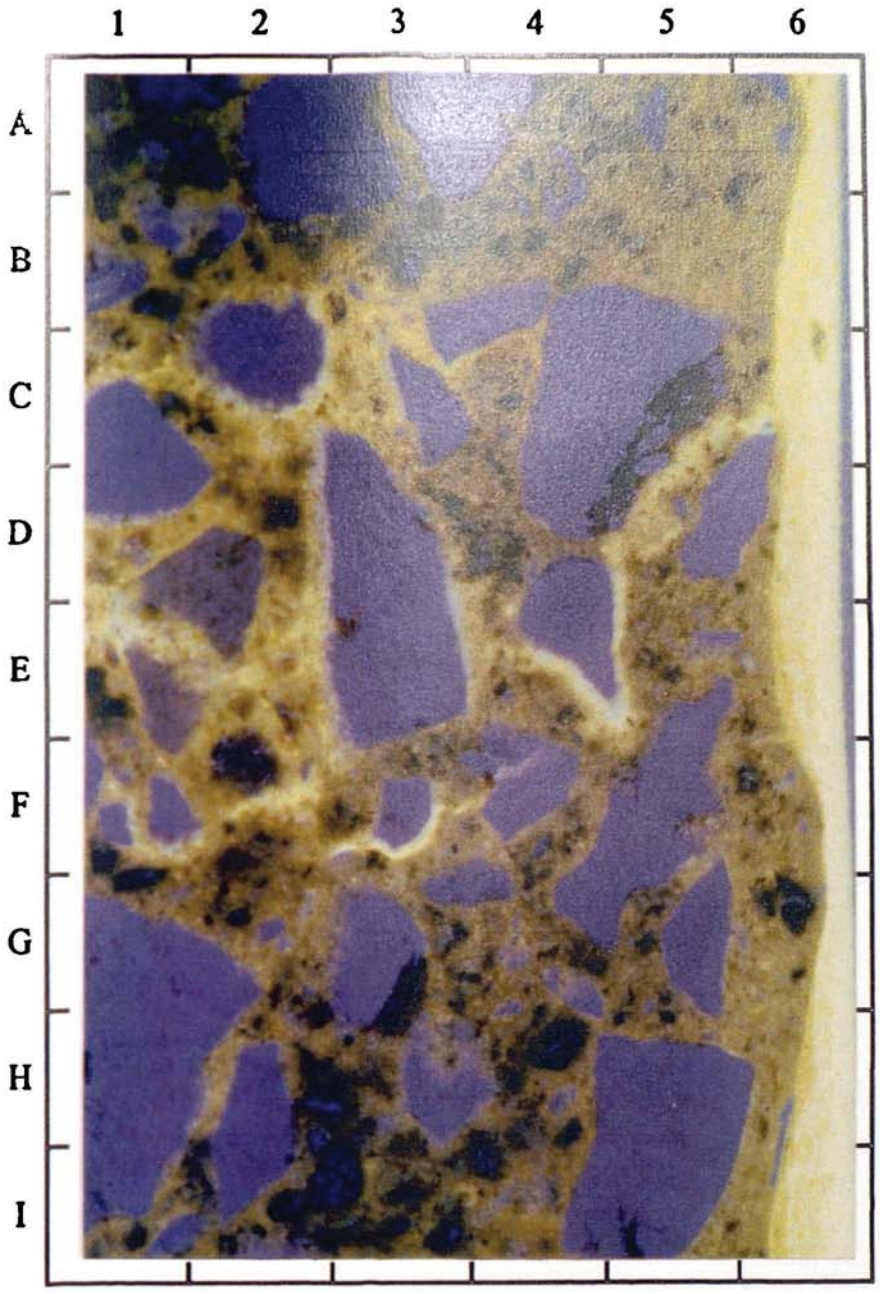
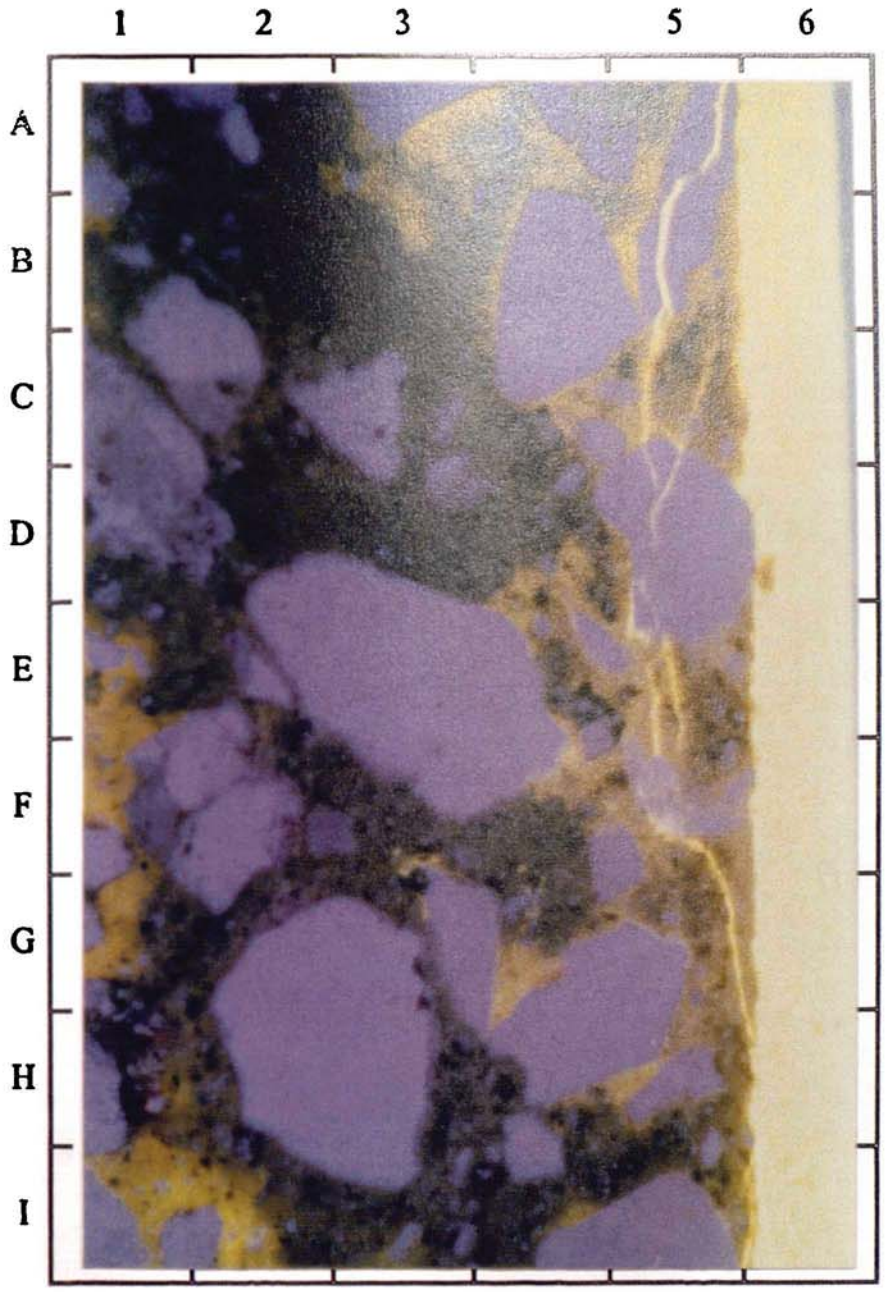


Plate G. 35 Sample A2, p, 0.1 % - 12 mm – Thin section, fluorescent light

Scale: The width of the photograph represents 1 mm

This view shows the typical distribution of microcracking below part of the surface of this sample subjected to abrasion resistance testing. The external surface runs along the right side of the field of view from A6 to I6 and areas of paste containing microcracks are visible for example in C5.



Appendix H: Indirect and non-destructive testing

Table H. 1 Calibration of ISAT rig set up

Test type	10 min $ml/m^2/s$	30 min $ml/m^2/s$	60 min $ml/m^2/s$
standard rig	0.0400	0.0200	0.0100
standard rig	0.0450	0.0225	0.0100
standard rig	0.0475	0.0250	0.0150
modified rig	0.0450	0.0225	0.0175
modified rig	0.0400	0.0200	0.0100
modified rig	0.0425	0.0275	0.0100

Table H. 2 Summary of significance tests on the ISAT rig set up

ISAT rig 1	ISAT rig 2	Duration (min)	Mean m_2	Mean m_2	Variance s_1^2	Variance s_2^2	t_{actual}	$t_{critical}$	Significant difference
standard	modified	10	0.0442	0.0425	0.00000972	0.00000417	0.6325	2.7760	No
standard	modified	30	0.0225	0.0233	0.00000417	0.00000972	0.3162	2.7760	No
standard	modified	60	0.0117	0.0125	0.00000556	0.00001250	0.2774	2.7760	No

Table H. 3 *Summary of significance tests on sensitivity of the ISAT (10 min) to mix variation and fibre inclusion for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.0433	0.0467	0.000010	0.000010	1.0690	2.7760	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0433	0.0950	0.000010	0.000050	9.4549	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0467	0.0950	0.000010	0.000050	8.8449	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.0433	0.0375	0.000010	0.000000	2.6458	2.7760	No
A2, s/c, 0.51 % - 45 mm	B5	0.0467	0.0558	0.000010	0.000006	3.3166	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.0950	0.0758	0.000050	0.000039	2.8750	2.7760	Yes
B4	B5	0.0375	0.0558	0.000000	0.000006	11.0000	2.7760	Yes
B4	B6	0.0375	0.0758	0.000000	0.000039	8.6932	2.7760	Yes
B5	B6	0.0558	0.0758	0.000006	0.000039	4.2426	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 4 *Summary of significance tests on sensitivity of the ISAT (30 min) to mix variation and fibre inclusion for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.0200	0.0283	0.000000	0.000006	5.0000	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0200	0.0442	0.000000	0.000010	10.9610	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0283	0.0442	0.000006	0.000010	5.7287	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.0200	0.0142	0.000000	0.000001	7.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.0283	0.0258	0.000006	0.000001	1.3416	2.7760	No
A3, s/c, 0.51 % - 45 mm	B6	0.0442	0.0433	0.000010	0.000006	0.3015	2.7760	No
B4	B5	0.0142	0.0258	0.000001	0.000001	9.8995	2.7760	Yes
B4	B6	0.0142	0.0433	0.000001	0.000006	15.6525	2.7760	Yes
B5	B6	0.0258	0.0433	0.000001	0.000006	9.3915	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 5 *Summary of significance tests on sensitivity of the ISAT (60 min) to mix variation and fibre inclusion for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.0142	0.0142	0.000001	0.000001	0.0000	2.7760	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0142	0.0258	0.000001	0.000010	4.9497	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0142	0.0258	0.000001	0.000010	4.9497	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.0142	0.0092	0.000001	0.000001	4.2426	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.0142	0.0133	0.000001	0.000001	0.7071	2.7760	No
A3, s/c, 0.51 % - 45 mm	B6	0.0258	0.0308	0.000010	0.000001	2.1213	2.7760	No
B4	B5	0.0092	0.0133	0.000001	0.000001	3.5355	2.7760	Yes
B4	B6	0.0092	0.0308	0.000001	0.000001	18.3848	2.7760	Yes
B5	B6	0.0133	0.0308	0.000001	0.000001	14.8492	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 6 S..... y of significance tests on sensitivity of the ISAT (10 min) to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_1	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.0467	0.0550	0.00000972	0.00000000	3.7796	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0467	0.0792	0.00000972	0.00000972	10.4232	2.7760	Yes
A2, s c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0467	0.0825	0.00000972	0.00000417	13.5978	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0467	0.0850	0.00000972	0.00000417	14.5465	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0550	0.0792	0.00000000	0.00000972	10.9610	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0550	0.0825	0.00000000	0.00000417	19.0526	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0550	0.0850	0.00000000	0.00000417	20.7846	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0792	0.0825	0.00000972	0.00000417	1.2649	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0792	0.0850	0.00000972	0.00000417	2.2136	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0825	0.0850	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.0592	0.0650	0.00000972	0.00000417	2.2136	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0592	0.0850	0.00000972	0.00000417	9.8031	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0592	0.1058	0.00000972	0.00000139	19.7990	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0650	0.0850	0.00000417	0.00000417	9.7980	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0650	0.1058	0.00000417	0.00000139	24.5000	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0850	0.1058	0.00000417	0.00000139	12.5000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.0475	0.0583	0.00000417	0.00000139	6.5000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0475	0.0825	0.00000417	0.00000417	17.1464	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0475	0.0842	0.00000417	0.00000139	22.0000	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0583	0.0825	0.00000139	0.00000417	14.5000	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0583	0.0842	0.00000139	0.00000139	21.9203	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0825	0.0842	0.00000417	0.00000139	1.0000	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.0383	0.0650	0.00000139	0.00000417	16.0000	2.7760	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.0425	0.0433	0.00000417	0.00000139	0.5000	2.7760	No
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0458	0.0533	0.00000139	0.00000139	6.3640	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm	0.0558	0.0467	0.00000556	0.00000972	3.3166	2.7760	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.0558	0.0550	0.00000556	0.00000000	0.5000	2.7760	No
B5	A2, s/c, 1.5 % - 45 mm	0.0558	0.0792	0.00000556	0.00000972	8.4423	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.0558	0.0825	0.00000556	0.00000417	12.0949	2.7760	Yes
B5	A2, s/c, 3.0 % - 45 mm	0.0558	0.0850	0.00000556	0.00000417	13.2288	2.7760	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.0558	0.0592	0.00000556	0.00000972	1.2060	2.7760	No
B5	A2, s/t, 1.0 % - 32 mm	0.0558	0.0650	0.00000556	0.00000417	4.1576	2.7760	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.0558	0.0850	0.00000556	0.00000417	13.2288	2.7760	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.0558	0.1058	0.00000556	0.00000139	26.8328	2.7760	Yes
B5	A2, s/fe, 0.51 % - 30 mm	0.0558	0.0475	0.00000556	0.00000417	3.7796	2.7760	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.0558	0.0583	0.00000556	0.00000139	1.3416	2.7760	No
B5	A2, s/fe, 1.5 % - 30 mm	0.0558	0.0825	0.00000556	0.00000417	12.0949	2.7760	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.0558	0.0842	0.00000556	0.00000139	15.2053	2.7760	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.0558	0.0383	0.00000556	0.00000139	9.3915	2.7760	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.0558	0.0650	0.00000556	0.00000417	4.1576	2.7760	Yes
B5	A2, p, 0.1 % - 12 mm	0.0558	0.0425	0.00000556	0.00000417	6.0474	2.7760	Yes
B5	A2, p, 0.51 % - 12 mm	0.0558	0.0433	0.00000556	0.00000139	6.7082	2.7760	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.0558	0.0458	0.00000556	0.00000139	5.3666	2.7760	Yes
B5	A2, sp, 0.51 % - 12.5, 60 mm	0.0558	0.0533	0.00000556	0.00000139	1.3416	2.7760	No
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.0425	0.0458	0.00000417	0.00000139	2.0000	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.0467	0.0592	0.00000972	0.00000972	4.0089	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.0467	0.0475	0.00000972	0.00000417	0.3162	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.0467	0.0383	0.00000972	0.00000139	3.5355	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, p, 0.51 % - 12 mm	0.0467	0.0433	0.00000972	0.00000139	1.4142	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0467	0.0533	0.00000972	0.00000139	2.8284	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.0592	0.0475	0.00000972	0.00000417	4.4272	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.0592	0.0383	0.00000972	0.00000139	8.8388	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.0592	0.0433	0.00000972	0.00000139	6.7175	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0592	0.0533	0.00000972	0.00000139	2.4749	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.0475	0.0383	0.00000417	0.00000139	5.5000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.0475	0.0433	0.00000417	0.00000139	2.5000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0475	0.0533	0.00000417	0.00000139	3.5000	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.0383	0.0433	0.00000139	0.00000139	4.2426	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0383	0.0533	0.00000139	0.00000139	12.7279	2.7760	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0433	0.0533	0.00000139	0.00000139	8.4853	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.0550	0.0650	0.00000000	0.00000417	6.9282	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.0550	0.0583	0.00000000	0.00000417	6.9282	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.0650	0.0583	0.00000417	0.00000139	4.0000	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.0792	0.0850	0.00000972	0.00000417	2.2136	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.0792	0.0825	0.00000972	0.00000417	1.2649	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.0850	0.0825	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.0825	0.1058	0.00000417	0.00000139	14.0000	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.0825	0.0842	0.00000417	0.00000139	1.0000	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.0825	0.0650	0.00000417	0.00000417	8.5732	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.1058	0.0842	0.00000139	0.00000139	18.3848	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.1058	0.0650	0.00000139	0.00000417	24.5000	2.7760	Yes
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.0842	0.0650	0.00000139	0.00000417	11.5000	2.7760	Yes

Table H. 7 Summary of significance tests on sensitivity of the ISAT (30 min) to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.0283	0.0242	0.00000556	0.00000139	2.2361	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0283	0.0350	0.00000556	0.00000417	3.0237	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0283	0.0383	0.00000556	0.00000139	5.3666	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0283	0.0358	0.00000556	0.00000556	3.1820	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0242	0.0350	0.00000139	0.00000417	6.5000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0242	0.0383	0.00000139	0.00000139	12.0208	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0242	0.0358	0.00000139	0.00000556	6.2610	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0350	0.0383	0.00000417	0.00000139	2.0000	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0350	0.0358	0.00000417	0.00000556	0.3780	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0383	0.0358	0.00000139	0.00000556	1.3416	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.0233	0.0283	0.00000139	0.00000556	2.6833	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0233	0.0400	0.00000139	0.00000417	10.0000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0233	0.0358	0.00000139	0.00000556	6.7082	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0283	0.0400	0.00000556	0.00000417	5.2915	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0283	0.0358	0.00000556	0.00000556	3.1820	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0400	0.0358	0.00000417	0.00000556	1.8898	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.0175	0.0275	0.00000000	0.00000417	6.9282	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0175	0.0375	0.00000000	0.00000417	13.8564	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0175	0.0342	0.00000000	0.00000139	20.0000	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0275	0.0375	0.00000417	0.00000417	4.8990	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0275	0.0342	0.00000417	0.00000139	4.0000	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0375	0.0342	0.00000417	0.00000139	2.0000	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.0192	0.0408	0.00000139	0.00000972	9.1924	2.7760	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.0192	0.0192	0.00000139	0.00000139	0.0000	2.7760	No
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0225	0.0300	0.00000417	0.00000417	3.6742	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm	0.0258	0.0283	0.00000139	0.00000556	1.3416	2.7760	No
B5	A2, s/c, 1.0 % - 45 mm	0.0258	0.0242	0.00000139	0.00000139	1.4142	2.7760	No
B5	A2, s/c, 1.5 % - 45 mm	0.0258	0.0350	0.00000139	0.00000417	5.5000	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.0258	0.0383	0.00000139	0.00000139	10.6066	2.7760	Yes
B5	A2, s/c, 3.0 % - 45 mm	0.0258	0.0358	0.00000139	0.00000556	5.3666	2.7760	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.0258	0.0233	0.00000139	0.00000139	2.1213	2.7760	No
B5	A2, s/t, 1.0 % - 32 mm	0.0258	0.0283	0.00000139	0.00000556	1.3416	2.7760	No
B5	A2, s/t, 1.5 % - 32 mm	0.0258	0.0400	0.00000139	0.00000417	8.5000	2.7760	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.0258	0.0358	0.00000139	0.00000556	5.3666	2.7760	Yes
B5	A2, s/fe, 0.51 % - 30 mm	0.0258	0.0175	0.00000139	0.00000000	10.0000	2.7760	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.0258	0.0275	0.00000139	0.00000417	1.0000	2.7760	No
B5	A2, s/fe, 1.5 % - 30 mm	0.0258	0.0375	0.00000139	0.00000417	7.0000	2.7760	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.0258	0.0342	0.00000139	0.00000139	7.0711	2.7760	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.0258	0.0408	0.00000139	0.00000972	6.3640	2.7760	Yes
B5	A2, p, 0.1 % - 12 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, p, 0.51 % - 12 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.0258	0.0225	0.00000139	0.00000417	2.0000	2.7760	No
B5	A2, sp, 0.51 % - 12.5, 60 mm	0.0258	0.0300	0.00000139	0.00000417	2.5000	2.7760	No
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.0192	0.0225	0.00000139	0.00000417	2.0000	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.0283	0.0233	0.00000556	0.00000139	2.6833	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.0283	0.0175	0.00000556	0.00000000	6.5000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.0283	0.0192	0.00000556	0.00000139	4.9193	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, p, 0.51 % - 12 mm	0.0283	0.0192	0.00000556	0.00000139	4.9193	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0283	0.0300	0.00000556	0.00000417	0.7559	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.0233	0.0175	0.00000139	0.00000000	7.0000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.0233	0.0192	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.0233	0.0192	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0233	0.0300	0.00000139	0.00000417	4.0000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.0175	0.0192	0.00000000	0.00000139	2.0000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.0175	0.0192	0.00000000	0.00000139	2.0000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0175	0.0300	0.00000000	0.00000417	8.6603	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.0192	0.0192	0.00000139	0.00000139	0.0000	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0192	0.0300	0.00000139	0.00000417	6.5000	2.7760	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0192	0.0300	0.00000139	0.00000417	6.5000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.0242	0.0283	0.00000139	0.00000556	2.2361	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.0242	0.0275	0.00000139	0.00000556	2.2361	2.7760	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.0283	0.0275	0.00000556	0.00000417	0.3780	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.0350	0.0400	0.00000417	0.00000417	2.4495	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.0350	0.0375	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.0400	0.0375	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.0383	0.0358	0.00000139	0.00000556	1.3416	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.0383	0.0342	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.0383	0.0408	0.00000139	0.00000972	1.0607	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.0358	0.0342	0.00000556	0.00000139	0.8944	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.0358	0.0408	0.00000556	0.00000972	1.8091	2.7760	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.0342	0.0408	0.00000139	0.00000972	2.8284	2.7760	Yes

Table H. 8 Summary of significance tests on sensitivity of the ISAT (60 min) to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_1	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.0142	0.0150	0.00000139	0.00000417	0.5000	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0142	0.0200	0.00000139	0.00000000	7.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0142	0.0225	0.00000139	0.00000417	5.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0142	0.0208	0.00000139	0.00000139	5.6569	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0150	0.0200	0.00000417	0.00000000	3.4641	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0150	0.0225	0.00000417	0.00000417	3.6742	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0150	0.0208	0.00000417	0.00000139	3.5000	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0200	0.0225	0.00000000	0.00000417	1.7321	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0200	0.0208	0.00000000	0.00000139	1.0000	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0225	0.0208	0.00000417	0.00000139	1.0000	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.0125	0.0167	0.00000000	0.00000139	5.0000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0125	0.0267	0.00000000	0.00000139	17.0000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0125	0.0175	0.00000000	0.00000417	3.4641	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0167	0.0267	0.00000139	0.00000139	8.4853	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0167	0.0175	0.00000139	0.00000417	0.5000	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0267	0.0175	0.00000139	0.00000417	5.5000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.0100	0.0125	0.00000000	0.00000417	1.7321	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0100	0.0158	0.00000000	0.00000139	7.0000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0100	0.0183	0.00000000	0.00000139	10.0000	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0125	0.0158	0.00000417	0.00000139	2.0000	2.7760	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0125	0.0183	0.00000417	0.00000139	3.5000	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0158	0.0183	0.00000139	0.00000139	2.1213	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.0133	0.0217	0.00000139	0.00000139	7.0711	2.7760	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.0117	0.0133	0.00000556	0.00000139	0.8944	2.7760	No
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0142	0.0175	0.00000139	0.00000000	4.0000	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm	0.0133	0.0142	0.00000139	0.00000139	0.7071	2.7760	No
B5	A2, s/c, 1.0 % - 45 mm	0.0133	0.0150	0.00000139	0.00000417	1.0000	2.7760	No
B5	A2, s/c, 1.5 % - 45 mm	0.0133	0.0200	0.00000139	0.00000000	8.0000	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.0133	0.0225	0.00000139	0.00000417	5.5000	2.7760	Yes
B5	A2, s/c, 3.0 % - 45 mm	0.0133	0.0208	0.00000139	0.00000139	6.3640	2.7760	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.0133	0.0125	0.00000139	0.00000000	1.0000	2.7760	No
B5	A2, s/t, 1.0 % - 32 mm	0.0133	0.0167	0.00000139	0.00000139	2.8284	2.7760	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.0133	0.0267	0.00000139	0.00000139	11.3137	2.7760	No
B5	A2, s/t, 2.0 % - 32 mm	0.0133	0.0175	0.00000139	0.00000417	2.5000	2.7760	No
B5	A2, s/fe, 0.51 % - 30 mm	0.0133	0.0100	0.00000139	0.00000000	4.0000	2.7760	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.0133	0.0125	0.00000139	0.00000417	0.5000	2.7760	No
B5	A2, s/fe, 1.5 % - 30 mm	0.0133	0.0158	0.00000139	0.00000139	2.1213	2.7760	No
B5	A2, s/fe, 2.0 % - 30 mm	0.0133	0.0183	0.00000139	0.00000139	4.2426	2.7760	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.0258	0.0408	0.00000139	0.00000972	6.3640	2.7760	Yes
B5	A2, p, 0.1 % - 12 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, p, 0.51 % - 12 mm	0.0258	0.0192	0.00000139	0.00000139	5.6569	2.7760	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.0258	0.0225	0.00000139	0.00000417	2.0000	2.7760	No
B5	A2, sp, 0.51 % - 12.5, 60 mm	0.0258	0.0300	0.00000139	0.00000417	2.5000	2.7760	No
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.0192	0.0225	0.00000139	0.00000417	2.0000	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.0283	0.0233	0.00000556	0.00000139	2.6833	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.0283	0.0175	0.00000556	0.00000000	6.5000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.0283	0.0192	0.00000556	0.00000139	4.9193	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, p, 0.51 % - 12 mm	0.0283	0.0192	0.00000556	0.00000139	4.9193	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0283	0.0300	0.00000556	0.00000417	0.7559	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.0233	0.0175	0.00000139	0.00000000	7.0000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.0233	0.0192	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.0233	0.0192	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0233	0.0300	0.00000139	0.00000417	4.0000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.0175	0.0192	0.00000000	0.00000139	2.0000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.0175	0.0192	0.00000000	0.00000139	2.0000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0175	0.0300	0.00000000	0.00000417	8.6603	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.0192	0.0192	0.00000139	0.00000139	0.0000	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0192	0.0300	0.00000139	0.00000417	6.5000	2.7760	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.51 % - 12.5, 60 mm	0.0192	0.0300	0.00000139	0.00000417	6.5000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.0242	0.0283	0.00000139	0.00000556	2.2361	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.0242	0.0275	0.00000139	0.00000556	2.2361	2.7760	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.0283	0.0275	0.00000556	0.00000417	0.3780	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.0350	0.0400	0.00000417	0.00000417	2.4495	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.0350	0.0375	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.0400	0.0375	0.00000417	0.00000417	1.2247	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.0383	0.0358	0.00000139	0.00000556	1.3416	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.0383	0.0342	0.00000139	0.00000139	3.5355	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.0383	0.0408	0.00000139	0.00000972	1.0607	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.0358	0.0342	0.00000556	0.00000139	0.8944	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.0358	0.0408	0.00000556	0.00000972	1.8091	2.7760	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.0342	0.0408	0.00000139	0.00000972	2.8284	2.7760	Yes

Table H. 9 *Summary of significance tests on sensitivity of the impact test to mix variation and fibre inclusion for samples cured in polythene sheeting (PS)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.1567	0.0867	0.000022	0.000022	14.8492	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1567	0.3333	0.000022	0.000156	18.7383	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.0867	0.3333	0.000022	0.000156	26.1630	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.1567	0.0833	0.000022	0.000022	15.5563	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.0867	0.1600	0.000022	0.000067	11.0000	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.3333	0.3133	0.000156	0.000022	2.1213	2.7760	No
B4	B5	0.0833	0.1600	0.000022	0.000067	11.5000	2.7760	Yes
B4	B6	0.0833	0.3133	0.000022	0.000022	48.7904	2.7760	Yes
B5	B6	0.1600	0.3133	0.000067	0.000022	23.0000	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 10 *Summary of significance tests on sensitivity of the impact test to mix variation and fibre inclusion for samples cured with curing compound (CC)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.1700	0.1133	0.000067	0.000022	8.5000	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1700	0.2000	0.000067	0.000067	3.6742	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1133	0.2000	0.000022	0.000067	13.0000	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.1700	0.1000	0.000067	0.000067	8.5732	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	B5	0.1133	0.1400	0.000022	0.000067	4.0000	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.2000	0.3133	0.000067	0.000156	10.7517	2.7760	Yes
B4	B5	0.1000	0.1400	0.000067	0.000067	4.8990	2.7760	Yes
B4	B6	0.1000	0.3133	0.000067	0.000156	20.2386	2.7760	Yes
B5	B6	0.1400	0.3133	0.000067	0.000156	16.4438	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 11 *Summary of significance tests on sensitivity of the impact test to mix variation and fibre inclusion for samples cured in air (AC)*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51 % - 45 mm	0.1967	0.1833	0.000156	0.000089	1.2060	2.7760	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1967	0.3467	0.000156	0.000156	12.0268	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.1833	0.3467	0.000089	0.000156	14.7741	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.1967	0.2200	0.000156	0.000067	2.2136	2.7760	No
A2, s/c, 0.51 % - 45 mm	B5	0.1833	0.2500	0.000089	0.000067	7.5593	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.3467	0.3933	0.000156	0.000089	4.2212	2.7760	Yes
B4	B5	0.2200	0.2500	0.000067	0.000067	3.6742	2.7760	No
B4	B6	0.2200	0.3933	0.000067	0.000089	19.6542	2.7760	Yes
B5	B6	0.2500	0.3933	0.000067	0.000089	16.2525	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 12 Summary of significance tests on sensitivity of the impact test to different curing regimes of selected mixes

Specimen ID*	Curing		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
	1	2	m_2	m_2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	PS	AC	0.1567	0.1967	0.000022	0.000156	4.2426	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	PS	CC	0.1567	0.1700	0.000022	0.000067	2.0000	2.7760	No
A1, s/c, 0.51 % - 45 mm	AC	CC	0.1967	0.1700	0.000156	0.000067	2.5298	2.7760	No
A2, s/c, 0.51 % - 45 mm	PS	AC	0.0867	0.1833	0.000022	0.000089	12.9692	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	PS	CC	0.0867	0.1133	0.000022	0.000022	5.6569	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	AC	CC	0.1833	0.1133	0.000089	0.000022	9.3915	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	PS	AC	0.3333	0.3467	0.000156	0.000156	1.0690	2.7760	No
A3, s/c, 0.51 % - 45 mm	PS	CC	0.3333	0.2000	0.000156	0.000067	12.6491	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	AC	CC	0.3467	0.2000	0.000156	0.000067	13.9140	2.7760	Yes
B4	PS	AC	0.0833	0.2200	0.000022	0.000067	20.5000	2.7760	Yes
B4	PS	CC	0.0833	0.1000	0.000022	0.000067	2.5000	2.7760	No
B4	AC	CC	0.2200	0.1000	0.000067	0.000067	14.6969	2.7760	Yes
B5	PS	AC	0.1600	0.2500	0.000067	0.000067	11.0227	2.7760	Yes
B5	PS	CC	0.1600	0.1400	0.000067	0.000067	2.4495	2.7760	No
B5	AC	CC	0.2500	0.1400	0.000067	0.000067	13.4722	2.7760	Yes
B6	PS	AC	0.3133	0.3933	0.000022	0.000089	10.7331	2.7760	Yes
B6	PS	CC	0.3133	0.3133	0.000022	0.000156	0.0000	2.7760	No
B6	AC	CC	0.3933	0.3133	0.000089	0.000156	7.2363	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	PS	AC	0.1500	0.2200	0.000067	0.000067	8.5732	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	PS	AC	0.1600	0.2100	0.000067	0.000067	6.1237	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	PS	AC	0.1900	0.2700	0.000067	0.000067	9.7980	2.7760	Yes
A2, s/c, 3.0 % - 45 mm	PS	AC	0.2033	0.3467	0.000022	0.000156	15.2028	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	PS	AC	0.0800	0.1667	0.000067	0.000022	13.0000	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	PS	AC	0.1033	0.1800	0.000022	0.000067	11.5000	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	PS	AC	0.0967	0.2033	0.000022	0.000022	22.6274	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	PS	AC	0.2133	0.2300	0.000022	0.000067	2.5000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	PS	AC	0.0967	0.1333	0.000022	0.000022	7.7782	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	PS	AC	0.1067	0.1500	0.000022	0.000067	6.5000	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	PS	AC	0.1267	0.1967	0.000022	0.000022	14.8492	2.7760	Yes
A2, s/fe, 2.0 % - 30 mm	PS	AC	0.1333	0.2933	0.000022	0.000089	21.4663	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	PS	AC	0.1167	0.2200	0.000022	0.000067	15.5000	2.7760	Yes
A2, s/s, 2 0 % - 35 mm	PS	AC	0.1633	0.2400	0.000022	0.000067	11.5000	2.7760	Yes
A2, p, 0.1 % - 12 mm	PS	AC	0.1200	0.1867	0.000000	0.000022	20.0000	2.7760	Yes
A2, p, 0.51 % - 12 mm	PS	AC	0.1367	0.2300	0.000022	0.000067	14.0000	2.7760	Yes
A2, sp, 0.1 % - 12.5, 60 mm	PS	AC	0.1133	0.1700	0.000022	0.000067	8.5000	2.7760	Yes
A2, sp, 0.51 % - 12.5, 60 mm	PS	AC	0.1533	0.2800	0.000022	0.000067	19.0000	2.7760	Yes
A2, s/c, 0.51 % - 60 mm	PS	AC	0.2567	0.2800	0.000156	0.000067	2.2136	2.7760	No
A2, s/c, 0.64 % - 60 mm	PS	AC	0.1533	0.2267	0.000022	0.000022	15.5563	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	PS	AC	0.0867	0.1833	0.000022	0.000089	12.9692	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	PS	AC	0.1033	0.2300	0.000022	0.000067	25.9589	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	PS	AC	0.0900	0.2567	0.000067	0.000422	15.2753	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	PS	AC	0.0733	0.2967	0.000022	0.000289	26.4252	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	PS	AC	0.0883	0.3367	0.000114	0.000689	17.7187	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 1.0 %	PS	AC	0.1783	0.3200	0.000181	0.000467	10.6369	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	PS	AC	0.1900	0.2700	0.000067	0.000067	9.7980	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	PS	AC	0.1400	0.2433	0.000167	0.000156	10.0958	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	PS	AC	0.1067	0.2133	0.000122	0.000156	11.5213	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	PS	AC	0.0917	0.1700	0.000114	0.000067	9.8616	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	PS	AC	0.0517	0.1000	0.000047	0.000067	8.2260	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 1.0 %	PS	AC	0.1433	0.3000	0.000289	0.000267	11.6465	2.3650	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table H. 13 Summary of significance tests on sensitivity of the impact tests to steel fibre shape and volume for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.0867	0.1500	0.000022	0.000067	9.5000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.0867	0.1600	0.000022	0.000067	11.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.0867	0.1900	0.000022	0.000067	15.5000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.0867	0.2033	0.000022	0.000022	24.7487	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.1500	0.1600	0.000067	0.000067	1.2247	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.1500	0.1900	0.000067	0.000067	4.8990	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1500	0.2033	0.000067	0.000022	8.0000	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.1600	0.1900	0.000067	0.000067	3.6742	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1600	0.2033	0.000067	0.000022	6.5000	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1900	0.2033	0.000067	0.000022	2.0000	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.0800	0.1033	0.000067	0.000022	3.5000	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.0800	0.0967	0.000067	0.000022	2.5000	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0800	0.2133	0.000067	0.000022	20.0000	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.1033	0.0967	0.000022	0.000022	1.4142	2.7760	No
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.1033	0.2133	0.000022	0.000022	23.3345	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.0967	0.2133	0.000022	0.000022	24.7487	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.0967	0.1067	0.000022	0.000022	2.1213	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.0967	0.1267	0.000022	0.000022	6.3640	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.0967	0.1333	0.000022	0.000022	7.7782	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.1067	0.1267	0.000022	0.000022	4.2426	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1067	0.1333	0.000022	0.000022	5.6569	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1267	0.1333	0.000022	0.000022	1.4142	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.1167	0.1633	0.000022	0.000022	9.8995	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm	0.1600	0.0867	0.000067	0.000022	11.0000	2.7760	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.1600	0.1500	0.000067	0.000067	1.2247	2.7760	No
B5	A2, s/c, 1.5 % - 45 mm	0.1600	0.1600	0.000067	0.000067	0.0000	2.7760	No
B5	A2, s/c, 2.0 % - 45 mm	0.1600	0.1900	0.000067	0.000067	3.6742	2.7760	Yes
B5	A2, s/c, 3.0 % - 45 mm	0.1600	0.2033	0.000067	0.000022	6.5000	2.7760	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.1600	0.0800	0.000067	0.000067	9.7980	2.7760	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.1600	0.1033	0.000067	0.000022	8.5000	2.7760	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.1600	0.0967	0.000067	0.000022	9.5000	2.7760	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.1600	0.2133	0.000067	0.000022	8.0000	2.7760	Yes
B5	A2, s/fe, 0.51 % - 30 mm	0.1600	0.0967	0.000067	0.000022	9.5000	2.7760	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.1600	0.1067	0.000067	0.000022	8.0000	2.7760	Yes
B5	A2, s/fe, 1.5 % - 30 mm	0.1600	0.1267	0.000067	0.000022	5.0000	2.7760	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.1600	0.1333	0.000067	0.000022	4.0000	2.7760	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.1600	0.1167	0.000067	0.000022	6.5000	2.7760	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.1600	0.1633	0.000067	0.000022	0.5000	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.0867	0.0800	0.000022	0.000022	0.0001	1.0000	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.0867	0.0967	0.000022	0.000022	2.1213	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.0867	0.1167	0.000022	0.000022	6.3640	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.0800	0.0967	0.000067	0.000022	2.5000	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.0800	0.1167	0.000067	0.000022	5.5000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.0967	0.1167	0.000022	0.000022	4.2426	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.1500	0.1033	0.000067	0.000022	7.0000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.1500	0.1067	0.000067	0.000022	6.5000	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.1033	0.1067	0.000022	0.000022	0.7071	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.1600	0.0967	0.000067	0.000022	9.5000	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.1600	0.1267	0.000067	0.000022	5.0000	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.0967	0.1267	0.000022	0.000022	6.3640	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.1900	0.2133	0.000067	0.000022	3.5000	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.1900	0.1333	0.000067	0.000022	8.5000	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.1900	0.1633	0.000067	0.000022	4.0000	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.2133	0.1333	0.000022	0.000022	16.9706	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.2133	0.1633	0.000022	0.000022	10.6066	2.7760	Yes
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.1333	0.1633	0.000022	0.000022	6.3640	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 14 Summary of significance tests on sensitivity of the impact tests to steel fibre shape and volume for samples cured in air

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.0 % - 45 mm	0.1833	0.2200	0.000089	0.000067	4.1576	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.1833	0.2100	0.000089	0.000067	3.0237	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.1833	0.2700	0.000089	0.000067	9.8271	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.1833	0.3467	0.000089	0.000156	14.7741	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.2200	0.2100	0.000067	0.000067	1.2247	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.2200	0.2700	0.000067	0.000067	6.1237	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.2200	0.3467	0.000067	0.000156	12.0167	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.2100	0.2700	0.000067	0.000067	7.3485	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.2100	0.3467	0.000067	0.000156	12.9653	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.2700	0.3467	0.000067	0.000156	7.2732	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.1667	0.1800	0.000022	0.000067	2.0000	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.1667	0.2033	0.000022	0.000022	7.7782	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.1667	0.2300	0.000022	0.000067	9.5000	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.1800	0.2033	0.000067	0.000022	3.5000	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.1800	0.2300	0.000067	0.000067	6.1237	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.2033	0.2300	0.000022	0.000067	4.0000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.1333	0.1500	0.000022	0.000067	2.5000	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.1333	0.1967	0.000022	0.000022	13.4350	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1333	0.2933	0.000022	0.000089	21.4663	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.1500	0.1967	0.000067	0.000022	7.0000	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1500	0.2933	0.000067	0.000089	16.2525	2.7760	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.1967	0.2933	0.000022	0.000089	12.9692	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.2200	0.2400	0.000067	0.000067	2.4495	2.7760	No
B5	A2, s/c, 0.51 % - 45 mm	0.2500	0.1833	0.000067	0.000089	7.5593	2.7760	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.2500	0.2200	0.000067	0.000067	3.6742	2.7760	Yes
B5	A2, s/c, 1.5 % - 45 mm	0.2500	0.2100	0.000067	0.000067	4.8990	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.2500	0.2700	0.000067	0.000067	2.4495	2.7760	No
B5	A2, s/c, 3.0 % - 45 mm	0.2500	0.3467	0.000067	0.000156	9.1706	2.7760	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.2500	0.1667	0.000067	0.000022	12.5000	2.7760	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.2500	0.1800	0.000067	0.000067	8.5732	2.7760	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.2500	0.2033	0.000067	0.000022	7.0000	2.7760	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.2500	0.2300	0.000067	0.000067	2.4495	2.7760	No
B5	A2, s/fe, 0.51 % - 30 mm	0.2500	0.1333	0.000067	0.000022	17.5000	2.7760	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.2500	0.1500	0.000067	0.000067	12.2474	2.7760	Yes
B5	A2, s/fe, 1.5 % - 30 mm	0.2500	0.1967	0.000067	0.000022	8.0000	2.7760	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.2500	0.2933	0.000067	0.000089	4.9135	2.7760	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.2500	0.2200	0.000067	0.000067	3.6742	2.7760	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.2500	0.2400	0.000067	0.000067	1.2247	2.7760	No
A2, s/c, 0.51 % - 45 mm	A2, s/t, 0.51 % - 32 mm	0.1833	0.1667	0.000089	0.000089	0.0000	2.2361	No
A2, s/c, 0.51 % - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.1833	0.1333	0.000089	0.000022	6.7082	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, s/s, 0.51 % - 35 mm	0.1833	0.2200	0.000089	0.000067	4.1576	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.1667	0.1333	0.000022	0.000022	7.0711	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.1667	0.2200	0.000022	0.000067	8.0000	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.1333	0.2200	0.000022	0.000067	13.0000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.2200	0.1800	0.000067	0.000067	4.8990	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.2200	0.1500	0.000067	0.000067	8.5732	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.1800	0.1500	0.000067	0.000067	3.6742	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.2100	0.2033	0.000067	0.000022	1.0000	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.2100	0.1967	0.000067	0.000022	2.0000	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.2033	0.1967	0.000022	0.000022	1.4142	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.2700	0.2300	0.000067	0.000067	4.8990	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.2700	0.2933	0.000067	0.000089	2.6458	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.2700	0.2400	0.000067	0.000067	3.6742	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.2300	0.2933	0.000067	0.000089	7.1813	2.7760	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.2300	0.2400	0.000067	0.000067	1.2247	2.7760	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.2933	0.2400	0.000089	0.000067	6.0474	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 15 Summary of significance tests on sensitivity of the impact test to fibre type and volume for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
B5	A2, p, 0.1 % - 12 mm	0.1600	0.1200	0.000067	0.000000	6.9282	2.7760	Yes
B5	A2, p, 0.51 % - 12 mm	0.1600	0.1367	0.000067	0.000022	3.5000	2.7760	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.1600	0.1133	0.000067	0.000022	7.0000	2.7760	Yes
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.1600	0.1533	0.000067	0.000022	1.0000	2.7760	No
B5	A2, HP, 0.04 % - 12 mm	0.1600	0.1033	0.000067	0.000022	13.4397	2.2280	Yes
B5	A2, HP, 0.21 % - 12 mm	0.1600	0.1244	0.000067	0.000025	8.2078	2.2280	Yes
B5	A2, HP, 0.41 % - 12 mm	0.1600	0.1389	0.000067	0.000030	4.6355	2.2280	Yes
B5	A2, HP, 0.83 % - 12 mm	0.1600	0.1544	0.000067	0.000002	1.7678	2.2280	No
B5	A2, HD, 0.02 % - 12 mm	0.1600	0.1996	0.000067	0.000043	7.7544	2.2280	Yes
B5	A2, GSF, 0.54 % - 50 mm	0.1600	0.1848	0.000067	0.000035	5.1940	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, p, 0.1 % - 12 mm	0.0867	0.1200	0.000022	0.000000	10.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, p, 0.51 % - 12 mm	0.0867	0.1367	0.000022	0.000022	10.6066	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.0867	0.1133	0.000022	0.000022	5.6569	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.0867	0.1533	0.000022	0.000022	14.1421	2.7760	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.04 % - 12 mm	0.0867	0.1033	0.000022	0.000022	4.8412	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.21 % - 12 mm	0.0867	0.1244	0.000022	0.000025	10.5430	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.41 % - 12 mm	0.0867	0.1389	0.000022	0.000030	13.5677	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, HP, 0.83 % - 12 mm	0.0867	0.1544	0.000022	0.000002	34.1000	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, HD, 0.02 % - 12 mm	0.0867	0.1996	0.000022	0.000043	25.1389	2.2280	Yes
A2, s/c, 0.51 % - 45 mm	A2, GSF, 0.54 % - 50 mm	0.0867	0.1848	0.000022	0.000035	23.8748	2.2280	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.1200	0.1367	0.000000	0.000022	5.0000	2.7760	Yes
A2, p, 0.1 % - 12 mm	A2, GSF, 0.54 % - 50 mm	0.1200	0.1848	0.000000	0.000035	17.3617	2.2280	Yes
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.1133	0.1533	0.000022	0.000022	8.4853	2.7760	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.21 % - 12 mm	0.1033	0.1244	0.000022	0.000025	8.7178	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.1033	0.1389	0.000022	0.000030	13.9659	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.1033	0.1544	0.000022	0.000002	29.0930	2.1200	Yes
A2, HP, 0.04 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.1033	0.1996	0.000022	0.000043	33.7066	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.1244	0.1389	0.000025	0.000030	5.5432	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.1244	0.1544	0.000025	0.000002	16.2816	2.1200	Yes
A2, HP, 0.21 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.1244	0.1996	0.000025	0.000043	25.8332	2.1200	Yes
A2, HP, 0.41 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.1389	0.1544	0.000019	0.000002	9.4210	2.1200	Yes
A2, HP, 0.41 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.1389	0.1996	0.000030	0.000043	20.1489	2.1200	Yes
A2, HP, 0.83 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.1544	0.1996	0.000002	0.000043	18.9381	2.1200	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.04 % - 12 mm	0.1200	0.1033	0.000000	0.000022	5.5902	2.2280	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.21 % - 12 mm	0.1200	0.1244	0.000000	0.000025	1.4142	2.2280	No
A2, p, 0.1 % - 12 mm	A2, HP, 0.41 % - 12 mm	0.1200	0.1389	0.000000	0.000030	5.4867	2.2280	Yes
A2, p, 0.1 % - 12 mm	A2, HP, 0.83 % - 12 mm	0.1200	0.1544	0.000000	0.000002	34.6591	2.2280	Yes
A2, p, 0.1 % - 12 mm	A2, HD, 0.02 % - 12 mm	0.1200	0.1996	0.000000	0.000043	19.1842	2.2280	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 16 Summary of significance tests on sensitivity of the impact test to steel fibre length and volume for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.51 % - 45 mm (a)	0.1322	0.0867	0.000022	0.000022	13.2327	2.2280	Yes
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.51 % - 45 mm (b)	0.1322	0.0737	0.000022	0.000004	32.5929	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 45 mm (b)	0.0867	0.0737	0.000022	0.000004	6.1872	2.2280	Yes
A2, s/c, 0.26 % - 50 mm	A2, s/c, 0.51 % - 50 mm	0.1863	0.1578	0.000013	0.000007	17.6650	2.1200	Yes
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.51 % - 60 mm (a)	0.2789	0.2567	0.000015	0.000156	4.3033	2.2280	Yes
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.51 % - 60 mm (b)	0.2789	0.2178	0.000015	0.000010	34.7851	2.1200	Yes
A2, s/c, 0.26 % - 60 mm	A2, s/c, 0.64 % - 60 mm	0.2789	0.1533	0.000015	0.000022	42.1126	2.2280	Yes
A2, s/c, 0.51 % - 60 mm (a)	A2, s/c, 0.51 % - 60 mm (b)	0.2567	0.2178	0.000156	0.000010	7.8262	2.2280	Yes
A2, s/c, 0.51 % - 60 mm (a)	A2, s/c, 0.64 % - 60 mm	0.2567	0.1533	0.000156	0.000022	10.9602	2.7760	Yes
A2, s/c, 0.51 % - 60 mm (b)	A2, s/c, 0.64 % - 60 mm	0.2178	0.1533	0.000010	0.000022	24.5095	2.2280	Yes
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.26 % - 50 mm	0.1322	0.1863	0.000022	0.000013	25.6101	2.1200	Yes
A2, s/c, 0.26 % - 45 mm	A2, s/c, 0.26 % - 60 mm	0.1322	0.2789	0.000022	0.000015	68.1645	2.1200	Yes
A2, s/c, 0.26 % - 50 mm	A2, s/c, 0.26 % - 60 mm	0.1863	0.2789	0.000013	0.000015	49.2665	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 50 mm	0.0867	0.1578	0.000022	0.000007	29.2119	2.2280	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 60 mm (a)	0.0867	0.2567	0.000022	0.000156	18.0312	2.7760	Yes
A2, s/c, 0.51 % - 45 mm (a)	A2, s/c, 0.51 % - 60 mm (b)	0.0867	0.2178	0.000022	0.000010	49.8641	2.2280	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 50 mm	0.0737	0.1578	0.000004	0.000007	71.7837	2.1200	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 60 mm (a)	0.0737	0.2567	0.000004	0.000156	38.8603	2.2280	Yes
A2, s/c, 0.51 % - 45 mm (b)	A2, s/c, 0.51 % - 60 mm (b)	0.0737	0.2178	0.000004	0.000010	111.1429	2.1200	Yes
A2, s/c, 0.51 % - 50 mm	A2, s/c, 0.51 % - 60 mm (a)	0.1578	0.2567	0.000007	0.000156	20.3114	2.2280	Yes
A2, s/c, 0.51 % - 50 mm	A2, s/c, 0.51 % - 60 mm (b)	0.1578	0.2178	0.000007	0.000010	40.8202	2.1200	Yes
B5	A2, s/c, 0.26 % - 45 mm	0.1600	0.1322	0.000067	0.000022	6.5881	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm (a)	0.1600	0.0867	0.000067	0.000022	11.0000	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm (b)	0.1600	0.0737	0.000067	0.000004	26.8687	2.2280	Yes
B5	A2, s/c, 0.26 % - 50 mm	0.1600	0.1863	0.000067	0.000013	6.9621	2.2280	Yes
B5	A2, s/c, 0.51 % - 50 mm	0.1600	0.1578	0.000067	0.000007	0.6455	2.2280	No
B5	A2, s/c, 0.26 % - 60 mm	0.1600	0.2789	0.000067	0.000015	30.8882	2.2280	Yes
B5	A2, s/c, 0.51 % - 60 mm (a)	0.1600	0.2567	0.000067	0.000156	9.1706	2.7760	Yes
B5	A2, s/c, 0.51 % - 60 mm (b)	0.1600	0.2178	0.000067	0.000010	16.1245	2.2280	Yes
B5	A2, s/c, 0.64 % - 60 mm	0.1600	0.1533	0.000067	0.000022	1.0000	2.7760	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 17 Summary of significance tests on sensitivity of the impact tests to superplasticizer and steel fibre volume for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_2	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.0867	0.1033	0.000022	0.000022	4.4096	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.0867	0.0900	0.000022	0.000067	0.5774	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.0867	0.0733	0.000022	0.000022	3.5277	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.0867	0.0883	0.000022	0.000114	0.2277	2.3650	No
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.0867	0.1783	0.000022	0.000181	10.1141	2.3650	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.1033	0.0900	0.000022	0.000067	3.1623	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.1033	0.0733	0.000022	0.000022	10.0623	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.1033	0.0883	0.000022	0.000114	2.8749	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.1033	0.1783	0.000022	0.000181	11.7770	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.0900	0.0733	0.000067	0.000022	3.9528	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.0900	0.0883	0.000067	0.000114	0.2774	2.2280	No
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.0900	0.1783	0.000067	0.000181	12.5622	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.0733	0.0883	0.000022	0.000114	2.8749	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.0733	0.1783	0.000022	0.000181	16.4879	2.2280	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s c, 0.51 % - 45 mm - SP 1.0 %	0.0883	0.1783	0.000114	0.000181	11.7281	2.2280	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.0 %	0.1600	0.0867	0.000067	0.000022	11.0000	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.1600	0.1033	0.000067	0.000022	11.6132	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.1600	0.0900	0.000067	0.000067	10.6927	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.1600	0.0733	0.000067	0.000022	17.7614	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.1600	0.0883	0.000067	0.000114	9.0223	2.3650	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.1600	0.1783	0.000067	0.000181	1.9149	2.3650	No
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.1900	0.1400	0.000067	0.000167	5.4006	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.1900	0.1067	0.000067	0.000122	10.2062	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.1900	0.0917	0.000067	0.000114	12.3795	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.1900	0.0517	0.000067	0.000047	23.5433	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1900	0.1433	0.000067	0.000289	3.9712	2.3650	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.1400	0.1067	0.000167	0.000122	4.3853	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.1400	0.0917	0.000167	0.000114	6.4524	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.1400	0.0517	0.000167	0.000047	13.5057	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1400	0.1433	0.000167	0.000289	0.3492	2.2280	No
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.1067	0.0917	0.000122	0.000114	2.1828	2.2280	No
A2, s/c, 2 0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.1067	0.0517	0.000122	0.000047	9.4479	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1067	0.1433	0.000122	0.000289	4.0437	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.0917	0.0517	0.000114	0.000047	7.0466	2.2280	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.0917	0.1433	0.000114	0.000289	5.7566	2.2280	Yes
A2, s/c, 0 51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.0517	0.1433	0.000047	0.000289	11.1803	2.2280	Yes
B5	A2, s/c, 2.0 % - 45 mm- SP 0.0 %	0.1600	0.1900	0.000067	0.000067	3.6742	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.1600	0.1400	0.000067	0.000167	2.1602	2.3650	No
B5	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.1600	0.1067	0.000067	0.000122	6.5320	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.1600	0.0917	0.000067	0.000114	8.6027	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.1600	0.0517	0.000067	0.000047	18.4375	2.3650	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1600	0.1433	0.000067	0.000289	1.4183	2.3650	No
A2, s/c, 0.51 % - SP 0.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.0867	0.1900	0.000022	0.000067	15.5000	2.7760	Yes
A2, s/c, 0.51 % - SP 0.1 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.1033	0.1400	0.000011	0.000167	6.1492	2.2280	Yes
A2, s/c, 0.51 % - SP 0.2 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.0967	0.1067	0.000011	0.000122	1.9365	2.2280	No
A2, s/c, 0.51 % - SP 0.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.0733	0.0917	0.000011	0.000114	3.6667	2.2280	Yes
A2, s/c, 0.51 % - SP 0.75 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.0867	0.0517	0.000078	0.000047	7.0000	2.2280	Yes
A2, s/c, 0.51 % - SP 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1733	0.1433	0.000078	0.000289	3.5032	2.2280	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table H. 18 Summary of significance tests on sensitivity of the impact tests to superplasticizer and steel fibre volume for samples cured in air

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	m_1	m_2	s_1^2	s_2^2			
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.1833	0.2300	0.000089	0.000067	5.2915	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.1833	0.2567	0.000089	0.000422	4.5873	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.1833	0.2967	0.000089	0.000289	8.2462	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.1833	0.3367	0.000089	0.000689	7.7754	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.0 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.1833	0.3200	0.000089	0.000467	8.2000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.2300	0.2567	0.000067	0.000422	1.7056	2.7760	No
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.2300	0.2967	0.000067	0.000289	5.0000	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.2300	0.3367	0.000067	0.000689	5.4880	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.1 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.2300	0.3200	0.000067	0.000467	5.5114	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.2567	0.2967	0.000422	0.000289	2.1213	2.7760	No
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.2567	0.3367	0.000422	0.000689	3.3941	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.2 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.2567	0.3200	0.000422	0.000467	3.0042	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.2967	0.3367	0.000289	0.000689	1.8091	2.7760	No
A2, s/c, 0.51 % - 45 mm - SP 0.5 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.2967	0.3200	0.000289	0.000467	1.2005	2.7760	No
A2, s/c, 0 51 % - 45 mm - SP 0.75 %	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.3367	0.3200	0.000689	0.000467	0.6934	2.7760	No
B5	A2, s/c, 0.51 % - 45 mm - SP 0.0 %	0.2500	0.1833	0.000067	0.000089	7.5593	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.1 %	0.2500	0.2300	0.000067	0.000067	2.4495	2.7760	No
B5	A2, s/c, 0.51 % - 45 mm - SP 0.2 %	0.2500	0.2567	0.000067	0.000422	0.4264	2.7760	No
B5	A2, s/c, 0.51 % - 45 mm - SP 0.5 %	0.2500	0.2967	0.000067	0.000289	3.5000	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 0.75 %	0.2500	0.3367	0.000067	0.000689	4.4590	2.7760	Yes
B5	A2, s/c, 0.51 % - 45 mm - SP 1.0 %	0.2500	0.3200	0.000067	0.000067	4.2866	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.2700	0.2433	0.000067	0.000156	2.5298	2.7760	No
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.2700	0.2133	0.000067	0.000156	5.3759	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.2700	0.1700	0.000067	0.000067	12.2474	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.2700	0.1000	0.000067	0.000067	20.8207	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.0 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.2700	0.3000	0.000067	0.000267	2.3238	2.7760	No
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.2433	0.2133	0.000156	0.000156	2.4054	2.7760	No
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.2433	0.1700	0.000156	0.000067	6.9570	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.2433	0.1000	0.000156	0.000067	13.5978	2.7760	Yes
A2, s/c, 2 0 % - 45 mm - SP 0.1 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.2433	0.3000	0.000156	0.000267	3.9001	2.7760	Yes
A2, s/c, 2 0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.2133	0.1700	0.000156	0.000067	4.1110	2.7760	Yes
A2, s/c, 2 0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.2133	0.1000	0.000156	0.000067	10.7517	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.2 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.2133	0.3000	0.000156	0.000267	5.9648	2.7760	Yes
A2, s/c, 2 0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.1700	0.1000	0.000067	0.000067	8.5732	2.7760	Yes
A2, s/c, 2.0 % - 45 mm - SP 0.5 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1700	0.3000	0.000067	0.000267	10.0698	2.7760	Yes
A2, s/c, 0.51 % - 45 mm - SP 0.75 %	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.1000	0.3000	0.000067	0.000267	15.4919	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm- SP 0.0 %	0.2500	0.2700	0.000067	0.000067	2.4495	2.7760	No
B5	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.2500	0.2433	0.000067	0.000156	0.6325	2.7760	No
B5	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.2500	0.2133	0.000067	0.000156	3.4785	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.2500	0.1700	0.000067	0.000067	9.7980	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.2500	0.1000	0.000067	0.000067	18.3712	2.7760	Yes
B5	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.2500	0.3000	0.000067	0.000267	3.8730	2.7760	Yes
A2, s/c, 0.51 % - SP 0.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.0 %	0.1833	0.2700	0.000089	0.000067	9.8271	2.7760	Yes
A2, s/c, 0.51 % - SP 0.1 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.1 %	0.2300	0.2433	0.000067	0.000156	1.2649	2.7760	No
A2, s/c, 0.51 % - SP 0.2 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.2 %	0.2567	0.2133	0.000422	0.000156	2.5495	2.7760	No
A2, s/c, 0.51 % - SP 0.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.5 %	0.2967	0.1700	0.000289	0.000067	9.5000	2.7760	Yes
A2, s/c, 0.51 % - SP 0.75 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 0.75 %	0.3367	0.1000	0.000689	0.000067	12.1764	2.7760	Yes
A2, s/c, 0.51 % - SP 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm - SP 1.0 %	0.3200	0.3000	0.000467	0.000267	1.0445	2.7760	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length, superplasticizer volume

Table H. 19 Ball cratering, reports and proceedings database (Owen-Jones & Gee, 1997)

No.	Reference title	Lubricated or Unlubricated (L/U)	Material	Test method	Friction measured?	Wear type
1.	Gahlin R, Larsson M, Hedenqvist P, Jacobson S & Hogmark S, (1997) Crater grinder method as a means for coating wear evaluation - an update, Surface & Coatings Technology, Vol. 90, No. 1 – 2, pp. 107 – 114.	NA	Coatings	Ball cratering	No	Abrasion
2.	Hogmark S & Hedenqvist P, (1994) Tribological characterisation of thin, hard coatings, Wear, Vol. 179, pp. 147 – 154.	U	Ceramic coatings	Ball cratering, block-on-ring, erosion	No	Sliding wear, erosion, and abrasion.
3.	Rutherford KL & Hutchings IM (1997) Theory and application of a micro-scale abrasive wear test, Journal of testing and evaluation, March 1997, pp. 250 – 260.	U	No specific material mentioned	Ball cratering	Yes	Abrasion
4.	Rutherford KL & Hutchings IM (1996) A micro-abrasive wear test, with particular application to coated systems, Surface coatings and technology, Vol. 79, pp. 231 – 239.	NA	Coatings, other materials	Ball cratering	No	Abrasion

Table H. 20 Summary of significance tests on sensitivity of the ball cratering test to mix variation and fibre inclusion for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51% - 45 mm	0.157454	0.102178	0.000006	0.000780	2.7890	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.157454	0.180905	0.000006	0.000017	7.0000	2.7760	Yes
A2, s/c, 0.51% - 45 mm	A3, s/c, 0.51 % - 45 mm	0.102178	0.180905	0.000780	0.000017	3.9442	2.7760	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.157454	0.154104	0.000006	0.000208	0.3244	2.7760	No
A2, s/c, 0.51% - 45 mm	B5	0.102178	0.164154	0.000780	0.000073	3.0011	2.7760	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.180905	0.194305	0.000017	0.000090	1.8353	2.7760	No
B4	B5	0.154104	0.164154	0.000208	0.000073	0.8485	2.7760	No
B4	B6	0.154104	0.194305	0.000208	0.000090	3.2967	2.7760	Yes
B5	B6	0.164154	0.194305	0.000073	0.000090	3.3425	2.7760	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 21 Summary of significance tests on sensitivity of the ball cratering test to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.0 % - 45 mm	0.102178	0.145729	0.000780	0.000067	2.1158	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.5 % - 45 mm	0.102178	0.150754	0.000780	0.000051	2.3838	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/c, 2.0 % - 45 mm	0.102178	0.155779	0.000780	0.000067	2.6041	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/c, 3.0 % - 45 mm	0.102178	0.187605	0.000780	0.000157	3.9465	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.145729	0.150754	0.000067	0.000051	0.6547	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.145729	0.155779	0.000067	0.000067	1.2247	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.145729	0.187605	0.000067	0.000157	3.9528	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.150754	0.155779	0.000051	0.000067	0.6547	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.150754	0.187605	0.000051	0.000157	3.6168	2.7760	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.155779	0.187605	0.000067	0.000157	3.0042	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.112228	0.134003	0.000292	0.000006	1.7857	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.112228	0.172529	0.000292	0.000073	4.4653	2.7760	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.112228	0.20938	0.000292	0.002716	2.5052	2.7760	No
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.134003	0.172529	0.000006	0.000073	6.1470	2.7760	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.134003	0.20938	0.000006	0.002716	2.0433	2.7760	No
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.172529	0.20938	0.000073	0.002716	0.9868	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.120603	0.159129	0.000471	0.000292	1.9722	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.120603	0.157454	0.000471	0.000174	2.0515	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.120603	0.180905	0.000471	0.000118	3.5132	2.7760	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.159129	0.157454	0.000292	0.000174	0.1098	2.7760	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.159129	0.180905	0.000292	0.000118	1.5215	2.7760	No
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.157454	0.180905	0.000174	0.000118	1.9415	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.157454	0.167504	0.000359	0.000022	0.7276	2.7760	No
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.102178	0.115578	0.000039	0.000017	2.5298	2.7760	No
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.118928	0.154104	0.000443	0.000006	2.3479	2.7760	No
B5	A2, s/c, 0.51% - 45 mm	0.164154	0.102178	0.000073	0.000780	3.0011	2.7760	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.164154	0.145729	0.000073	0.000067	2.2000	2.7760	No
B5	A2, s/c, 1.5 % - 45 mm	0.164154	0.150754	0.000073	0.000051	1.7056	2.7760	No
B5	A2, s/c, 2.0 % - 45 mm	0.164154	0.155779	0.000073	0.000067	1.0000	2.7760	No
B5	A2, s/c, 3.0 % - 45 mm	0.164154	0.187605	0.000073	0.000157	2.1864	2.7760	No
B5	A2, s/t, 0.51 % - 32 mm	0.164154	0.112228	0.000073	0.000292	3.8451	2.7760	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.164154	0.134003	0.000073	0.000006	4.8107	2.7760	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.164154	0.172529	0.000073	0.000073	0.9806	2.7760	No
B5	A2, s/t, 2.0 % - 32 mm	0.164154	0.20938	0.000073	0.002716	1.2111	2.7760	No
B5	A2, s/fe, 0.51 % - 30 mm	0.164154	0.120603	0.000073	0.000471	2.6399	2.7760	No
B5	A2, s/fe, 1.0 % - 30 mm	0.164154	0.159129	0.000073	0.000292	0.3721	2.7760	No
B5	A2, s/fe, 1.5 % - 30 mm	0.164154	0.157454	0.000073	0.000174	0.6030	2.7760	No
B5	A2, s/fe, 2.0 % - 30 mm	0.164154	0.180905	0.000073	0.000118	1.7150	2.7760	No
B5	A2, s/s, 0.51 % - 35 mm	0.164154	0.157454	0.000073	0.000359	0.4558	2.7760	No
B5	A2, s/s, 2.0 % - 35 mm	0.164154	0.167504	0.000073	0.000022	0.4851	2.7760	No
B5	A2, p, 0.1 % - 12 mm	0.164154	0.102178	0.000073	0.000039	8.2735	2.7760	Yes
B5	A2, p, 0.51 % - 12 mm	0.164154	0.115578	0.000073	0.000017	7.2500	2.7760	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.164154	0.118928	0.000073	0.000443	2.8149	2.7760	Yes
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.164154	0.154104	0.000073	0.000006	1.6036	2.7760	No
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.102178	0.118928	0.000039	0.000443	1.0783	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/t, 0.51 % - 32 mm	0.102178	0.112228	0.000780	0.000292	0.4341	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.102178	0.120603	0.000780	0.000471	0.7366	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, s/s, 0.51 % - 35 mm	0.102178	0.157454	0.000780	0.000359	2.3161	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, p, 0.51 % - 12 mm	0.102178	0.115578	0.000780	0.000017	0.6713	2.7760	No
A2, s/c, 0.51% - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.102178	0.154104	0.000780	0.000006	2.6200	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.112228	0.120603	0.000292	0.000471	0.4287	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.112228	0.157454	0.000292	0.000359	2.5069	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.112228	0.115578	0.000292	0.000017	0.2697	2.7760	No
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.112228	0.154104	0.000292	0.000006	3.4340	2.7760	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.120603	0.157454	0.000471	0.000359	1.8084	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.120603	0.115578	0.000471	0.000017	0.3216	2.7760	No
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.120603	0.154104	0.000471	0.000006	2.1693	2.7760	No
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.157454	0.115578	0.000359	0.000017	3.0542	2.7760	Yes
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.157454	0.154104	0.000359	0.000006	0.2481	2.7760	No
A2, p, 0.51 % - 12 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.115578	0.154104	0.000017	0.000006	11.5000	2.7760	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.145729	0.134003	0.000067	0.000006	1.9415	2.7760	No
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.145729	0.159129	0.000067	0.000292	1.0000	2.7760	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.134003	0.159129	0.000006	0.000292	2.0604	2.7760	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.102178	0.172529	0.000051	0.000073	8.9544	2.7760	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.102178	0.157454	0.000051	0.000174	5.2178	2.7760	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.172529	0.157454	0.000073	0.000174	1.3568	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.155779	0.20938	0.000067	0.002716	1.4368	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.155779	0.180905	0.000067	0.000118	2.6112	2.7760	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.155779	0.167504	0.000067	0.000022	1.7500	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.20938	0.180905	0.002716	0.000118	0.7565	2.7760	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.20938	0.167504	0.002716	0.000022	1.1317	2.7760	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.180905	0.167504	0.000118	0.000022	1.6000	2.7760	No

Table H.22 (a) Scratch test: Papers, reports and proceedings database (Owen-Jones & Gee, 1997)

No.	Reference title	Lubricated or Unlubricated (L/U)	Material	Test method	Friction measured?	Wear type
1.	Adewoye OO & Page TF (1981) Frictional deformation and fracture in polycrystalline SiC and Si_3N_4, Wear, Vol. 70, pp. 37 – 50.	U	Ceramics, SiC, silicon nitride	Scratch test	Yes	Abrasion
2.	Ahn JM & Danyluk S (1989) A study of subsurface damage generation by single scratches of silicon, Materials Research Society Symposium Proceedings, Vol. 140, pp. 319 – 323.	U	Silicon	Scratch test	No	Abrasion
3.	Brose Van Groenou A, Maan N & Veldkamp JDB (1975) Scratching experiments on various ceramic materials, Philips research reports, Vol. 30, pp. 320 – 359.	U	Ceramics	Scratch test	Yes	Abrasion
4.	Donaldson KY & Hasslemann DPH (1986) Comparative single-point diamond scratching behaviour of a cordierite glass and glass-ceramic, Journal of the American ceramic society, Vol. 69, No. 12, pp. C296 – C298.	U	Glass	Scratch test	No	Abrasion
5.	Enomoto Y & Yamanaka K (1986) Observation via cathodoluminescence of static and sliding damage sapphire crystals, Journal of materials science, Vol. 21, pp. 1487 – 1490.	U	Ceramics, alumina	Scratch test	No	Abrasion
6.	Gerk AP (1976) The relationship of time-dependent hardness and scratch hardness, J. Phys. D: Appl. Phys., Vol. 9, pp. 179 – 181.	U	Ceramics, germanium	Scratch test	No	Abrasion
7.	Ishigaki H, Ogino K, Hida A & Shikata R (1990) Effect of particle size on friction and wear zirconia, Proceedings of the Japan International Tribology Conference, Nagoya, 1990, pp. 719 – 724.	U	Ceramics, zirconia	Scratch test, rolling wear, ultrasonic cavitation	No	Abrasion, cavitation, rolling contact.
8.	Kapsa P & Enomoto Y (1988) Sliding damage on hot-pressed and sintered silicon nitride caused by a diamond tip under controlled humidity, Wear, Vol. 127, pp. 65 – 83.	U	Ceramics, silicon nitride	Scratch test	Yes	Abrasion
9.	Lamy B, & Berlie J (1984) Brittleness analysis and polymeric materials by means of scratching experiments, Journal of materials science letters, Vol. 3, pp. 1069 – 1070.	U	Ceramics, plastics	Scratch test	No	Abrasion
10.	Lawn BR, (1966) Partial cone crack formation in a brittle material loaded with a sliding spherical indenter, Proc. Royal society, Vol. 299, A, pp. 307 – 316.	U	Glass	Scratch test	No	Abrasion
11.	Lawn BR, Wiederhorn SM & Roberts DE (1984) Effect of sliding friction forces on the strength of brittle materials, Journal of materials science, Vol. 19, pp. 2561 – 2 569.	U	Glass	Scratch test	No	Abrasion

Table H.22 (b) Scratch test: Papers, reports and proceedings database (Owen-Jones & Gee, 1997)

No.	Reference title	Lubricated or Unlubricated (L/U)	Material	Test method	Friction measured?	Wear type
12.	Mann N & Brose Van Groenou A (1977) Low speed scratch experiments of steels, Wear, Vol. 42, pp. 365 – 390.	U	Metals, alloys	Scratch test	Yes	Abrasion
13.	Mathia TG & Lamy B (1986) Sclerometric characterisation of nearly brittle materials, Wear, Vol. 108, pp. 385 – 399.	U	Ceramics	Scratch test	Yes	Abrasion
14.	Nocker H & Hornbogen E (1989) Friction and wear measurements with a new metallographic scratching method, Pract. Met., Vol. 26, pp. 455 – 463.	U	No specific material mentioned	Scratch test	Yes	Abrasion
15.	Ohnaka T & Hirohashi M (1994) Failure modes and frictional force in scratch test of TiN coated by ion plating, Conf. Proc. 37th Japan Cong. On Mat. Res., September 1993, Kyoto, Japan, pp. 98 – 103.	U	Coatings, titanium nitride	Scratch test	Yes	Abrasion, scratching
16.	Powell BD & Tabor D (1970) The failure of titanium carbide under static and sliding contact, J. Phys. D: Appl. Phys., Vol. 3, and pp. 783 – 788.	U	Ceramics, TiC	Scratch test	No	Abrasion
17.	Prasad SV & Kosel TH (1984) A study of carbide removal mechanisms during quartz abrasion, Wear, Vol. 95, pp. 87 – 102.	U	Metals, alloys	Scratch test	No	Abrasion
18.	Shetty DK, Wright IG & Stropki JT (1985) Slurry erosion of WC-Co cermerts and ceramics, ASLE transactions, Vol. 28, pp. 123 – 133.	L	Ceramics, hard metals	Scratch test	No	Abrasion
19.	Steijn RP (1969) Friction wear of rutile single crystals, ASLE transactions, Vol. 12, pp. 21 – 33.	U	Ceramics, sapphire	Scratch test	Yes	Abrasion
20.	Subramanian C, Strafford KN, Wilks TP, Ward LP & McMillan W (1993) Influence of substrate roughness on the scratch adhesion of titanium nitride coatings, Surface and coatings technology, Vol. 62, pp. 529 – 535.	U	Coatings, titanium nitride	Scratch test	No	Abrasion
21.	Wilshaw TR & Rothwell R (1971) Instrumented scratch test for measuring the fracture behaviour of strong solids, Nature Physical science, Vol. 229, pp. 155 – 157.	U	Ceramics	Scratch test	No	Abrasion
22.	Yan C & Zhang L (1995) Single point scratching of 6061 Al alloy reinforced by different ceramic particles, Applied composite materials, Vol. 1, pp. 431 – 447.	U	MMC, composites	Scratch test	Yes	Abrasion

Table H. 23 Summary of significance tests on sensitivity of the scratch test to mix variation and fibre inclusion for samples cured in polythene sheeting

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51% - 45 mm	0.088833	0.085800	0.000058	0.000069	1.4505	2.0021	No
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.088833	0.091833	0.000058	0.000080	1.3759	2.0021	No
A2, s/c, 0.51% - 45 mm	A3, s/c, 0.51 % - 45 mm	0.085800	0.091833	0.000069	0.000080	2.6656	2.0021	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.088833	0.097800	0.000058	0.000045	4.7556	2.0021	Yes
A2, s/c, 0.51% - 45 mm	B5	0.085800	0.102667	0.000069	0.000200	5.5437	2.0021	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.091833	0.112233	0.000080	0.000306	5.5912	2.0021	Yes
B4	B5	0.097800	0.102667	0.000045	0.000200	1.6753	2.0021	No
B4	B6	0.097800	0.112233	0.000045	0.000306	4.1471	2.0021	Yes
B5	B6	0.102667	0.112233	0.000200	0.000306	2.2904	2.0021	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 24 Summary of significance tests on sensitivity of the scratch test to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.0 % - 45 mm	0.085800	0.087233	0.000069	0.000062	0.6759	2.0021	No
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.5 % - 45 mm	0.085800	0.100733	0.000069	0.000127	5.7478	2.0021	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 2.0 % - 45 mm	0.085800	0.108967	0.000069	0.000265	6.8244	2.0021	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 3.0 % - 45 mm	0.085800	0.123633	0.000069	0.000190	12.6681	2.0021	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.087233	0.100733	0.000062	0.000127	5.2932	2.0021	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.087233	0.108967	0.000062	0.000265	6.4714	2.0021	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.087233	0.123633	0.000062	0.000190	12.3593	2.0021	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.100733	0.108967	0.000127	0.000265	2.2382	2.0021	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.100733	0.123633	0.000127	0.000190	6.9275	2.0021	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.108967	0.123633	0.000265	0.000190	3.7014	2.0021	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.089900	0.095267	0.000288	0.000083	1.4992	2.0021	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.089900	0.124533	0.000288	0.000258	7.9763	2.0021	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.089900	0.129900	0.000288	0.000211	9.6412	2.0021	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.095267	0.124533	0.000083	0.000258	8.5268	2.0021	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.095267	0.129900	0.000083	0.000211	10.8757	2.0021	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.124533	0.129900	0.000258	0.000211	1.3342	2.0021	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.089600	0.089600	0.000048	0.000369	0.0000	2.0021	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.089600	0.120233	0.000048	0.000096	13.7430	2.0021	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.089600	0.137367	0.000048	0.000526	10.7378	2.0021	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.103700	0.120233	0.000170	0.000096	5.4544	2.0021	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.103700	0.137367	0.000170	0.000526	6.8710	2.0021	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.120233	0.137367	0.000096	0.000526	3.6991	2.0021	Yes
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.091067	0.093500	0.000040	0.000104	1.0908	2.0021	No
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.089400	0.111867	0.000377	0.000079	5.6606	2.0021	Yes
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.091333	0.114833	0.000106	0.000594	4.7836	2.0021	Yes
B5	A2, s/c, 0.51% - 45 mm	0.102667	0.085800	0.000200	0.000069	5.5437	2.0021	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.102667	0.087233	0.000200	0.000062	5.1412	2.0021	Yes
B5	A2, s/c, 1.5 % - 45 mm	0.102667	0.100733	0.000200	0.000127	0.5760	2.0021	No
B5	A2, s/c, 2.0 % - 45 mm	0.102667	0.108967	0.000200	0.000265	1.5731	2.0021	No
B5	A2, s/c, 3.0 % - 45 mm	0.102667	0.123633	0.000200	0.000190	5.7204	2.0021	Yes
B5	A2, s/t, 0.51 % - 32 mm	0.102667	0.089900	0.000200	0.000288	3.1120	2.0021	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.102667	0.095267	0.000200	0.000083	2.3691	2.0021	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.102667	0.124533	0.000200	0.000258	5.5019	2.0021	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.102667	0.129900	0.000200	0.000211	7.2383	2.0021	Yes
B5	A2, s/fe, 0.51 % - 30 mm	0.102667	0.089600	0.000200	0.000048	4.4719	2.0021	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.102667	0.103700	0.000200	0.000170	0.2893	2.0021	No
B5	A2, s/fe, 1.5 % - 30 mm	0.102667	0.120233	0.000200	0.000096	5.4997	2.0021	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.102667	0.137367	0.000200	0.000526	6.9369	2.0021	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.102667	0.091067	0.000200	0.000040	4.0344	2.0021	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.102667	0.093500	0.000200	0.000104	2.8315	2.0021	Yes
B5	A2, p, 0.1 % - 12 mm	0.102667	0.089400	0.000200	0.000377	2.9741	2.0021	Yes
B5	A2, p, 0.51 % - 12 mm	0.102667	0.111867	0.000200	0.000079	2.9654	2.0021	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.102667	0.091333	0.000200	0.000106	3.4933	2.0021	Yes
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.102667	0.114833	0.000200	0.000594	2.3252	2.0021	Yes
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.089400	0.091333	0.000377	0.000106	0.4738	2.0021	No
A2, s/c, 0.51% - 45 mm	A2, s/t, 0.51 % - 32 mm	0.085800	0.089900	0.000069	0.000288	1.1684	2.0021	No
A2, s/c, 0.51% - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.085800	0.089600	0.000069	0.000048	1.8946	2.0021	No
A2, s/c, 0.51% - 45 mm	A2, s/s, 0.51 % - 35 mm	0.085800	0.091067	0.000069	0.000040	2.7188	2.0021	Yes
A2, s/c, 0.51% - 45 mm	A2, p, 0.51 % - 12 mm	0.085800	0.111867	0.000069	0.000079	11.5305	2.0021	Yes
A2, s/c, 0.51% - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.085800	0.114833	0.000069	0.000594	6.0717	2.0021	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.089900	0.089600	0.000288	0.000048	0.0881	2.0021	No
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.089900	0.091067	0.000288	0.000040	0.3467	2.0021	No
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.089900	0.111867	0.000288	0.000079	6.1681	2.0021	Yes
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.089900	0.114833	0.000288	0.000594	4.5193	2.0021	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.089600	0.091067	0.000048	0.000040	0.8421	2.0021	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.089600	0.111867	0.000048	0.000079	10.6254	2.0021	Yes
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.089600	0.114833	0.000048	0.000594	5.3620	2.0021	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.091067	0.111867	0.000040	0.000079	10.2461	2.0021	Yes
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.091067	0.114833	0.000040	0.000594	5.0814	2.0021	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.111867	0.114833	0.000079	0.000594	0.6155	2.0021	No
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.087233	0.095267	0.000062	0.000083	3.5938	2.0021	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.087233	0.103700	0.000062	0.000170	5.8228	2.0021	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.095267	0.103700	0.000083	0.000170	2.8522	2.0021	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.100733	0.124533	0.000127	0.000258	6.5288	2.0021	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.100733	0.120233	0.000127	0.000096	7.0293	2.0021	Yes
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.124533	0.120233	0.000258	0.000096	1.2298	2.0021	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.108967	0.129900	0.000265	0.000211	5.1656	2.0021	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.108967	0.137367	0.000265	0.000526	5.4365	2.0021	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.108967	0.093500	0.000265	0.000104	4.3319	2.0021	Yes
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.129900	0.137367	0.000211	0.000526	1.4813	2.0021	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.129900	0.093500	0.000211	0.000104	11.0432	2.0021	Yes
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.137367	0.093500	0.000526	0.000104	9.4100	2.0021	Yes

Table H. 25 *Summary of significance tests on sensitivity of the base hardness test – depth readings – to mix variation and fibre inclusion for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51% - 45 mm	0.131667	0.052222	0.00204	0.00171	5.3545	2.0336	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.131667	0.242222	0.00204	0.00752	4.6637	2.0336	Yes
A2, s/c, 0.51% - 45 mm	A3, s/c, 0.51 % - 45 mm	0.052222	0.242222	0.00171	0.00752	8.1570	2.0336	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.131667	0.143889	0.00204	0.00333	0.6876	2.0336	No
A2, s/c, 0.51% - 45 mm	B5	0.052222	0.249611	0.00171	0.00740	8.5274	2.0336	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.242222	0.331667	0.00752	0.00723	3.0374	2.0336	Yes
B4	B5	0.143889	0.249611	0.00333	0.00740	4.2067	2.0336	Yes
B4	B6	0.143889	0.331667	0.00333	0.00723	7.5342	2.0336	Yes
B5	B6	0.249611	0.331667	0.00740	0.00723	2.7973	2.0336	Yes

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 26 *Summary of significance tests on sensitivity of the base hardness test – width readings – to mix variation and fibre inclusion for samples cured in polythene sheeting*

Specimen ID*		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A1, s/c, 0.51 % - 45 mm	A2, s/c, 0.51% - 45 mm	0.237778	0.175556	0.00253	0.00051	3.1909	2.1200	Yes
A1, s/c, 0.51 % - 45 mm	A3, s/c, 0.51 % - 45 mm	0.237778	0.308889	0.00253	0.00277	2.7644	2.1200	Yes
A2, s/c, 0.51% - 45 mm	A3, s/c, 0.51 % - 45 mm	0.175556	0.308889	0.00051	0.00277	6.5859	2.1200	Yes
A1, s/c, 0.51 % - 45 mm	B4	0.237778	0.252222	0.00253	0.00217	0.5959	2.1200	No
A2, s/c, 0.51% - 45 mm	B5	0.175556	0.272222	0.00051	0.01004	2.6615	2.1200	Yes
A3, s/c, 0.51 % - 45 mm	B6	0.308889	0.311111	0.00277	0.00472	0.0726	2.1200	No
B4	B5	0.252222	0.272222	0.00217	0.01004	0.5119	2.1200	No
B4	B6	0.252222	0.311111	0.00217	0.00472	2.0061	2.1200	No
B5	B6	0.272222	0.311111	0.01004	0.00472	0.9054	2.1200	No

* Specimen ID = Mix No, fibre type, fibre volume, fibre length

Table H. 27 Summary of significance tests on sensitivity of the base hardness test – depth readings – to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID		Mean		Variance		t_{actual}	$t_{critical}$	Significant difference
1	2	1	2	s_1^2	s_2^2			
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.0 % - 45 mm	0.052222	0.099444	0.00171	0.00297	2.8485	2.0336	Yes
A2, s c, 0.51% - 45 mm	A2, s/c, 1.5 % - 45 mm	0.052222	0.146667	0.00171	0.00407	5.1219	2.0336	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 2.0 % - 45 mm	0.052222	0.188889	0.00171	0.02009	3.8167	2.0336	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 3.0 % - 45 mm	0.052222	0.252222	0.00171	0.01684	6.0550	2.0336	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.099444	0.146667	0.00297	0.00407	2.3205	2.0336	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.099444	0.188889	0.00297	0.02009	2.4287	2.0336	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.099444	0.252222	0.00297	0.01684	4.4758	2.0336	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.146667	0.188889	0.00407	0.02009	1.1199	2.0336	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.146667	0.252222	0.00407	0.01684	3.0093	2.0336	Yes
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.188889	0.252222	0.02009	0.01684	1.3588	2.0336	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.028889	0.061111	0.00119	0.00365	1.9092	2.0336	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.028889	0.128889	0.00119	0.00144	8.0385	2.0336	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.028889	0.147778	0.00119	0.00401	6.8018	2.0336	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.061111	0.128889	0.00365	0.00144	3.9139	2.0336	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.061111	0.147778	0.00365	0.00401	4.0825	2.0336	Yes
A2, s/t, 1.5 % - 32 mm	A2, s t, 2.0 % - 32 mm	0.128889	0.147778	0.00144	0.00401	1.0550	2.0336	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.082222	0.122778	0.00146	0.00324	2.4380	2.0336	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.082222	0.129444	0.00146	0.00419	2.5889	2.0336	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.082222	0.172222	0.00146	0.00313	5.4772	2.0336	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.122778	0.129444	0.00324	0.00419	0.3188	2.0336	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.122778	0.172222	0.00324	0.00313	2.5542	2.0336	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.129444	0.172222	0.00419	0.00313	2.0612	2.0336	Yes
A2, s/s, 0.51 % - 35 mm	A2, s/s, 2.0 % - 35 mm	0.066667	0.140000	0.00142	0.00340	4.3533	2.0336	Yes
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.045556	0.165556	0.00111	0.01032	4.6276	2.0336	Yes
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.086111	0.183333	0.00523	0.00464	4.0349	2.0336	Yes
B5	A2, s/c, 0.51% - 45 mm	0.249611	0.052222	0.00740	0.00171	8.5274	2.0336	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.249611	0.099444	0.00740	0.00297	6.0806	2.0336	Yes
B5	A2, s/c, 1.5 % - 45 mm	0.249611	0.146667	0.00740	0.00407	3.9620	2.0336	Yes
B5	A2, s/c, 2.0 % - 45 mm	0.249611	0.188889	0.00740	0.02009	1.5099	2.0336	No
B5	A2, s/c, 3.0 % - 45 mm	0.249611	0.252222	0.00740	0.01684	0.0691	2.0336	No
B5	A2, s/t, 0.51 % - 32 mm	0.249611	0.028889	0.00740	0.00119	9.8190	2.0336	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.249611	0.061111	0.00740	0.00365	7.3911	2.0336	Yes
B5	A2, s/t, 1.5 % - 32 mm	0.249611	0.128889	0.00740	0.00144	5.2923	2.0336	Yes
B5	A2, s/t, 2.0 % - 32 mm	0.249611	0.147778	0.00740	0.00401	3.9309	2.0336	Yes
B5	A2, s/fe, 0.51 % - 30 mm	0.249611	0.082222	0.00740	0.00146	7.3304	2.0336	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.249611	0.122778	0.00740	0.00324	5.0686	2.0336	Yes
B5	A2, s/fe, 1.5 % - 30 mm	0.249611	0.129444	0.00740	0.00419	4.6009	2.0336	Yes
B5	A2, s/fe, 2.0 % - 30 mm	0.249611	0.172222	0.00740	0.00313	3.1093	2.0336	Yes
B5	A2, s/s, 0.51 % - 35 mm	0.249611	0.066667	0.00740	0.00142	8.0287	2.0336	Yes
B5	A2, s/s, 2.0 % - 35 mm	0.249611	0.140000	0.00740	0.00340	4.3483	2.0336	Yes
B5	A2, p, 0.1 % - 12 mm	0.249611	0.045556	0.00740	0.00111	9.1206	2.0336	Yes
B5	A2, p, 0.51 % - 12 mm	0.249611	0.165556	0.00740	0.01032	2.6030	2.0336	Yes
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.249611	0.086111	0.00740	0.00523	5.9985	2.0336	Yes
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.249611	0.183333	0.00740	0.00464	2.4899	2.0336	Yes
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.045556	0.086111	0.00111	0.00523	2.1010	2.0336	Yes
A2, s/c, 0.51% - 45 mm	A2, s/t, 0.51 % - 32 mm	0.052222	0.028889	0.00171	0.00119	1.7884	2.0336	No
A2, s/c, 0.51% - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.052222	0.082222	0.00171	0.00146	2.1977	2.0336	Yes
A2, s/c, 0.51% - 45 mm	A2, s/s, 0.51 % - 35 mm	0.052222	0.066667	0.00171	0.00142	1.0645	2.0336	No
A2, s/c, 0.51% - 45 mm	A2, p, 0.51 % - 12 mm	0.052222	0.045556	0.00171	0.02232	0.1773	2.0336	No
A2, s/c, 0.51% - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.052222	0.183333	0.00171	0.00464	6.7845	2.0336	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.028889	0.082222	0.00119	0.00146	4.2722	2.0336	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.028889	0.066667	0.00119	0.00142	3.0479	2.0336	Yes
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.028889	0.045556	0.00119	0.02232	0.4482	2.0336	No
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.028889	0.183333	0.00119	0.00464	8.3398	2.0336	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.082222	0.066667	0.00146	0.00142	1.1939	2.0336	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.082222	0.045556	0.00146	0.02232	0.9802	2.0336	No
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.082222	0.183333	0.00146	0.00464	5.3359	2.0336	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.066667	0.045556	0.00142	0.02232	0.5648	2.0336	No
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.066667	0.183333	0.00142	0.00464	6.1758	2.0336	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.045556	0.183333	0.02232	0.00464	3.4593	2.0336	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.099444	0.061111	0.00297	0.00365	1.9424	2.0336	No
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.099444	0.122778	0.00297	0.00324	1.2210	2.0336	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.061111	0.122778	0.00365	0.00324	3.0615	2.0336	Yes
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.146667	0.128889	0.00407	0.00144	0.9868	2.0336	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.146667	0.129444	0.00407	0.00419	0.7809	2.0336	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.128889	0.129444	0.00144	0.00419	0.0305	2.0336	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.188889	0.147778	0.02009	0.00401	1.0920	2.0336	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.188889	0.172222	0.02009	0.00313	0.4510	2.0336	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.188889	0.140000	0.02009	0.00340	1.3152	2.0336	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.147778	0.172222	0.00401	0.00313	1.1932	2.0336	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.147778	0.140000	0.00401	0.00340	0.3726	2.0336	No
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.172222	0.140000	0.00313	0.00340	1.6443	2.0336	No

Table H. 28 Summary of significance tests on sensitivity of the base hardness test – width readings – to fibre shape, type and volume for samples cured in polythene sheeting

Specimen ID 1	Specimen ID 2	Mean 1	Mean 2	Variance s_1^2	Variance s_2^2	t_{actual}	$t_{critical}$	Significant difference
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.0 % - 45 mm	0.175556	0.195556	0.00051	0.00140	1.2923	2.1200	No
A2, s/c, 0.51% - 45 mm	A2, s/c, 1.5 % - 45 mm	0.175556	0.226667	0.00051	0.00249	2.6383	2.1200	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 2.0 % - 45 mm	0.175556	0.273333	0.00051	0.00320	4.5383	2.1200	Yes
A2, s/c, 0.51% - 45 mm	A2, s/c, 3.0 % - 45 mm	0.175556	0.298111	0.00051	0.02000	2.4201	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 1.5 % - 45 mm	0.195556	0.226667	0.00140	0.00249	1.4106	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.195556	0.273333	0.00140	0.00320	3.2427	2.1200	Yes
A2, s/c, 1.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.195556	0.298111	0.00140	0.02000	1.9827	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 2.0 % - 45 mm	0.226667	0.273333	0.00249	0.00320	1.7500	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.226667	0.298111	0.00249	0.02000	1.3474	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/c, 3.0 % - 45 mm	0.273333	0.298111	0.00320	0.02000	0.4601	2.1200	No
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.0 % - 32 mm	0.144444	0.226667	0.00291	0.00436	2.7277	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.144444	0.252222	0.00291	0.00335	3.8516	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.144444	0.297778	0.00291	0.00760	4.2307	2.1200	Yes
A2, s/t, 1.0 % - 32 mm	A2, s/t, 1.5 % - 32 mm	0.226667	0.252222	0.00436	0.00335	0.8234	2.1200	No
A2, s/t, 1.0 % - 32 mm	A2, s/t, 2.0 % - 32 mm	0.226667	0.297778	0.00436	0.00760	1.8399	2.1200	No
A2, s/t, 1.5 % - 32 mm	A2, s t, 2.0 % - 32 mm	0.252222	0.297778	0.00335	0.00760	1.2316	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.0 % - 30 mm	0.168889	0.200000	0.00152	0.00089	1.7925	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.168889	0.226667	0.00152	0.00160	2.9252	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.168889	0.327000	0.00152	0.01357	3.6404	2.1200	Yes
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 1.5 % - 30 mm	0.200000	0.226667	0.00089	0.00160	1.5119	2.1200	No
A2, s/fe, 1.0 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.200000	0.327000	0.00089	0.01357	2.9873	2.1200	Yes
A2, s/fe, 1.5 % - 30 mm	A2, s/fe, 2.0 % - 30 mm	0.226667	0.327000	0.00160	0.01357	2.3041	2.1200	Yes
A2, s/s, 0 51 % - 35 mm	A2, s s, 2.0 % - 35 mm	0.195556	0.222222	0.00309	0.00191	1.0669	2.1200	No
A2, p, 0.1 % - 12 mm	A2, p, 0.51 % - 12 mm	0.097778	0.282222	0.00137	0.00360	7.4016	2.1200	Yes
A2, sp, 0.1 % - 12.5, 60 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.200000	0.257778	0.00018	0.00217	3.3707	2.1200	Yes
B5	A2, s/c, 0.51% - 45 mm	0.272222	0.175556	0.01004	0.00051	2.6615	2.1200	Yes
B5	A2, s/c, 1.0 % - 45 mm	0.272222	0.195556	0.01004	0.00140	2.0272	2.1200	No
B5	A2, s/c, 1.5 % - 45 mm	0.272222	0.226667	0.01004	0.00249	1.1512	2.1200	No
B5	A2, s/c, 2.0 % - 45 mm	0.272222	0.273333	0.01004	0.00320	0.0273	2.1200	No
B5	A2, s/c, 3.0 % - 45 mm	0.272222	0.298111	0.01004	0.02000	0.4225	2.1200	No
B5	A2, s/t, 0.51 % - 32 mm	0.272222	0.144444	0.01004	0.00291	3.1755	2.1200	Yes
B5	A2, s/t, 1.0 % - 32 mm	0.272222	0.226667	0.01004	0.00436	1.0739	2.1200	No
B5	A2, s/t, 1.5 % - 32 mm	0.272222	0.252222	0.01004	0.00335	0.4889	2.1200	No
B5	A2, s/t, 2.0 % - 32 mm	0.272222	0.297778	0.01004	0.00760	0.5443	2.1200	No
B5	A2, s/fe, 0.51 % - 30 mm	0.272222	0.168889	0.01004	0.00152	2.7183	2.1200	Yes
B5	A2, s/fe, 1.0 % - 30 mm	0.272222	0.200000	0.01004	0.00089	1.9541	2.1200	No
B5	A2, s/fe, 1.5 % - 30 mm	0.272222	0.226667	0.01004	0.00160	1.1943	2.1200	No
B5	A2, s/fe, 2.0 % - 30 mm	0.272222	0.327000	0.01004	0.01357	1.0083	2.1200	No
B5	A2, s/s, 0.51 % - 35 mm	0.272222	0.195556	0.01004	0.00309	1.8924	2.1200	No
B5	A2, s/s, 2.0 % - 35 mm	0.272222	0.222222	0.01004	0.00191	1.2939	2.1200	No
B5	A2, p, 0.1 % - 12 mm	0.272222	0.097778	0.01004	0.00137	4.6186	2.1200	Yes
B5	A2, p, 0.51 % - 12 mm	0.272222	0.282222	0.01004	0.00360	0.2422	2.1200	No
B5	A2, sp, 0.1 % - 12.5, 60 mm	0.272222	0.200000	0.01004	0.00018	2.0209	2.1200	No
B5	A2, sp, 0.5 % - 12.5, 60 mm	0.272222	0.257778	0.01004	0.00217	0.3697	2.1200	No
A2, p, 0.1 % - 12 mm	A2, sp, 0.1 % - 12.5, 60 mm	0.097778	0.200000	0.00137	0.00018	7.3424	2.1200	Yes
A2, s/c, 0.51% - 45 mm	A2, s/t, 0.51 % - 32 mm	0.175556	0.144444	0.00051	0.00291	1.5031	2.1200	No
A2, s/c, 0.51% - 45 mm	A2, s/fe, 0.51 % - 30 mm	0.175556	0.168889	0.00051	0.00152	0.4180	2.1200	No
A2, s/c, 0.51% - 45 mm	A2, s/s, 0.51 % - 35 mm	0.175556	0.195556	0.00051	0.00309	0.9422	2.1200	No
A2, s/c, 0.51% - 45 mm	A2, p, 0.51 % - 12 mm	0.175556	0.282222	0.00051	0.00360	4.7068	2.1200	Yes
A2, s/c, 0.51% - 45 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.175556	0.257778	0.00051	0.00217	4.4869	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, s/fe, 0.51 % - 30 mm	0.144444	0.168889	0.00291	0.00152	1.0382	2.1200	No
A2, s/t, 0.51 % - 32 mm	A2, s/s, 0.51 % - 35 mm	0.144444	0.195556	0.00291	0.00309	1.8655	2.1200	No
A2, s/t, 0.51 % - 32 mm	A2, p, 0.51 % - 12 mm	0.144444	0.282222	0.00291	0.00360	4.8304	2.1200	Yes
A2, s/t, 0.51 % - 32 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.144444	0.257778	0.00291	0.00217	4.4947	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, s/s, 0.51 % - 35 mm	0.168889	0.195556	0.00152	0.00309	1.1106	2.1200	No
A2, s/fe, 0.51 % - 30 mm	A2, p, 0.51 % - 12 mm	0.168889	0.282222	0.00152	0.00360	4.4816	2.1200	Yes
A2, s/fe, 0.51 % - 30 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.168889	0.257778	0.00152	0.00217	4.1367	2.1200	Yes
A2, s/s, 0.51 % - 35 mm	A2, p, 0.51 % - 12 mm	0.195556	0.282222	0.00309	0.00360	2.9978	2.1200	Yes
A2, s/s, 0.51 % - 35 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.195556	0.257778	0.00309	0.00217	2.4256	2.1200	Yes
A2, p, 0.51 % - 12 mm	A2, sp, 0.5 % - 12.5, 60 mm	0.282222	0.257778	0.00360	0.00217	0.9104	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/t, 1.0 % - 32 mm	0.195556	0.226667	0.00140	0.00436	1.1596	2.1200	No
A2, s/c, 1.0 % - 45 mm	A2, s/fe, 1.0 % - 30 mm	0.195556	0.200000	0.00140	0.00089	0.2626	2.1200	No
A2, s/t, 1.0 % - 32 mm	A2, s/fe, 1.0 % - 30 mm	0.226667	0.200000	0.00436	0.00089	1.0415	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/t, 1.5 % - 32 mm	0.226667	0.252222	0.00249	0.00335	0.9459	2.1200	No
A2, s/c, 1.5 % - 45 mm	A2, s/fe, 1.5 % - 30 mm	0.226667	0.226667	0.00249	0.00160	0.0000	2.1200	No
A2, s/t, 1.5 % - 32 mm	A2, s/fe, 1.5 % - 30 mm	0.252222	0.226667	0.00335	0.00160	1.0273	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/t, 2.0 % - 32 mm	0.273333	0.297778	0.00320	0.00760	0.6654	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/fe, 2.0 % - 30 mm	0.273333	0.327000	0.00320	0.01357	1.1722	2.1200	No
A2, s/c, 2.0 % - 45 mm	A2, s/s, 2.0 % - 35 mm	0.273333	0.222222	0.00320	0.00191	2.0231	2.1200	No
A2, s/t, 2.0 % - 32 mm	A2, s/fe, 2.0 % - 30 mm	0.297778	0.327000	0.00760	0.01357	0.5681	2.1200	No
A2, s/t, 2.0 % - 32 mm	A2, s/s, 2.0 % - 35 mm	0.297778	0.222222	0.00760	0.00191	2.1924	2.1200	Yes
A2, s/fe, 2.0 % - 30 mm	A2, s/s, 2.0 % - 35 mm	0.327000	0.222222	0.01357	0.00191	2.3822	2.1200	Yes

Figure H. 1 Generalised plot of abrasion depth vs. impact indentation for samples

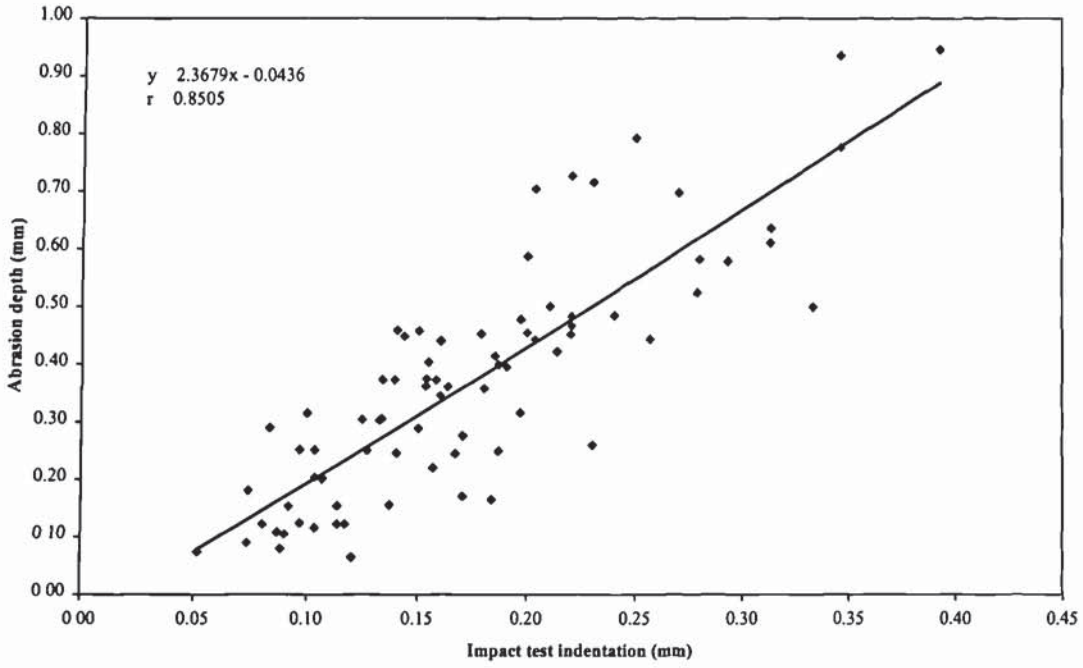
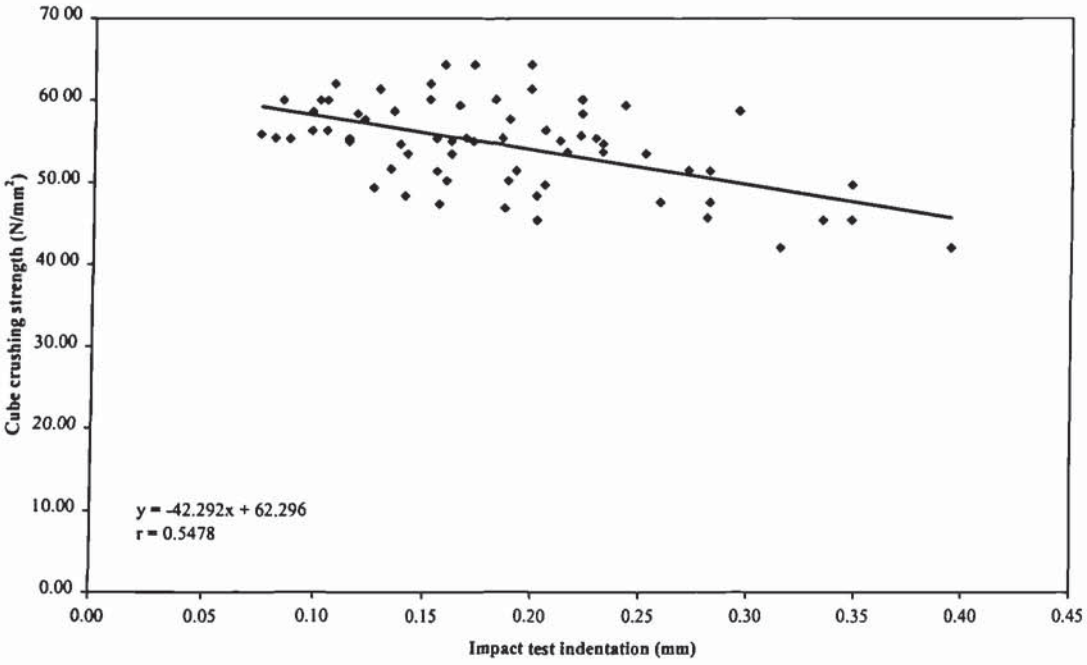


Figure H. 2 Generalised plot of cube crushing strength vs. impact indentation



Appendix I: Abrasion resistance of heavy-duty industrial concrete floors

Table I. 1 *Mix design certificate for C35 and C40 ready mix concretes*

To: 44012133333389 From: Tarmac Fax: at: 14-JUN-2001-11:30 Doc:767 Page: 001

MIX DESIGN CERTIFICATE: Mini Mix

Mix Design Certificate	1000999604	Quotation Number	1000995981
Dated	14.06.2001	Your Ref.	MG024313

Aceminimix
Sales Office
Whitehall House,Whitehall Road
Halesowen
West Midlands
B63 3LE
Tel 0121 585 5559
Fax 0121 585 5557

To: ASTON UNIVERSITY
DIRECTOR OF FINANCE
ASTON UNIVERSITY
ASTON
B4 7ET

Site DEPT OF CIVIL ENGINEERING
SUMPNER BUILDING
ASTON

F.A.O: Vasso Our Representative: CUSTOMER SERVICES

Specification	Our Ref.:	
Plant	Acemix (W.	Acemix (W.
Concrete Grade	C40	C35
Cement Type	PC	PC
Maximum Aggregate Size (mm)	0	0
Target Slump (mm)	100	75
Minimum Cement Content	325	300
Max Water / Cement Ratio	0.52	

Mix Design: Materials & Mix Proportions: kg/m^3 at SSD		
PC	375	330
20-5mm	1179	1179
Sand	671	722
Water	180	175
Aggregate/ Cement Ratio	4.93	5.76
Water/ Cement Ratio	0.48	0.53
Percentage Fines	36.27	37.98

Please Note:

HEALTH & SAFETY
When cement is mixed with water, alkali is released. Prevent skin contact with wet cement or concrete by wearing suitable clothing. If cement or concrete enters the eye, immediately wash it out thoroughly with clean water and seek medical treatment without delay. Wash wet concrete off the skin immediately.

For and on behalf of
Aceminimix

This design is relevant to the above quotation of which it is a part thereof and subject to our Standard Conditions of Sale
This certificate is for illustrative purposes only, the materials and mix design(s) are those in current production, these may be changed and/or modified when material properties vary or supply sources change.

Technical Department

TARMAC CENTRAL LIMITED TRADING AS ACEMINIMIX, TRU MINIMIX
REGISTERED IN ENGLAND NUMBER 3140503
REGISTERED OFFICE:TUNSTEAD HOUSE,BUXTON,DERBYSHIRE,SK17 8TG

A member of the Anglo American plc Group

Appendix J: List of publications

ABSTRACTS AND SHORT PAPERS

- Vassou V (1997) Strengthening of Degraded reinforced concrete beams in the Model Analysis As A Design Tool Newsletter No. 81, Institution of Structural Engineers Informal Study Group, December.
- Sadegzadeh M, Kettle RJ & Vassou V (2001) The influence of glass, polypropylene and steel fibres on the physical properties of concrete, Concrete, April 2001, Vol. 35, No. 4, pp. 12– 13.
- Sadegzadeh M, Vassou V & Kettle RJ (2002) Abrasion resistance of industrial concrete floors: What lies beneath the curing compound?, Concrete, September 2002, Vol. 36, No. 8, pp. 30 – 33.

CONTRIBUTIONS TO SYMPOSIA AND COMPILED VOLUMES

- Kettle RJ, Vassou V & Sadegzadeh M (2000) Comparative investigations using three accelerated abrasion testers, Proceedings of the 10th BCA Annual Conference on Higher Education and the Concrete Industry, Concrete Communication Conference, 29-30 June 2000, British Cement Association, Berkshire, pp.383-395.
- Vassou V & Kettle RJ (2000) Abrasion resistance of fibre reinforced concrete floors, Proceedings of Materials Week, International Congress on Advanced Materials, 25 – 28 September, ICM-International Congress Centre, Munich (download from www.materialsweek.org/proceedings).
- V Vassou, RJ Kettle & M Sadegzadeh (2001) The concrete abrasion test apparatus in accordance with the BS 8204 (Part 2: 1999). The reality! Proceedings of the 9th International Conference on Structural Faults & Repair – 2001, ed. Forde MC, CD - ROM: ISBN: 0-947644-47-4, Engineering Technics Press, Edinburgh.
- M Sadegzadeh, RJ Kettle & V Vassou (2001) Influence of glass, polypropylene and steel fibres on physical properties of concrete, Proceedings of the 9th International Conference on Structural Faults & Repair – 2001, ed. Forde MC, CD - ROM: ISBN: 0-947644-47-4, Engineering Technics Press, Edinburgh.
- V Vassou, RJ Kettle & M Sadegzadeh (2002) A summary of the developments in the abrasion resistance testing of industrial concrete floors, in Concrete floors and slabs, Proceedings of the International Congress Challenges of Concrete Construction, University of Dundee, 5-6 September 2002, eds. RK Dhir, MD Newlands & TA Harrison, pp. 245 – 259.

- M Sadegzadeh, RJ Kettle & V Vassou (2003) Curing compound and Abrasion Resistance, 5th International Colloquium "Industrial Floors 2003", 21-23 January, Stuttgard/Ostfildern, Germany Vol. II, pp. 951 – 954.

REFEREED PAPERS IN PRIMARY JOURNALS

- V Vassou, RJ Kettle & M Sadegzadeh (2002) The relative performance of abrasion apparatus in accordance with BS 8204 (Part 2: 1999), ASTM, Cement, Concrete & Aggregates, Vol. 24, No. 2, pp. 72 – 79.