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WORKABILITY AMD MATURITY PROPERTIES OF GROUND GRANULATED BLASTFURNACE SLAG CONCRETES

by

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ABSTRACT

The intimate mixing of ordinary Portland cement (OPC) with ground granulated blastfurnace slag (GGBS) to produce a cementitious binder for concrete has several environmental, technical and economic advantages which have led to it becoming accepted in many countries.

Almost all published work on GGBS concretes in the United Kingdom has used GGBS from a single long-established source. Several sources of GGBS are now available, so an extensive project was undertaken by the author to determine the importance of the origin and grinding of the granulate.

In the main programme of research two types of GGBS were incorporated in concrete mixes with three cementitious contents and three cementitious blends. Five different curing conditions and five ages of testing were employed. Alternative methods of assessing the workability, hydration characterisics, strength and potential durability were examined.

The results seem to indicate that both the level and source of GGBS in the cementitious blend have an important bearing on fresh and hardened concrete properties; dependent on other factors, such as the cement content, age and curing conditions. The relationships between the hardened concrete assessment parameters were also found to be influenced by the presence of GGBS. Novel tests to assess the mix stability, hydration characteristics and potential durability of concrete performed favourably.

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ABBREVIATIONS

Fig	Figure
Tab	Table
BS	British Standard publication
OPC	ordinary Portland cement (BS 12)
GGBS	ground granulated blastfurnace slag (BS 6699)
PFA	pulverised fuel-ash (BS 3892)
RHPC	rapid-hardening Portland cement
SRPC	sulphate-resisting Portland cement
PBFC	Portland blastfurnace cement (BS 146)
LHPBFC	low heat Portland blastfurnace cement (BS 4246)
PPFAC	Portland pulverised-fuel ash cement (BS 6588)
C	lime (CaO)
A	alumina (A^O^)
S	silica (Si02)
F	ferric oxide (Fe^^)
C^S	tricalcium silicate (Alite)
C2S	dicalcium silicate (Belite)
C^A	tricalcium aluminate
CjjAF	tetracalcium alumino ferrite
C&CA	Cement and Concrete Association
BRE	Building Research Establishment
CIRIA	Construction Industry Research and Information Association
BRMCA	British Ready-Mixed Concrete Associaton
QSRMC	Quality Scheme for Ready-Mixed Concrete
ACI	American Concrete Institute
MCR	Magazine of Concrete Research
NDT	non-destructive testing
ASR	alkali-silica reaction
UPV	ultrasonic pulse velocity
MAD	mean absolute deviation
ABS	absolute

NOTATION

f0	compressive strength (MPa)
fct	tensile splitting strength (MPa)
fof	flexural strength (MPa)
fc(e)	equivalent cube strength (MPa)
Ecq	dynamic modulus of elasticity (GPa)
Ec	static modulus of elasticity (GPa)
Eu	stiffness constant (GPa)
V	ultrasonic pulse velocity (km/s)
F	dynamic Poisson’s ratio
f	density (kg/m^)
t	time (seconds,minutes,hours,days)
T	temperature (°C)
L	length (mm)
TCH	torque change (Nm)
log	logarithm to base 10
In	natural logarithm
m	arithmetic mean
a	coefficient term
b	index term in power or exponential relation
c	intercept term in linear relation
sd	standard deviation
se	standard error
n	number of observations
df	degrees of freedom
Cm	Cement Content
Rp	GGBS level
Ty	GGBS Type
Cu	Curing
Bk	Block
SS	sum of squares
MS	mean sum of squares
xo> N	Rosin-Rammler coefficients

Waste or by-products from quarrying, mining or power production have a long history of use in the building and construction industries. Their use is prompted by the need to : reduce the cost and importation of materials, conserve energy and natural resources, avoid quarrying and tipping, and where possible improve the quality of construction.

A survey (1) of major industrial by-products and waste materials was conducted on behalf of the Department of the Environment in the early 1970's. This yielded four categories of residue:

a) quarrying waste,
b) mining waste and tailings,
c) metallurgical slags, and
d) fuel combustion residues.

All the categories find use in construction. Typical uses are as a fill or roadstone, in brick or block making, and in concrete.

Concrete is usually a composite of aggregates in a cement binder. It is an obvious candidate for the use of residue materials since its aggregates consume natural stone, gravel and sand, whilst the manufacture of Portland cement requires limestone, clay, gypsum and a large input of energy. Indeed, in the United Kingdom artificial aggregates are used to produce lightweight concrete, and ground granulated blastfurnace slag (GGBS) from iron smelting or pulverized-fuel ash (PFA) from coal combustion are used to partially replace OPC.

The potential of GGBS was slow to be realised. Of the nine million tonnes of blastfurnace slag produced in 1971, less than two percent was used as a cementitious material (1). The use and sources of GGBS have burdgeoned in the 1980's, yet published data relating to these new sources is scarce. At the same time increasing demands are being made on materials in terms of construction cost, complexity and quality. There is a real need to know how the use of these materials will affect the ability to place and compact the fresh concrete, the properties of the concrete as it hardens, and the long-term performance. It is the former two topics which this thesis specifically seeks to address.

The reported results come from an extensive investigation conducted by the author, at Sheffield City Polytechnic, between 1985 and 1988.

2.1 Introduction

The following five sections examine the evolution of cement and concrete production, the interrelationship between the design, properties and performance of concrete, and the nature of cement replacement materials. The final section of the chapter catalogues previous research, appropriate to this investigation.

2.2 Historical Note

The earliest concrete was discovered, forming a hut floor,in Yugoslavia and dates from approximately 5600 BC (2). The word concrete derives from the latin ’concretus’ meaning compounded. Indeed, the distinguishing characteristic of concrete is its compounding of water, cement, and aggregates.

The early evolution of concrete is really that of the cementitious component. The early cements, consisting essentially of lime, were weak and would not set underwater. Around 200 BC the Romans started using fine volcanic ash from near Pozzuoli in their concrete. This ash when mixed with lime produced a strong, hydraulic cement. This ’pozzolanic’ cement found widespread use and exists to this day in the remains of the theatre at Pompeii.

After the fall of the Roman empire,cement and concrete declined in use until a renaissance in the 18th Century. John Smeaton working on the Eddystone Lighthouse developed a cement consisting of burnt limestone and pozzolana. Experiments by John Aspdin, a Leeds builder, culminated in him taking out a patent for the manufacture of ’Portland cement’ in October 1824.

The hydraulic potential of blastfurnace slag were discovered by Emil Langen in Germany ,in 1862, and production of cement incorporating GGBS followed three years later. Despite the considerable history of use of pozzolanic cements in concrete, the use of PFA as a source of pozzolana only became apparent in the 1930’s, through work in America (3)•

GGBS was originally mixed with lime to produce a cement.

This method of production became redundant with the discovery that GGBS could be activated by combining with Portland cement, to form Portland blastfurnace cement, or calcium sulphate to form supersulphated cement. The initial method of combining the Portland cement with GGBS was to intergrind the clinker with the slag to produce a 'composite' cement. However in 1933 the Trief process was patented, in which the granulated slag is wet-ground to form a slurry for blending with Portland cement at the mixer. A logical extension of this process was the separate dry-grinding of granulated slag for within-mixer blending. This first began in South Africa in 1958, and was introduced in the United Kingdom six years later. In 1969 separate GGBS, marketed under the trade name "Cemsave", began full production from Scunthorpe using locally available slag.

A list of the developments in the use of GGBS is given in Reference 3* The most significant of these have been : the recognition that GGBS can beneficially effect durability; the acceptance of within-mixer blending; and the increase in the number of sources of GGBS.

GGBS is currently manufactured in at least six locations in the United Kingdom, including: Scunthorpe in the East Midlands, Purfleet in the South East, Aberthaw in Wales, Padeswood in the North West, and Clyde in Scotland (4). Major projects employing the material include the Anchor Steelworks (1964),the Wet Sleedale Dam (1965), and the Humber Bridge (1974).

2.3 Concrete Properties and Performance

Producing good concrete is a matter of controlling certain factors, such as the mix design and curing, in order to obtain specified levels of measured properties, which should in turn be reflected in a satisfactory performance of the concrete in service. The relationship between these three elements is indicated in Fig 2.3.

The term workability covers a number of characteristics of fresh concrete, including the its ability to be placed and compacted,

	FACTOR	PROPERTY	PERFORMANCE
	Mix Design Mixing W/C ratio	Workability Bleeding Segregation	Plastic Cracking
FRESH CONCRETE		Setting Hydration	Finishing Formwork Pressure Thermal Cracking
		Compaction Homogeneity Integrity	
	Curing		
HARDENED CONCRETE		Strength Elasticity	Formwork Striking Creep and Shrinkage Cracking
		Permeability Absorption	Durability frost attack abrasion chemical attack
		Stability	

Q Measured

O Required

Fig 2.3 : Some properties of concrete and their bearing upon performance.

and its stability. The workability of fresh concrete has an important bearing upon its hardened properties. The ability of a concrete to be placed and compacted will influence the amount of voids present in the hardened concrete, and consequently its strength and durability. A mix may be made more workable by adding water, however this additional water will itself leave small pores in the concrete upon evaporation.

The stability or 'cohesiveness' of fresh concrete determines the amount the constituents will separate out under gravity from a uniform mixture. This separation is termed bleeding when it involves a movement of water, and segregation when the solids are redistributed. Segregation reduces the homogeneity of the concrete and its ability to be fully compacted. Bleeding only becomes a problem when the water carries with it other constituents or collects under reinforcement. Indeed, bleeding may beneficially reduces the water-cement ratio of the concrete and mollify plastic shrinkage cracking.

The process of hydration and the absorption and evaporation of water leads to a loss of workability with time. During hydration the compounds in cement react with water and products are precipitated. These products eventually cause the cement paste to stiffen or set. This setting determines the end of concrete workability, the pressures exerted by the concrete on the formwork, and the time of some finishing processes. Hydration in addition to setting also produces heat. In restrained sections this heat may lead to thermal cracking.

The chief aims of the design, mixing and handling of the concrete prior to curing is to maximiseits compaction, homogeneity and integrity.

Curing of the concrete promotes hydration, the products of whichinterlock with each other and the aggregates. As a consequence the strength of the concrete increases and its porosity is reduced. The strength and elastic properties of the hardened concrete determine the degree of deformation and cracking under stress. The porosity of the concrete is reflected in its permeability and water absorption, that is the ease with which aggressive agents and water move into and through concrete, and thus has a large bearing upon its durability.

The aim of the curing and treatment of hardened concrete is to produce a material which has the required stability to loads and the environment.

2.4 Contemporary Cement Production

Portland cement consists of silicates and aluminates from clay or shale, and lime from chalk or limestone. Blends of these materials are heated in a rotary kiln at approximately 1400 °C, so that they burn and fuse to form a clinker. This clinker vitrifies upon cooling and is ground to a fine powder in a ball mill. Gypsum is added at this stage to prevent premature setting of the resulting cement. Several varieties of Portland cement are available; the most popular being ordinary, rapid-hardening and sulphate-resisting.

Three systems of blending and burning the constituents are currently in use: the wet process in which the raw constituents are blended and fed into the kiln as a slurry; and the semi-dry and dry processes in which the materials are blended as powders, and preheated prior to entering the kiln. The efficiency of the kiln depends greatly on the moisture content of the meal entering it. For this reason the semi-dry and dry processes are the favoured option in the United Kingdom.

The grinding system have evolved from open systems, in which all material simply exits the ball mill, to closed systems in which the material is passed through separators or classifiers. Particles which are too coarse are recycled through the mill, whilst the finer particles pass to the silo. This system leads to a more efficient use of grinding time and ensures a narrower range of particle sizes.

Hammer crushers and rollar presses which form the clinker into shattered cakes requiring substantially less grinding, are also being introduced.

Several changes in cement production have promoted the use of

GGBS as a replacement material. Firstly, changes from the wet to the dry and semi-dry processes have increased the ratio of C^S to C_2S (5) (Section 2.1) and the alkali levels in Portland cement. This had important implications for durability; increasing the heat of hydration and consequent danger of thermal cracking; increasing the risk of alkali-silica reaction; and maintaining the steady decline in the cement content required for strength compliance. Secondly, the oil crisis and restrictions on energy consumption forced a reduction in Portland cement production, leading to severe shortages of cement and a sharp rise in prices and imports (6).

These durability and price considerations have supported a sustained growth in the use of GGBS (Fig 2.4.a), and it is estimated that separate GGBS and the interground cement together account for over 10$ of the cementitious material used in the United Kingdom annually (7). Similar levels have been reached in other countries, such as Japan (Fig 2.4.b)(8).

In the United Kingdom blending of the cementitious components takes place in the mixer, whilst on the Continent the cement clinker and GGBS, or PFA, are predominantly interground. The within-mixer process has the advantage of allowing the individual grinding and the overall blend of the granulate, or ash, and the Portland cement to be adjusted. When intergrinding the hardness of the granulate results in preferential grinding of the softer clinker. Studies have indicated that within-mixer blending is as effective as intergrinding (9 ,10)-

The potential to produce an infinitely variable cement form just two silos of material is both the chief advantage and disadvantage of within-mixer blending. Extra care must be exercised in the storage and batching of separate GGBS.

2.5 Cement Replacement Materials

The principle cement replacement materials in use in the United Kingdom are GGBS and PFA. Although both materials are latent hydraulic binders, one distinction must be made: GGBS is intrinsically

800

BAXTER PRICE INDEX FOR CEMENT

ESTIMATED PRODUCTION OF GGBS
AND SLAG CEMENT (THOUSAND TONNES)

ESTIMATED CEMENT AND CLINKER NET
IMPORTS INTO UK (THOUSAND TONNES)

1972 1974 1976 1978 1980 1982 1984 1986

Year

Fig 2.H.a : Price and availability of Portland Cement in the UK, and the estimated combined sale of GGBS and PBFC (1972-1987)*

10 -

Q _ SLAG CEMENT
ANNUAL VALUE IN PARENTHESES (MILLION TONNES)

O – PFA CEMENT

7 of Total Cement Production

1970 1972 1974 1976 1978 1980 1982 1984 1986

Year

Fig 2.4.b : Portland Blastfurnace Cement and Fly Ash Cement production in Japan (1970-1986).

hydraulic whilst PFA is not.

2.5.1 GGBS

Blastfurnace slag is a by-product of the steel industry and results from the "fusion of limestone flux, with ash from coke, and the siliceous and aluminous residue remaining after the reduction and separation of the iron from the ore" (1). The slag has an important role in removing from the iron impurities such as sulphate, and its composition is carefully controlled. Molten slag is tapped from the base of the furnace and cooled selectively to form three very different materials:

a) Air-cooled slag is a dense crystalline material similar to a Basic rock. After crushing and grading it can be used as an artifical stone or concreting aggregate.

b) Foamed slag has a cellular structure similar to pumice. After processing the foamed slag is used as a lightweight concreting aggregate or raw material in glass manufacture.

c) Granulated slag is a vitreous material, resembling sand, formed by supercooling the molten slag under high pressure water jets. After grinding the GGBS can be used as a partial replacement for Portland cement.

The composition of the slag is carefully controlled as part of the iron production process. However long-term variation in the chemical and mineralogical composition of the slag may arise from changes in the ore, furnace operating conditions and granulation (11). The suitability of GGBS as a cement replacement material depends chiefly on the state of vitrification, although the chemical and mineralogical composition also influence the reactivity. BS 6699 specifies minimum levels for fineness, glass content, and a chemical modulus (Section 2.6.3).

2.5.2 PFA

PFA is the fine ash electrostatically precipitated from the flue gases of power stations, using pulverized bituminous coal as fuel. The material "consists principally of aluminosilicate glass spheres together with small quantities of crystalline materials" (3)• PFA varies in quality with the source of the coal, pulverization, furnace firing conditions, and the collection method.

The suitability of PFA as a cement replacement material depends on the fineness and residual carbon content. Selection of the ash by removal of the coarser, and higher carbon content, particles gives rise to two classes of PFA to BS 3892; the finer suitable for cement replacement, and the coarser suitable for fine aggregate replacement only. Certain power stations, such as Eggborough , which operate under stable 'base-load' conditions, and are supplied with coal of a consistent quality, are favoured sources of PFA.

2.5.3 Cement Chemistry

Portland cement is assumed to consist of a series of complex compounds or mineralogical phases built up from oxides; primarily: lime (CaO), alumina (A^O^), silica (Si02), magnesia, and ferric oxide. These five oxides also typically account for over *80%* of the composition of GGBS and PFA. The composition of various hydraulic materials is summarised in Fig 2.5 using a ternary diagram, indicating

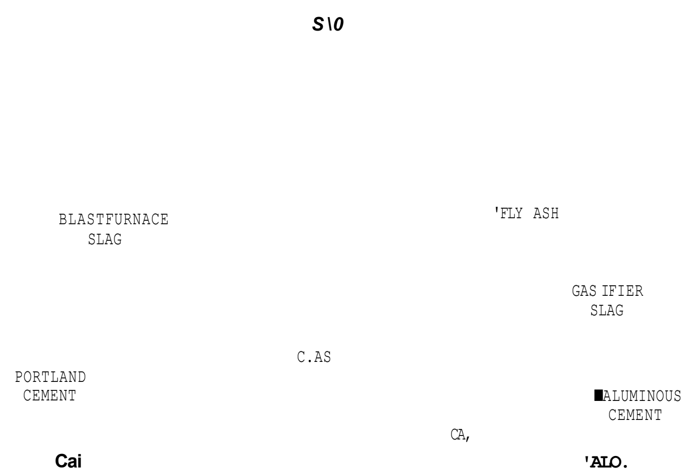


Fig 2.5 : Some hydraulic materials on a ternary composition diagram.

the percentages of lime, alumina and silica. OPC, GGBS and PFA form three separate zones, in order of decreasing lime content. As the lime content decreases the silica and alumina both increase, the silica showing the greater rise.

Bogue proposed (12) that the complex compounds in Portland cement are tricalcium silicate (CgS), dicalcium silicate (C2S), tricalcium aluminate (C^A) and tetracalcium aluminoferrite (C^AF). The tricalcium and dicalcium silicate react moderately and slowly respectively to form calcium silicate hydrate and lime. It is the tricalcium silicate hydrate which is responsible for much of the cementing strength of Portland cements. The tricalcium aluminate would react very fast , producing much heat and premature setting, in the absence of gypsum. However, because of the gypsum added to the clinker in the ball mill, the setting and heat of hydration of the cement are mainly determined by the reaction of the tricalcium silicate.

GGBS is intrinsically hydraulic in that it reacts on its own with water; albeit at a rate so slow as to be of no practical use. In an alkaline environment the reactions become much more rapid. Such an environment can be provided by the lime produced by the hydration reaction of Portland cement. Silicates in the slag react to form hydration products similar to Portland cement, that is: calcium silicate hydrate, calcium aluminate hydrate, and additionally calcium silicate aluminate hydrate.

The hydration of PFA is significantly different from the principal reaction of GGBS. Aluminates and silicates from the ash, and lime from the hydration of the Portland cement combine to form calcium aluminate hydrates and calcium silicates. A similar secondary pozzolanic reaction is thought to occur between acids from the GGBS and lime from the hydration of the Portland cement, in the gap between the clinker and slag grains. This secondary reaction has important implications for durability (Section 2.6.6.3).

The reaction of blended cements is moderated by the need of the GGBS or PFA component for lime. However, the higher activation energies of blended cements compared to Portland cements means this moderating effect can be overcome by raising the reaction temperature (Section 2.6.3).

2.5.4 A comparison of GGBS and PFA

The very different origins and characteristics of GGBS and PFA are reflected in some practical aspects of their use (see Tab 2.5). PFA generally requires no grinding, and the lower energy requirement for processing PFA means it can be theoretically sold at a lower price than GGBS. However, the chemistry of the material limits the amount of OPC that can be replaced, and consequently the cost saving that can be made. The British Standard for specifying ready-mixed concrete, BS 5328,limits the proportion of PFA to 35$, whereas GGBS may be used to replace up to 90$ of the OPC.

The GGBS particles are similar in shape, size and relative density to clinker grains and GGBS is simply substituted on a mass basis for OPC, with a slight reduction in the water content of the mix. In contrast the PFA particles are smooth hollow spheres with a much lower density and higher fineness than clinker grains. Substitution of OPC by PFA on a mass basis increases both the volume of powder and the workability; this is usually compensated for by a reduction in the fine aggregate and water contents. Unlike GGBS the composition of PFA is not controlled as part of the production process, but is dictated by the operating conditions of the power station. Indeed possible variation in the quality of PFA hindered its early development.

Despite the aforementioned differences in PFA and GGBS there are similarities in the specification and use of the materials. Both have:

1) specifications to cover the blended cement at lower and higher replacement levels for normal and low-heat applications respectively (BS 146 (0-65$ GGBS), BS 4246 (50-90$ GGBS), BS 6588 (15-35$ PFA) and BS 6610 (35-50$ PFA);

Tab 2.5 : Some Differences Between GGBS and PFA.

Aspect	PFA	GGBS
Reaction	Pozzolanic reaction with lime	activated in alkaline environment
Maximum and Normal level in blend	50% 20%	90% 50%
Cost	third of OPC	two-thirds of OPC
Processing and Energy used*	Classified 1-2% of OPC	Ground 3-5% of OPC
Workability	Increased	Slight Increase
Bleeding	Decreased	Increased
Variability	high	low
Identification	spherical particles under magnification	white in colour
Mix Design philosophy	fine aggregate replacement	similar to OPC
Admixture dosage	higher due to absorption	usually normal

* PFA figures vary according to degree of processing required.

Fulton, 1974 (14), working with separately ground South African slags, used a modified Vebe test to study the effect of GGBS level on concrete "vibratability". He showed that for a constant water-cement ratio the time of compaction decreased consistently with GGBS level.

Taylor, 1974 (15), in an article on cost reduction with GGBS commented that "when the quantity of free-water used in the mix is held constant an increased granulate content is associated with an increase in mix workability".

Atwell, 1974 (16), described the use of GGBS in the Anchor Steelworks. A constant workability was adopted for the project and "improved blend efficiencies could be achieved indicating a beneficial effect on workability with slag replacement".

Tattersall and Banfill, 1983 (17), reporting limited work by Arnold (1981), indicated that there is generally a decrease in both g and h with increasing GGBS level at a constant water content. These authors conducted a water demand test using constant workability mixes, containing up to 90$ GGBS. The water reduction achieved with GGBS mixes did not exceed 5$. In order to explain the maximum workability obtained by Fulton at 40$ GGBS the authors suggested that the increased powder content when replacing OPC by mass with GGBS took the effective fines content through an optimum value.

Ellis, 1985 (18), assessed the workability of various GGBS concretes using three British Standard methods and the two-point workability apparatus. Two series of mixes, with high and low fines contents, and cement replacement by volume and mass respectively, were produced. No consistent effect of GGBS upon workability was apparent. The reduced influence of GGBS level when replacing by volume in the first series of mixes seemed to indicate that powder volume is an important mechanism in the effect of slag upon workability. An optimum workability appeared to be obtained in the second series of mixes at about the 40$ GGBS level. The work confirmed the complexity of the effect of GGBS upon workability and the increased sensitivity

2) specifications to cover the separately ground material for within-mixer blending (BS 6699 and BS 3892 respectively);

3) schemes with the BRMCA to provide blend levels for different sources of cementitious materials to ensure compliance with the blended cement specification;

4) Agrement certficates to confirm their suitability for use in construction (numbers 82/1032 (13) and 85/1504);

5) the potential advantages of reducing the heat of hydration and the risk of sulphate attack and alkali-silica reaction;

6) the potential disadvantage of a lower early rate of strength development.

2.6 A Review of Previous Research

2.6.1 General

Most research carried out on the Continent into the effects of GGBS has employed composite cements, formed by intergrinding. Data on within-mixer blended cement generally comes from South Africa and the United Kingdom; virtually all published data in the United Kingdom relates to GGBS from the longest established source at Scunthorpe. The only significant research on slag types, found by the author, was that by Moss (1984), and Frearson and Uren (1986).

In this section previous research is discussed under the headings : workability, hydration andpotential reactivity,strength, elastic properties, and long-term performance. When examining the results of any investigation consideration must be given to the mix designs used, particularly the adoption of a constant workability or water content. Unless otherwise stated constant workability refers to a constant slump value.

2.6.2 Workability

This sub-section deals firstly with general workability, then looks at mix stability and workability loss.

of the two-point test over the British Standard methods.

Moss, 1984 (19), employed GGBS from Scunthrope and Purfleet in an investigation or air-entrained and platicized concretes of constant workability (compacting factor). He concluded "The partial replacement of cement by Cemsave effected water reductions. The most noticeable effect being within the region of up to 40% cement replacement". His results also indicate that the slag source affects the water demand, although the author made no mention of this.

2.6.2.2 Bleeding

Dean, 1987 (4), reported that small-scale laboratory tests carried out by the Frodingham Cement Company showed that although 70$ GGBS mixes displayed substantially increased bleed capacity over corresponding OPC mixes, at lower replacement levels the source of the OPC used in the blend was highly influential.

Wainwright, 1986 (20), reports that Cesarini and Frigione (1986) and Allard (1984) found the bleeding rate and total amount of bleed increased with the GGBS level for both constant water-cement ratio and constant workability mixes. However, he adds that "there is in the UK at least no evidence from site to suggest that concretes containing GGBS show any greater tendency to bleed than concretes of the same 28-day strength made from Portland cement".

2.6.2.3 Workability loss

Meusel and Rose, 1983 (21), examined the workability loss in high workability concrete containing up to 50$ GGBS at temperatures between 24°C and 27°C. They concluded that there was no significant difference in the rate of loss of slump between the different concretes.

Banfill, 1985 (22), using the two-point test examined the effect of interactions between GGBS and superplaticizers on workability loss, as well as hydration and strength development.He concluded that the rate of workability loss is unaffected by the slag replacement level and cementitious content.

2.6.3 Hydration and Potential Reactivity

2.6.3.1 Setting

Several authors have researched this topic and found increased times of set in cement pastes made with GGBS. However, there is disagreement about how standard setting time tests relate to practice.

Stutterheim, 1960 (9), reporting the construction of an irrigation canal with a blended cement containing 70% high-magnesia slag described how slow setting resulted in a slight delay to finishing operations.

Harrison and Spooner, 1986 (23), indicate that under standard conditions an increase in GGBS from 30% to 60% increases the initial set by about an hour, and the final set by about an hour and a half. Similar values have been suggested by Hogan and Meusel (20).

2.6.3*2 Heat of Hydration

Atwell, 1974 (16), concludes from measurements on site and laboratory simulations that "temperature rise was reduced, and the time to peak increased as the slag proportion was increased".

Bamforth, 1980 (24), in an article on the performance of mass concrete in the foundations for a grinding mill, states that "The effect of cement replacement was in each case to reduce the peak temperature rise by about 8°C". He concluded that for pours up to two and a half metres deep GGBS and PFA were effective in reducing the temperature rise. For deeper pours the benefits of reduced temperature rise were outweighed by the increased stiffness of slag concretes.

VJainwright, 1985 (25), generated 'adiabatic' temperature profiles in the laboratory which indicated that the temperature rise coefficient fell from around 11 to 8°C/100 kg of cement when 70$ GGBS was used to replace OPC in mixes containing approximately 440 kg/m^3 of cement.

Cannon, 1985 (26), combined data from fourteen sites, using several Portland cement sources and one source of GGBS. The temperature rise coefficients in pours with a least lateral dimension of one metre were 13,11 and 7 °C per 100 kg of cement for OPC, PBFC and LHPBFC mixes respectively. The beneficial effect of using slag was much reduced when the least lateral dimension increased to three metres.

Harrison, 1981 (27), in a guide on early age crack control presents an estimate of the minimum reduction in temperature when using up to 80/6 GGBS, for section thicknesses of one and half tothree metres. The guide indicates a reduction in the temperature rise of a tenth for 40% GGBS, and a third for 80% GGBS, compared to OPC.

The important influence of the reaction temperature upon the reaction rate and the heat evolution of blended cements has been mentioned by a number of authors, including Atwell (16)•

2.6.3.3 Potential Reactivity

The potential reactivity of GGBS is a function of the properties of the granulate and its grinding. The final reactivity in service will be dependent on additional factors such as the activating cement and the reaction temperature; however this section concentrates on the chemical, mineralogical and physical properties of the slag alone.

Parker and Nurse, 1949 (28), applied a number of moduli to the 90-day compressive strength results from a wide range of British slags. They concluded that for blends of constant fineness, containing 35% GGBS with a fixed source of clinker, the German modulus

$$M1 = \frac{CaO + MgO + 1/3\ A1203}{Si02 + 2/3\ A1203}$$

gave the best correlation with strength, when combined with a measure of the percentage of non-crystalline particles in the slag, using transmitted light microscopy.

Demoulian et al, 1980 (29), examined fifteen moduli and found that M2 = CaO + MgO + Al^^,

Si02

which was incorporated in the German Standard DIN 1164, gave the best correlation with strength. The usefulness of pure glasscontent as a measure of hydraulicity was questioned by these authors, who stated that "perfect vitrification of slag is not the criterion of its optimal reactivity in slag cements". The adequacy of approaches based solely on chemical moduli or degree of vitrification has been challenged by a number of workers (30 ,31)•

Frearson and Uren, 1986 (30), in a review of the nature of slag containing Merwinitic crystalline inclusions, compared GGBS from Scunthorpe, having Melilite inclusions, with that from Purfleet, having Merwinite inclusions. The authors indicated that Merwinitic inclusions, although reducing the proportion of pure glass, did not practically deplete the reserve of glass for reaction, and actually increased the alumina levels and consequently the reactivity of the remaining glass. They suggested that the Purfleet slag should give rise to a higher rate of strength development than the Scunthorpe slag by virtue of its higher chemical modulus and Merwinitic inclusions.

Mehta, 1983 (31), reviewing the work of Wada and Ikawa, states that "particles less that 10 microns contributed to early strength development in concrete (until 28 days), whereas 10 to 40 micron particles continued to hydrate thereafter....in short the ground granulated slag for use as mineral admixture in concrete should contain few particles above 45 microns and a considerable portion of particles below 10 microns in order to improve the early strength development".

Hogan and Rose, 1986 (32), in a paper describing a slag activity test using mortar indicated that the fineness of the GGBS has less effect at 1 and 28 days that at 3 and 7 days. Stutterheim reported a similar effect (9).

Regourd, 1986 (33), reporting work he carried out in the early 1980's , indicated that if the Arrhenius law for rates of chemical reaction was applied to hydration data for OPC and a blended cement containing 70$ GGBS it yielded activation energies of 50 and 46 kJ/mol respectively. The larger activation energies for slag cement was also reported by Roy and Idorn (34), and explains why slag cements can benefit from raised reaction temperatures.

2.6.4 Strength

Consideration of this topic has been split into three areas:

1) The effect of mix design and curing upon the compressive strength.
2) In situ strength and the use of maturity functions.
3) The effect of mix design and curing upon the indirect tensile strength.

2.6.4.1 Compressive Strength

Compressive strength development is influenced by a number of factors, chiefly: cementitious type and content, water-cement ratio, chemical admixtures, and curing temperature and humidity. Wainwright (20) states that "genrally for equivalent cement contents and water-cement ratios, the higher the GGBS content the slower the development of strength, but the higher the long-term gain". In practice concrete is designed to a constant workability. Atwell, 1974 (16), reporting on the Anchor Steelworks project states that "the efficiency of a blend relative to 100$ OPC will be improved when workability is the constraint".

Harrison and Spooner, 1986 (23), report that "for mixes designed on the basis of equal 28-day strength and workability using 40$ GGBS the 3-day strength is about 50-60$ of the OPC concrete and at 7 days about 65-75$. Similarly, using 70$ GGBS these figures drop to about 30-35$ at 3 days and 50-65$ at 7 days". The importance of the reaction temperature was acknowledged by these authors. They comment that "at 5°C the strength of the PBFC concrete at 1 day is only 50$ of that of the equivalent OPC concrete (equal 28 day strength at 20°C)".

Pratas, 1987 (35), in a dissertation the early strength development of Cemsave concretes, wrote "replacements of 30 and 50$ led to reductions in the 28-day strength of the order of 20$ and 30$ respectively", in mixes manufactured to a constant workability and strength grade, and cured at 5°C. In contrast, "at 30°C the replaced mixes are stronger than the control within 14 days".

Moss, 1984 (19), carried out an extensive investigation into the effects of combinations of plasticizer or air-entraining agents and GGBS upon the water demand and strength development of concrete. GGBS was derived from two sources: Civil and Marine, Purfleet and Frodingham Cement, Scunthorpe. Concrete was made to a constant workability (compacting factor) and was standard cured throughout. He observed that "Cemsave derived from Civil and Marine was more reactive. It exhibited higher compressive strengths than the equivalent concrete with Frodingham Cement Co. Cemsave". Moss also found that the 28-day strength of plasticized GGBS concretes was equal to or exceeded that of plain OPC concretes. Unplasticized concrete containing 70$ GGBS had compressive strengths at 3 and 28 days which were only approximately 25$ and 80$ of the OPC control respectively. This percentage rose with reduced GBBS level and increasing cementitious content.

2.6.4.2 In Situ Strength

The slower early rate of strength development of GGBS concretes would be expected to be reflected in higher formwork striking times; there are however no published guidelines. Atwell (16) reported no unusual delays in striking formwork on the Anchor project, although a reduced level of GGBS had to be adopted in certain circumstances.

Curing specimens at fixed temperatures, or alongside the formwork, does not give an accurate indication of the strength development in the structure, where heat produced by the hydration reaction results in an imposed temperature cycle. In order to overcome this discrepancy temperature matched curing (TMC) was developed *(26).*

Bamforth 1980 (24), reporting TMC work on mass structures utilising OPC, PFA and GGBS noted that "the effect of the early temperature cycle.... was to accelerate the early rate of strength gain. At 28 days, however, although the strengths of the concrete containing replacement materials were enhanced by the temperature cycle, the strength of the OPC concrete was significantly impaired".

Wainwright and Tolloczko 1985 (25), compared standard and temperature cycled curing ,using artificial 'adiabatic' temperature profiles. They found that OPC concretes produced a higher adiabatic temperature rise, resulting in cycled strengths higher at early ages but lower at later ages than for standard curing. The slag concrete did not benefit from cycled-curing at early ages but was less detrimentally affected by these at later ages. They state "under adiabatic conditions concretes containing 70% slag have reached or exceeded the strength of equivalent OPC concrete by,7 days".

Pratas 1978 (35), in a dissertation on the early-age strength development in concrete containing Cemsave examined the use of maturity functions for formwork striking. He observed that a single relationship could be used under wet curing for temperatures between 5°C and 30°C.

Wainwright and Reeves 1981 (36), applied the Nurse-Saul function (Section C.2.1) to strength data from fixed and cycled curing of concretes containing OPC and blends of OPC with 30, 50 and 70% GGBS. They observed that the strength-maturity relationship was temperature dependent for both OPC and slag cement concretes, leading to higher strengths at higher temperatures. In the case of OPC this trend was reversed at later maturities. Two factors were proposed for the unimpaired later strength of concrete containing Cemsave: "Firstly it reduces the overall percentage of C^S in the blended cement and hence reduces the volume of less dense C^S hydrates.... Secondly in slowing down the overall rate of the hydration reaction, the addition of Cemsave allows the more dense C2S hydration products to form and predominate”.

2.6.4.3 Indirect Tensile Strength

Stutterheim 1960 (9), measured the modulus of rupture of standard cured specimens made from six blended cements and an OPC control. The author, commenting on the modulus of rupture-compressive strength relationship for a typical slag cement and the OPC control, states "the relationship clearly differs appreciably for the two types of cement

Wainwright 1986 (25), recorded the tensile splitting strength of cylinders made from OPC and cement blends, containing 50% and 70$ GGBS, under fixed and cycled curing. He concluded "Concretes containing slag have a higher tensile strength for an equivalent compressive strength than OPC concretes. The largest difference recorded for the normal cured concrete was 0.7 MPa (19$) and 1.2 MPa (40$) for adiabatic cured".

2.6.5 Elastic Properties

These comprise the four parameters: static modulus of elasticity, dynamic modulus of elasticity, Poisson’s ratio, and the ultrasonic pulse velocity. The latter three parameters are linked by a fundamental equation (Section C.2.3).

2.6.5.1 Elastic Modulus

Neville and Brooks 1975 (37), carried out a study into the time-dependent behaviour of concrete containing 0,30 and 50$ GGBS, and cured in water and in air. The mix proportions were adjusted to give constant workability (VeBe) and 28-day strength. The authors reported that "There was no definite difference in the static modulus of elasticity of the three mixes for any of the curing conditions but it is possible that on prolonged storage in water .... Cemsave concrete had a slightly higher modulus. Also, on prolonged dry storage the modulus of Cemsave concrete tended to decrease, while that of Portland cement concretes remained constant”.

Bamforth, 1980 (24), reported static elastic moduli for slag concretes under cycled-curing were approximately 8 GPa greater, at any compressive strength, than for OPC concrete of equal workability and 28-day strength.

Wainwright and Tolloczko, 1986 (25), measured the static and dynamic elastic moduli of constant workability mixes, with cementitious contents of 300 and 400 kg/m^ and GGBS levels of 0, 40 and 70/e GGBS, under standard and cycled curing. Only the static elastic modulus data was presented in detail, however the authors determined that under standard curing slag cement concrete had a slightly lower elastic modulus at lower compressive strengths (less than 40 MPa) and a higher modulus at higher strengths, than OPC concrete. The difference between slag and OPC concrete was less than 5 GPa at any compressive strength. Under cycled curing separation of the modulus-strength relationships with blend was more marked, although according to the authors the maximum increase in the elastic modulus for slag cement concrete over OPC was, at 12%, similar to that under standard curing.

Stutterheim, 1960 (9), reporting studies on concrete containing mixed and interground blends of OPC with high-magnesia slags states that "Poisson’s ratios for all these cements including the portland cement, are nearly the same at each respective test age....It will be seen that although the modulus-age relationships are not the same for the various cements the compressive strength-dynamic modulus relatonships are closely similar".

2.6.5.2 Ultrasonic Pulse Velocity

Little published data on the effect of using blended cement upon the strength-UPV relationship could be found. Facaoaru 1969 (38) in a review of non-destructive research in Romania states that "The use of high quality ,rapid-hardening cements leads to an increase in the strength corresponding to a given pulse velocity, whereas, on the contrary, the use of cements containing a large proportion of inert or nearly inert additions (like slag) decreases the strength, corresponding to a given pulse velocity".

2.6.6 Long-term Performance

Consideration is given firstly to those aspects relating to the physical stability of the concrete, such as creep, shrinkage and abrasion resistance. Porosity, water absorption and permeability, which have bearing on both the physical and chemical stability are considered next, followed by a brief summary of specific chemical stability problems, such as sulphate attack and alkali-silica reaction.

2.6.6.1 Creep and Shrinkage

Neville and Brooks, 1975 (37) looking at the time-dependent behavour of concrete containing Cemsave observed that "For a constant stress-strength ratio, the basic and accelerated creep of Cemsave concrete are appreciably smaller than in Portland cement concrete.... however for air-storage the total creep of Cemsave concrete is slightly higher than in ordinary Portland cement concrete. Futhermore, "both types of concrete exhibit similar shrinkage,but the. modulus of elasticity of cemsave decreases somewhat with prolonged dry storage". The authors attributed the reduced creep of Cemsave concrete to a reduced paste content due to a lower water content , and its continued strength development at later ages.

Bamforth 1980 (24), reached similar conclusions for mass concrete. He noted that at a constant sress-strength ratio "the reduction in creep (basic) is in proportion to the level of replacement using slag".

2.6.6.2 Abrasion and Frost Resistance

Chaplin, 1986 (39), using the C&CA accelerated abrasion apparatus tested OPC and blended cement mixes, including a 50% GGBS blend. Three types of fine aggregate were employed, and mixes were made to a constant workability, and subject to different curing. Whilst there was "no detectable trend in the wear depth results for the slabs cured under polythene or with a resin curing compound....greatest depths of wear were obtained from the air-cured specimens containing GGBS".

The degree to which concrete is affected by frost depends on its strength, permeabilty, degree of saturation, and air entrainment. Early damage to concrete can result from premature exposure to freezing. Later damage can result from repeated cycles of freezing, coupled with scaling arising from the application of deicing salts.

Hansen et al, (40), 1958 carried out freeze-thaw tests on slabs of concrete containing PBFC from different sources, and with different finenesses. Precise experimental details were not given by the author, however no effect of cement fineness or source could be discerned.

Moss 1984, (19) 1984, reports that "the use of air entraining agents is not significantly changed by the replacement of cement by Cemsave".

2.6.6.3 Porosity

This topic covers four related areas: hydrate structure, water absorption, permeability, and diffusivity.

The hydrate structure of OPC becomes more porous at higher temperatures. Bakker, 1983 (41), attributes this to a poorer dispersion of the hydration products, which are precipitated closer to the reacting grains. In blended cements the secondary pozzolanic reaction between the excess calcium hydroxide from the clinker and acid components from the GGBS leads to products being deposited in the gap between the grains. Under higher temperatures this reaction counters any loss of permeability due to poor dispersal of the main hydration products.

Roy and Idorn, 1982 (3^), in a review of research on slag hydration also describe this long-term supplementary hydration. They conclude that "development of a dense microstructure, a fine pore structure, and a lower capillary porosity generates materials with very low permeability and ionic diffusivities".

Feldman, 1983 (M2), credited slag cements with a discontinous pore structure, low permeability and lime content, whilst Roy and Parker, 1983 (M3), observed smaller critical pore radii and lower pore volumes in slag cements.

Gjorv and Vennesland, 1979 (MM), using well-cured cylindrical mortar specimens immersed in seawater, concluded that "Portland cements may give as much as two to five times higher chloride penetration than blended cements ". The results indicate that the diffusion of chloride ions into the concrete is dependent not only on the permeability and chloride binding capacity, but also on the ion exchange capacity of the system. Page et al, 1981 (M5), using paste discs inserted in a diffusion cell reached similar conclusions.

2.6.6.M Chemical Stability

The effect of GGBS use upon the chemical stability of concrete is summarised in Tab 2.6. Several areas of dispute exist, probably arising from differing experimental conditions. In well-cured concrete the incorporation of GGBS lowers the level of reactive components and the permeability and diffusivity. However, this is countered by increased sensitivity to poor curing, and a reduced alkali reserve.

A comprehensive review of the effects of GGBS upon concrete durability has been presented by Reeves, 1971 (M6)• More recently, important research has been published on the topics of carbonation and alkali-silica reaction. Litvan and Meyer, 1986 (M7) indicate that in service GGBS concretes suffer from higher levels of carbonation than OPC concretes and, in contrast to OPC concretes, the permeability increases after carbonation. Hobbs, in early work (48), seemed to favour the use of GGBS in concrete to reduce the risk of alkali-silica reaction. Subsequent work (49) by the same author contradicts these findings.

A brief summary of the effects of GGBS use upon chemical stability and other properties of concrete is given in Section 3.2.

Tab 2.6 : The Chemical Stability of GGBS Concretes.

Aspect	Mechanism	Effect of GGBS
Sulphate Attack	sulphates react with lime and calcium aluminate hydrate to form expansive products	L reduction in lime lower permeability
Acid Attack	acids react with cement to form water soluble salts which are then leached	D
Carbonation	Carbon di oxide reacts with lime and protective alkalinity around reinforcement is removed	D,H depletion of lime more curing sensitive
Chloride Attack	Chloride attacks passivating iron oxide film on reinforcement	L ion diffusivity reduced
ASR	hydroxyl ions and siliceous aggregates react to form expansive hygroscopic gel	D,L dilution of alkalis

L Lower risk
D Disputed
H Higher risk

3.1 Introduction

The purpose of any research could be summarised as the verification of the accepted, the resolution of the disputed, and the illumination of the neglected. This chapter firstly examines the accepted, disputed and neglected areas of the effect of GBBS use, and then details the scope and objectives of the research undertaken. Care was taken to consider both academic and industrial interests when determining the scope, in order that the work would be both independent and commercially relevant.

3.2 Some aspects of the use of GGBS

The suitability of a material for use in a particular situation depends upon a number of factors, most notably, construction cost and engineering performance. It can be concluded from Chapter 2 that the main reasons for using GGBS is to obtain specific hydration or durability characteristics. Concrete incorporating GGBS as part of the cementitous binder is credited with (13) a reduced heat of hydration, greater sulphate resistance (to Class 3 soil conditions, as defined in BRE Digest 250, for >70% GGBS), and a reduced expansion due to alkali-silica reaction (>50% GGBS recommended).

In addition to its beneficial effects, GGBS also introduces several problems. A modified version of a Table presented in a C&CA guidance note on composite cements (23) is shown inTab 3.2. From this it can be observed that thereduced hydration rate in GGBS concretes, particularly at low ambient temperatures, may lead to an extension of the setting, curing and formwork striking times. The universally acknowledged advantages of using GGBS are the potential to reduce the temperature rise and increase the resistance to sulphate attack. Unfortunately, formwork costs and construction time are important elements in the overall expenditure, whilst the greater care required with curing conflicts with common site practice.

Several areas of GGBS use requiring further research have been highlighted by other workers. Tattersall and Banfill observed

Tab 3-2 : Changes in concrete practice when using GGBS.

Aspect	Change	Note
Workability	Slight Increase	5 litre reduction in water demand
Bleeding and Plastic Cracking	Increased Risk	as the GGBS level increases
Formwork Pressure	Increased	by about 10-20 kN/m2
Working and Finishing time6	Extended	higher GGBS levels lower temperatures
Formwork Striking	Delayed	Current tables of times for Portland cement only
Curing	Increased Care needed	Time (days) for different Ambient Conditions* Average 80/(t + 10) Poor 140/(t + 10)

* t ie the average surface temperature of concrete
Poor ambient conditions signifies RH < 50% and not protected from sun and wind.

thatdata on the effect upon rheology of GGBS substitution of OPC was limited (17). Wainwright made the same point, and suggested that information was lacking on other topics (20), including bleeding and plastic cracking, and the influence of slag content and composition and curing environment, upon the modulus of elasticity.

The author observes that:

a) In general, research conducted on the Continent has used blended cements formed by intergrinding, whilst work in the United Kingdom has used within-mixer blends containing GGBS from just one source.

b) Previous work on cement replacements has avoided applying low curing temperatures continuously from casting.

c) Most guidance on mix design and formwork striking and curing times originates from research on Portland cements.

d) There is little published work on the effect of GGBS upon non-destructive test parameters.

Scope

The Academic Input

The academic requirement for the project was that it should produce a package of research suitable for completion within two years, and the experimentation and the formulation of conclusions should be as objective as possible. The proposed title of the project confines it to an investigation of the workability and maturity properties of concrete containing GGBS. The term workability covers a number of characteristics of concrete when fresh; the maturity properties characterize the hydration and hardening of concrete. The project therefore encompasses the performance of concrete from the fresh to the hardenend states, but excludes long-term considerations such as creep and shrinkage.

To comply with the academic requirements the number of mixes in the main programme of research were not to exceed one hundred, a broad base of experimental techniques were to be included, and the experimentation was to have a factorial design. These elements will now be considered in more detail.

The adoption of alternative techniques for measuring properties allow trends to be collaborated and patterns in the behaviour of the various test methods to be formed. The test methods chosen for the main programme of research were as follows:

1) Workability was to be assessed subjectively and using the slump, compacting factor and two-point tests. The number of workability test was limited by manpower to three. Choice of the compacting factor test over the Vebe test was a result of concern about the poor end-point of the latter test. The inclusion of a subjective assessment of workability was in recognition of the shortcomings of workability tests.

2) Strength of the concrete was to be assessed using compression and indirect tensile tests. The compression testing of standard specimens is the most commmon compliance criteria for concrete. In certain cases, such as pavement construction, the indirect tensile strength from splitting or flexure tests becomes important. Curing space was limited, so the compression and tensile splitting tests were to use 100 mm cubes, and the beam for flexural testing was also used as a specimen for longitudinal ultrasonic pulse velocity and electrodynamic measurements.

3) The elastic properties of the concrete were to be assessed from the dynamic elastic modulus and ultrasonic pulse velocity. These parameters have the advantage of being non-destructive. They have no fundamental connection with strength although UPV has found use on site in determining the comparative quality of concrete. When measured in conjunction with density these parameters can be used to calculate the dynamic Poisson’s ratio.

In addition to the above, limited work was to be conducted into the hydration characteristics of each mix, using vacuum flask calorimetry and pulse velocity measurement at very early ages, and the potential durability, using water absorption measurements.

The factorial design, adopted for the experimental work, is very useful where a number of factors are being varied since it permits their individual and interaction effects to be quantified (50). The technique requires factors to be kept constant or systematically adjusted to set levels. In the simplest designs each possible combination of levels of each factor must be obtained, with at least two replications. This leads to L^xL2xL^...x LnxR treatments, where L ^ is the in the number of levels of factor 1, and there are n factors and R replications.

3.3.2 The Industrial Input

The collaborating establishments (Frodingham Cement Limited, Scunthorpe, and Civil and Marine Limited, Purfleet) supply separately ground granulated blastfurnace slag for use in concrete. It was logical that this project would use GGBS supplied by them in within-mixer blends. Following a meeting with the collaborating establishments in January 1986 it was decided that the project should employ:

a) 3 cementitious contents of 200,300 and 400 kg/m

b) 3 replacement levels of 0,40 and 70% (by mass);

c) 2 GGBS types supplied from Scunthorpe and Purfleet;

d) 5 curing temperatures of 5,10,20,40°C;

e) 2 humidities (at 20°C); and

f) 5 ages for testing of 1,3,7,28 and 91 days.

It was also decided that a single ordinary Portland cement produced by Castle cement, Ketton and a fixed water-cement ratio should be used throughout.

The 3 cementitious contents, 3 GGBS levels and 2 GGBS types leads to eighteen mix designs (Section 3.3.1). In fact mixes containing *0%* GGBS of the two types are identical, reducing the number of different mix designs to 15. Limits on the number of cube moulds meant that specimens for all the regimes could not be cast from the same mix. This fact, coupled with the logistical problems of handling five regimes simultaneously led to the work being divided into two parts (see Section 6.2). In the first part the curing temperatures were 40°C and 20°C, and in the second the temperatures were 10°C and 5°C. With replication in each of the two parts the total number of mixes is sixty; well below the limit of one hundred mixes.

3.4 Objectives

3.4.1 Primary

The author considered that the five primary objectives of the study were to:

1) Observe the effects of GGBS type and level upon the workability, strength and elastic properties of concrete; and the influence of cement content, curing and age upon these effects.
2) Identify and quantify the effect of factors upon the workability and maturity properties measured, and isloate systematic trends and optimums in the the relationship between the response and control variables with regard to forming a predictive model.
3) Compare the patterns in behaviour and sensitivities of the alternative assessment methods, and where possible define the relationship between each.
4) Examine the usefulness of novel techniques for describing the hydration characteristics and potential durability.
5) Attempt to isolate the physical characteristics behind the mix constituents and proportioning which leads to the observed effects.

3.^.2 Secondary

In response to observations within the main programme of research it was decided to examine mixes and properties outside the rigid factorial experimental design. Firstly, mixes were observed to bleed and segregate in the two-point test (Section 5.2.2) and work was undertaken to test the hypothesis that the change in torque during a prolonged period of shearing was a measure of mix stability. Secondly, well-defined trends in workability were observed when increasing the GGBS level from 0% to 70%. To ascertian if these trends were maintained 100$ GGBS mixes were produced at each of the cementitious contents. Finally, the main programme of research adopted a constant water-cement ratio. The sensitivity of the properties of the different mix designs to adjustment of this ratio was investigated in a secondary study «

3.5 Summary

In the main programme of research concrete produced at 3 cement contents, 3 GGBS levels and 2 GGBS types, was to be cured under 5 regimes and tested at 5 ages. The workability of the fresh concrete was to be assessed using British Standard methods, the two-point apparatus, and subjectively. The strength of the concrete in compression and indirect tension were to be evaluated. The elastic properties, ultrasonic pulse velocity and dynamic elastic modulus, were to be measured.

A summary of the investigation is given in Tab 3*5.

The mainobjectives of thework are todefine the effects of themix proportions andconstituents,particularly GGBS level and

* Hereafter the main programme of research and secondary study are signified by initial capitals.

type, upon the workability and maturity properties of concrete, and to compare different methods of assessing the workability and mechanical properties. The major features of the work are the:

a) within-mixer blending of OPC with GGBS from two sources;

b) wide range of cement contents,GGBS levels and curing regimes;

c) broad base of assessment methods;

d) factorial experimental design; and

e) adoption of a constant water content.

Tab 3.5 : Summary of the Investigation

		MAIN PROGRAMME	100% GGBS Mixes	SECONDARY WORK Water Sensitivity
FRESH AND HARDENING CONCRETE PROPERTIES	Workability	Slump CF Two-point	Slump CF Two-point	Slump Two-point
	Hydration Characteristics	Vacuum flask Calorimetry		* Pulse Velocity at early ages
HARDENED CONCRETE PROPERTIES	Strength	Compressive ! Indirect Tensile		Compressive
	Elasticity	Dynamic Modulus Pulse Velocity		* Dynamic and Static Moduli
	Durability Potential	Water Absorption		
DESIGN		3 Cement Contents 3 GGBS Levels 2 GGBS Types 5 Ages 5 Curing Regimes		2 Cement Contents 3 GGBS Levels 2 GGBS Types 3 Ages 1 Curing Regime
		Randomised Block	Not randomised or replicated	

* Medium W/C ratio only
! 28 and 91 days only

4.1 Introduction

The purpose of mix design is to produce as economically as possible concrete with the required workability, hydration, strength, durability and aesthetic characteristics. Mixes were traditionally specified in terms of nominal volumetric proportions to facilitate site batching. However, the development of ready-mixed concrete was acknowledged in 1976 with the publication of BS 5328, the British Standard for specifying concrete. BS 5328 basically describes two classes of mix : ordinary prescribed mixes for building works and designed mixes for larger construction projects. In ordinary prescribed mixes the mix design and constituents to be used are specified in the standard; the proportion of GGBS, for example, is restricted to 65%. In contrast, the designed mixes allow a wider range of materials to be used, and are usually specified only in terms of the workability and compressive strength. The compressive strength is often quoted as a grade; this being the target strength to be attained by 95% of the concrete supplied.

The author felt it appropriate that this investigation into the performance of GGBS concretes should adopt designed mixes, in which performance is of prime importance and GGBS level is unrestricted.

The process of mix design is dealt with in the following sections.

4.2 Constraints upon the design

The scope of the work in Chapter 3 places several constraints upon the design. Firstly, the factorial experimental design necessitates a systematic adjustment of factors if their effects are to be rigorously quantified. The adoption of performance levels either of workability or strength across a range of cementitious contents and GGBS levels could be difficult to maintain without combined changes in several factors, which would make analysis difficult. Such an approach would also have the disadvantage of preselecting assessment methods for workability or strength, the validity of which this investigation would, in part, be testing. Secondly, the inclusion of the two-point workability test favours the use of an uncrushed gravel with a maximum size of 20 mm as the coarse aggregate. Thirdly, the collaborating establishment recommended the use of: two slag types from sources at Scunthorpe and Purfleet; three cement contents of 200,300 and 400 kg/m^; three replacement levels of 0,40 and *10%* GGBS by mass; and OPC from Castle Cement, Ketton.

The final, and arguably the most important, constraint upon the mix designs was that they should be representative of those used in the ready-mixed concrete industry. To this end, a survey of mix designs and mix design methods was carried out.

4.3 Mix Design Survey

4.3.1 Mix Design Methods

A number of methodologies exist for optimising the mix proportions. All of these take a small amount of information about the materials, and using a simple basis predict (with varying degrees of success) their performance in combination.

The design process tends to be as follows:

1) Workability and strength fix the water and cement contents.
2) Durability requirements may override the values from (1).
3) Aggregate properties determine the amount of fine or coarse aggregate in the mix.
4) The unknown quantities can be determined by subtraction of the known volumes from one cubic metre.

Mix design methods published by the ACI,BRE, C&CA and Road Research Laboratory (51 , 52 , 53 >54) were examined by the author. The approach taken by each method is represented in Fig 4.3*a. As the cement content changes, at least one of the other constituents is changed to maintain the same volume. None of the designs change all three remaining constituents. "Road Note 4" and "The Design of Normal Concrete Mixes" maintain a constant coarse aggregate content and water content respectively. The ACI and "Basic Mix" methods hold the contents of both water and coarse aggregate constant, adjusting the fines aggregate to maintain a constant volume of fines plus cement.

The numerical values obtained by applying the constraining factors to these mix design methods are shown in Tab 4.3.a.

4.3.2 Representative Designs

The author visited two ready-mixed concrete companies and also solicited the advice of two concrete technologists(55, 56,57,58). It was apparent that ready-mixed concrete companies did not operate using a design method but instead gathered information from site and ad hoc in the laboratory using locally available materials over a range of cement and water contents. From this information the batching books are compiled.

The four designs proposed for each of the three cement contents are shown in Tab 4.3.b. For the 300 kg/m^ cement content mix the water content shows a range of 160 to 170 kg/m-*, and the percentage fines ranges from 36 to 44. Two out of the four designs adopt both a constant water and coarse aggregate content.

Having ascertained that no design methods were universally employed it was decided that a typical 300 kg/mJ mix , with a target slump of 70-80 mm should be used as the design base. The higher and lower cement content designs were to be formed by keeping a constant volume of fines plus cement, consistent with the ACI and Basic Mix methods. It was provisionally decided toadopt a water content of 165 litres per cubic metre, and a percentage fines of 40. This produces the OPC control designs represented in Fig 4.3-b. In order to determine if this mix would be satisfactory, recourse was made to trial mixes.

(a) (b) (c)

CA CA CA

Water Water

FA FA

ernent ement Cement, Water

Increasing Cement Content

ACI Method Basic Mix Method

Road Note A

Design of Normal Concrete Mixes

Fig 4.3.a : Volumetric representation of some mix design philosophies.

COARSE AGGREGATE

WATER

FA

OPC

w/c	0.82	0.55	0.41
A/C	9.9	6.3	4.6
%Fines	41.8	39.4	36.7

Fig 4.3.b : Volumetric representation of the OPC control mixes

Tab 4.3.a : Mixes suggested by the survey of Design Methods.

Cement	Water	Fine Aggregate	Coarse Aggregate	W/C	A/C	%Fines
	ACI Method (211.1-77 and 211.3--75)				Slump 70 mm	
200	185	855	1050	0.92	9.5	44.9
300	185	770	1050	0.61	6.1	42.4
400	185	690	1050	0.46	4.3	39.6
	Road Note 4 (Hughes Modification)				Medium Workability	
200	* 165	780	1220	0.84	10.0	38.9
300	160	710	1220	0.54	6.5	36.8
400	170	610	1220	0.44	4.6	32.4
	Design of Normal Concrete Mixe6				Slump 30-60 mm	
200	180	880	1120	0.90	10.0	44.0 *
300	180	720	1180	0.60	6.3	38.0
400	180	630	1170	0.45	4.5	"35.0
	Basic Mix Method !				Slump 50-75 mm	
200	180	705	1220	0.90	9.6	36.6
300	180	620	1220	0.60	6.1	33.8
400	180	540	1220	0.45	4.4	30.6

* Extrapolated values
i Fine aggregate replacement of cement by volume extended from the Basic mix to give these proportions

Note:- The properties used in the design calculations relate to the materials employed for the trial mixes

Tab 4.3.b : Mixes suggested by the survey of Industry.

Batch Quantities (kg/m3)

Target Slump	Cement	Water	Fine Aggregate	Coarse Aggregate	W/C	A/C	%Fines
	200	170	895	1030	0.84	9.6	46.5
	300	170	800	1030	0.57	6 .1	43 .6
80 mm	400	175	710	1050	0.44	4.4	40.4
	200	165	890	1120	0.82	10.0	44.2
	300	165	805	1120	0.55	6.4	41. 8
50 mm	400	165	720	1120	0.41	4.6	39 .2
	200	180	810	1190	0. 90	10. 0	40. 5
	300	160	710	1240	0.54	6.5	36.4
50 mm	400	170	615	1250	0.43	4.7	33 .1
	200	175	830	1130	0.88	9.8	42. 2
	300	165	745	1160	0.55	6.3	39 .1
65 mm	400	175	655	1150	0 .44	4.6	36 .2

4. 4 Trial Mixes

A series of trial mixes encompassing over eighty mix designs was undertaken, examining the effect upon compressive strength and workability of GGBS level and the water, cement and fines contents.

The study upon the effect of GGBS level confirmed that mixes designed for ordinary Portland cement should remain sufficiently workable for testing when GGBS was incorporated. The results of the study into fines and water contents are summarised in Fig 4.4.a. The dashed lines indicate the lower and upper levels of workability for testing in the two-point apparatus and slump test respectively. It can be observed that use of 165 kg/m^ water content and the proportioning in Fig 4.3.b gives rise to a slump in the medium cement content mix of approximately 70 mm. The workability at the other cement contents falls within the acceptable range so the designs were deemed satisfactory.

The 200, 300 and 400 kg/m^ mixes would be expected to achieve strengths of 25,50 and 65 MPa respectively, at the adopted water content (see Fig 4.4.b), corresponding to compressive strength grades of C13» C40 and C55 for an assumed standard deviation of 5.5 MPa.

In the complementary work (see Section 6.2) 100% GGBS mixes were produced at the three cementitious contents, and the 300 and 400 kg/mJ cementitious content designs were repeated at low, medium and high water-cement ratios of : 0.50, 0.55 and 0.60; and 0.36, 0.41 and 0.46 respectively.

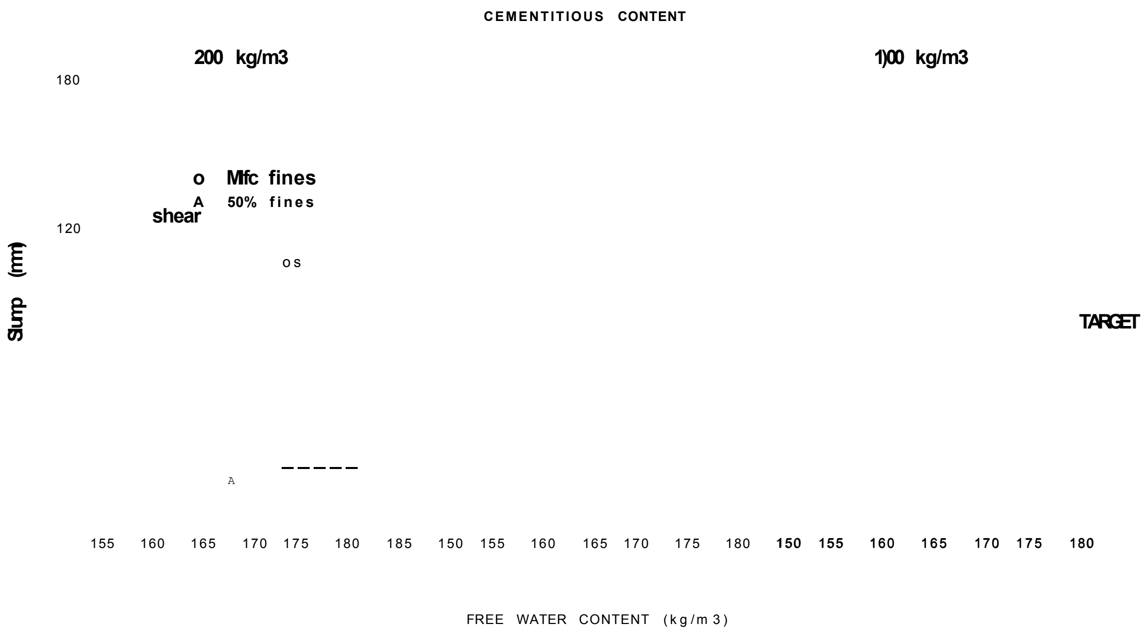


Fig 4.4.a : Effect of water and fines content upon slump for the OPC control mixes.

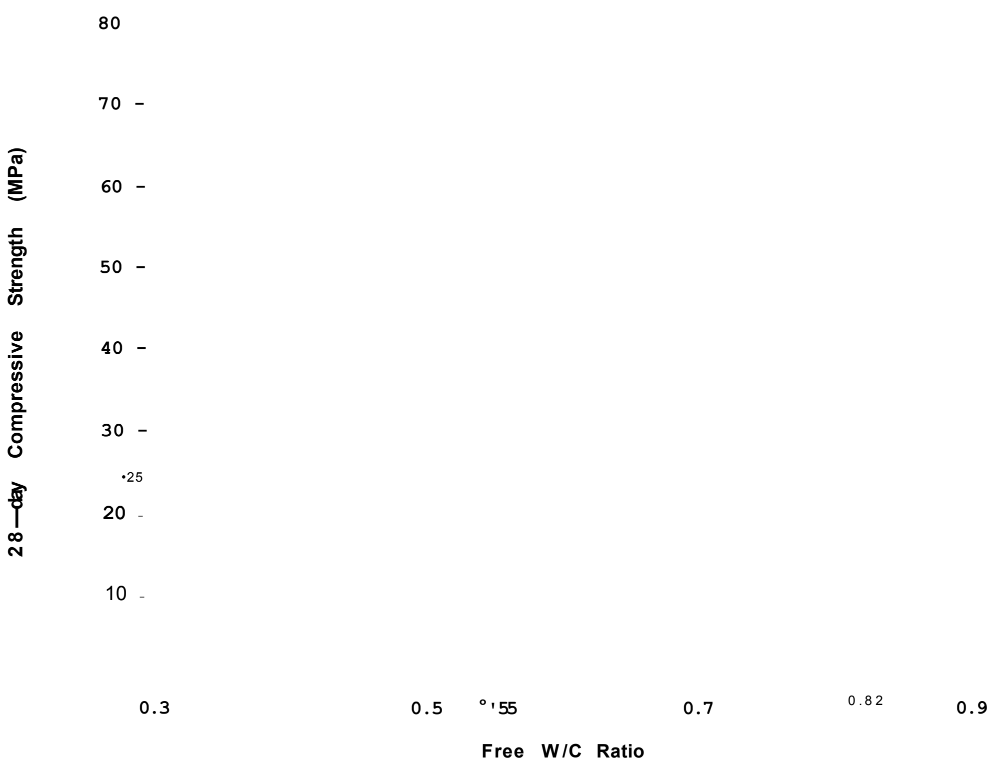


Fig 4.4.b : Compressive strength grades of the OPC control mixes

5.1 Introduction

This chapter gives background information on the test methods used in the investigation. The methods fall into one of three categories:

subjective - associated with a particular assessor;

empirical - associated with a particular piece of equipment; and

fundamental- associated with a particular theory.

The emphasis in the background information is on a description of novel test methods. British Standard test are accompanied by an appropriate reference, and fundamental tests are accompanied by their theoretical basis.

5.2 Workability Assessment

5.2.1 British Standard Tests

The key role of workability in influencing the hardened properties of concrete has already been discussed (Section 2.3). The slump and compacting factor tests (BS 1881, Parts 102 and 103 respectively) are empirical in nature and primarily assess the ability to place and compact fresh concrete. Other characterisitics of the concrete ,such as propensity to bleed and suitability to pump, may be important depending on job. Although it is unrealistic to expect a workability test to adequately assess all these aspects, it should be able of define the flow behaviour of concrete under the different working conditions encountered.

The relationship between shear stress and rate in concrete has been found to be approximately linear, as proposed in the Bingham model. Tattersall observes that in order to define this relationship for any concrete the shear stress at two shear rates must be known. Individually, the British Standard tests, which only operate at a fixed shear rate are inadequate, so Tattersall has developed a suitable two-point test (59).

PLATE J_

The two-£olnt aEgaratus OM mode,, fitted with a pressure transducer).

5.2.2 The Two-Point Apparatus

In the two-point test concrete contained within a cylindrical bowl is sheared by an impeller driven by an electrical motor operating through a hydraulic transmission (Plate 1). The hydraulic transmission, in addition to allowing the impeller speed to be infinitely varied, provides a simple method of impeller torque measurement. The pressure generated in the transmisson is displayed on a gauge and its value, net of pressure produced under machine idling, can be related by calibration to impeller torque (Fig A.1.a).

The relationship between impeller torque (T) and impeller speed (N) can be approximated by the linear equation

$$T = g + hN,$$

where T and N are respectively analogous to shear stress and shear rate, and the constants g and h are respectively analogous to yield stress and plastic viscosity in the Bingham model. Although it is possible to calibrate the apparatus using a Bingham plastic, this was outside the scope of the investigation (59).

A two-point apparatus manufactured by Tremix Engineering Limited, and operated in the LM mode for low to medium workability concretes, was used throughout the investigation. The author considered that there were several problems with the equipment:

a) The oil snubber in the hydraulic line caused an excessive amount of lag in the response of the pressure gauge. This was especially evident when calibrating the machine. The snubber was therefore removed from the hydraulic line and replaced by a needle-valve which permitted the degree of damping to be readily adjusted.

b) Significant idling pressure changes with machine running was a potential source of error in the calculated values of net pressure. The changes in idling pressure and oil temperature under different operating conditions were recorded (Figs A.1.b and A.1.c). This led to the recommendation to run the apparatus for 30 minutes before tests,at the highest speed employed, and maintain this speed between tests.

The fluctuation of the needle of the pressure gauge when testing concretes of low workability hampered the choice of a representative pressure value. A pressure transducer was attached to the hydraulic system, and this in turn connected to a computer sytem capable of recording and analysing these pressures (Fig 5.2). Further details of this development are given elsewhere (60).

Segregation of the sample during the test was characterised by the formation of a dewatered layer at the base of the bowl and a deviation from linearity of the speed-torque relationship. It was decided that the number of rotations of the impeller in each test should be reduced by limiting the duration at each speed, and biasing the speeds to lower values.

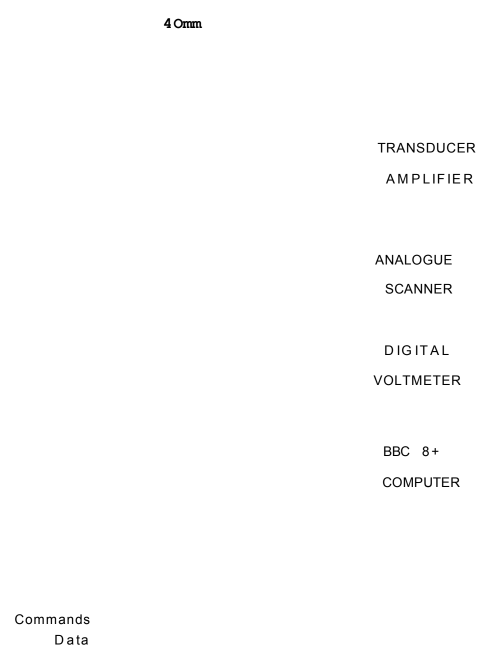


Fig 5.2 : The pressure transducer system.

Each two-point test requires a 40 kg sample of concrete. A sequence of nine impeller speeds (speed settings 6,5,4,3-5,3,2.5,2,1.5 and 1) was employed by the author. A further speed setting of 6 was introduced later to test the hypothesis that torque change after a period of shearing could be used to assess the mix stability. The time at each speed is 20 seconds. During this time the speed of the apparatus is measured using an optical tacometer and total pressure readings are taken at the rate of four per second using the pressure transducer. The idling pressure at each speed are recorded before and after each test.

A computer program in Section D.1 rapidly faciliates the conversion of the pressure values and coupling speeds to impeller torque and speed, and the regression of the latter to give the values (and confidence intervals) of g and h.

5.2.3 Subjective Assessment

The subjective assessment of workability has been tried out by several workers (61). Its popularity as a method of judging concrete on site, despite its dependence on the skill and experience of the assessor, underlines the shortcomings of the British Standard tests.

A crude assessment, early in the Main Programme, of the consistency of the mixes, on a scale proposed by Tattersall (61), was developed in blocks 2 to 4 of the Main Programme to include a subjective assesmment of the 'bleeding' and 'cohesion'. The assessment, made during the slump test by the same technician, was on a scale of 0 to 10; where low marks indicate low bleeding or unstable mixes and high marks indicate high bleeding or sticky mixes respectively.

5.3 Hydration Characteristics

Two methods of assessing the hydration characteristics were used : vacuum flask calorimetry and pulse velocity measurement. Both these methods have advantages over the determination of the heat of hydration to BS 4550 in that they:

a) operate on concrete;

b) do not require an adjustment to the mix proportions; and

c) are relatively simple to carry out.

5.3.1 Vacuum Flask Calorimetry

The sample under test is simply sealed within a domestic vacuum flask and its temperature is monitored. The thermal system lies between the isothermal and adiabatic because as the temperature within the flask rises heat is lost at a rate governed by the insulating characteristics of the flask and the temperature differential.

The technique has been used in industrial research to rank blended cements according to their heat of hydration. The relationship between the vacuum flask method and standard method of determining the heat of hydration has been reported by others (62).

Two types of wide-mouthed vacuum flask were tried. A flask with integral, rather than separate, outer and inner plastic shells was found to be easiest to handle. The flask containing approxiamtely 2 kg of compacted concrete is capped by a pierced rubber bung. A thermocouple wire in a plastic sheath is then inserted through the bung till its tip is mid-depth in the sample (Fig 5.3.a). A computer based temperature monitoring system, incorporating a 0°C reference, was developed to record the thermocouple temperature. The monitoring is usually at 20 minute intervals and is continued for at least ten hours after the peak temperature is attained.

Two vacuum flasks were used per mix and all the work was carried out in the relative humidity control room at 20°C.

The cooling curves for each flask can be used to calculate the cummulative heat loss, which when added to the observed temperatures produces an apparent adiabatic temperature (Section C.3.1). This is only a first-order correction since it does not take into consideration the effect of temperature upon the hydration reaction (16).

5.3*2 Pulse Velocity measurement at very early ages

The chief difficulties with measuring the pulse velocity in immature concrete are:

a) the severe attenuation of the pulse;

b) the need to achieve and maintain good contact between the transducers and the concrete as it bleeds and shrinks, whilst avoiding damage to the specimen; and

c) the sensitivity of the equipment to external vibrations.

Several researchers have successfully used the technique. Elvery and Ibrahim (63) used horizontal spring-mounted transucers bearing on the ends of a beam, still within its mould, to record the UPV from six hours onwards. They related these measurements to the compressive strength at different ages to see if the velocity could be used for predicting formwork striking times and the 28-day compressive strength. Van Der winden and Brant (64) used vertically mounted transducers, bearing by gravity on the upper and lower surfaces of a concrete frustrum, to record the UPV of fresh concrete (1 to 24 hours) containing plasticising and retarding additives. These measurements were used to judge the end of workability and the time for slipforming, in connection with construction of the Dunlin offshore platform.

A system similar to Van der Winden and Brant's was developed by the author using 50 kHz transducers aranged above and below approximately 1.5 kg of concrete, fully compacted within a conical mould (Fig 5.3.b). Contact between the transducers and the concrete is obtained by applying a coupling agent to the transducers and a mass to the cover plate; the contact being maintained by gravity.

The continuous transmission of pulses through concrete is thought to affect the development of mechanical properties, so a timer was used to turn the equipment on and off at intervals. The system includes an external amplifier to boost the received signal during the first two hours and a chart recorder connected to the

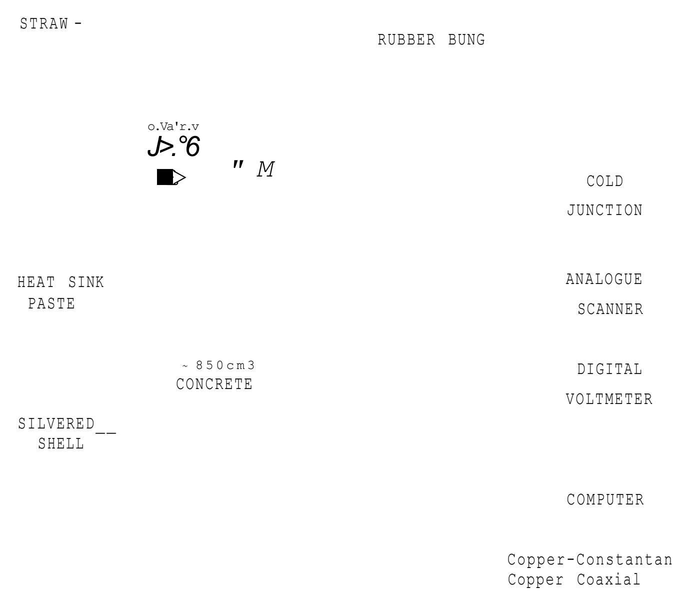


Fig 5.3.a : Vacuum flask calorimetry.

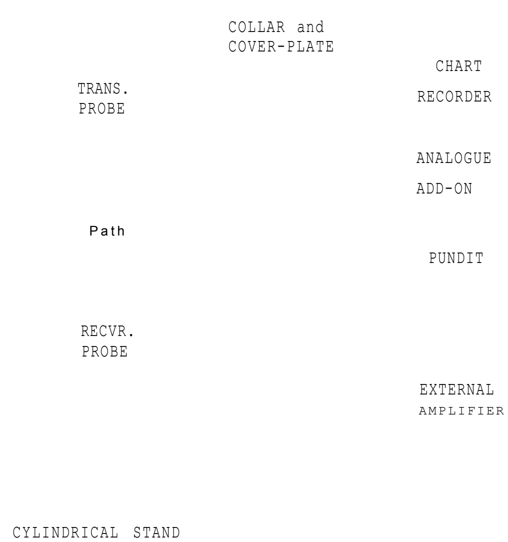


Fig 5.3.b : Pulse Velocity measurement at very early ages

PUNDIT set to record the transit time. Vibration of the equipment was reduced by placing it on a foam mat and inserting a foam strip between the mould and the cylindrical stand. Upon completion of the test the transit time can be converted to a pulse velocity by measuring the path length through the specimen using calipers.

All the work took place in a controlled environment at 20°C and 60% relative humidity.

5.4 Mechanical Properties

The author opted to divide the tests into those assessing strength and those assessing elastic properties. An equally valid classification would be that of destructive and non-destructive tests.

The compressive strength of standard cured specimens is the most widespread quality control parameter applied to concrete. The parameter is not fundamental, nor does it represent the intrinsic strength within a structure. An indication of the latter is given by non-destructive parameters such as the ultrasonic pulse velocity. The pulse velocity is usually used comparatively, although the compressive strength may be predicted providing a suitable calibration has been carried out.

5.4.1 Strength

The strength determination of concrete is carried out using a compression machine capable of applying force to thespecimen at the required rate, and displaying this forcewith the prescribed accuracy. The author used an Avery Denison 7226CB with an automatic loading rate control. The machine has a 3000kN capacity direct crushing facility for testing concrete cubes and a 1000 kN capacity transverse unit for testing beams in flexure, or weak cubes. The loading of the specimens followed the apppropriate British Standards with the loading rate set at the centre of the specified range.

Two measures of indirect tensile strength were obtained by splitting cubes and testing beams in flexure (BS 1881 : Parts 117 and

118). The flexural test is based on elastic theory and, for a downward load, assumes a maximum tensile stress at the lower face of the beam. The splitting test is based on obtaining a biaxial state of stress under narrow strips of loading either side of the specimen. This comprises a localised compressive stress zone adjacent to each strip, and running between these zones a plane of tensile stress which leads to splitting across the specimen.

In practice the stress block based on elastic theory is not strictly applicable in the flexure test due to redistribution of stresses and as a consequence of this the values are higher than would be obtained in splitting or direct tension.

5.^.2 Elasticity

The ultrasonic pulse velocity and dynamic elsatic modulus have advantages over the destructive strength tests in that, they allow a repeated measurement on the same specimen and have a fundamental basis in elastic theory.

E0(J = fV2 (1+p) (1-2p)

(1-V>)

Where:

E_{uq} is the dynamic elastic modulus (GPa);

V is the ultrasonic pulse velocity (km/s)

f is the density (kg/m^); and

p is the Poisson's ratio.

The pulse velocity is determined by measuring the time of transit of high frequency pulses of sound through a specimen, along a path of known length (BS 1881 : Part 203). The pulses are produced and received by transducers of a set frequency. 54 kHz transducers produce a pulse which is robust to the attenuation arising in immature concrete or over long path lengths. 200 kHz transducers, because of their smaller size and wavelength, may be used for cicumscribed work.

The author used the 54 kHz and 200 KHz transducers for measurements through cubes and beams respectively. These transducers were connected via coaxial cables to a CNS Electronics PUNDIT Mk IV, giving a digital display of transit time.

A system for underwater pulse velocity measurement was modified by the author. In this technique cubes are positioned underwater on a rubber block between 54 kHz sealed transducers. By recording the transit times with and without the cube the pulse velocity through the concrete can be calculated (Section C.2.2). The technique, in addition to being more rapid than conventional measurement in air, eliminates acoustic coupling gels and surface abrasion.

The dynamic elastic modulus of concrete is determined from the resonant frequency of the fundamental mode of longitudinal vibration in a beam (BS 1881 : Part 5). In long thin rods this resonant frequency (n) is related to the dynamic modulus and density (f) of the concrete by the equation

where L is the length of the specimen.

The author used a Cawkell Electrodynamic Materials Tester Type SCT4. A computer program incorporating a calibration relationship and the above equation was used to convert the dial setting, from the apparatus, to a modulus.

The static modulus is determined from stress and strain measurements on a 150 mm diameter and 300 mm long cylinder. Despite several cyles of loading (BS 1881 : Part 121) prior to testing the static modulus is always slightly lower than the dynamic modulus due to creep.

5.5 Potential Durability

In immature concrete the capillary pores are largely unsegmented, facilitating the ingress of aggressive agents in solution or as gases. As hydration proceeds the capillary pores are blocked by its products. The water absorbed under capillary action is therefore an indication of both the extent of hydration and the potential durability.

The British Standard water absorption tests are the simple immersion method (BS 1881 : Part 122) and the Initial Surface Absorption test (BS 1881 : Part 5). The latter test were considered too involved for use in this investigation, so attention was concentrated on the immersion method. This method, although simple, is empirical and has been criticised because of its sensitivity to the maturity of the concrete and the entrapment of air (65). The author modified a test for bricks, so that the complete contact of the immersion method was replaced by end-contact only. The method has the advantages of : reducing the air entrapment; allowing absorption to be measured through a chosen surface; and being less empirical than the standard method.

A core, 75mm in diameter and trimmed to 80 mm in length, is dried in and oven at 105°C for 48 hours and cooled for a futher 24 hours. The core is weighed to the nearest 0.1g and placed trimmed end down on a stiff foam pad in a container of water. A mass is placed on the top of the core to ensure a good contact with the foam, and the container is sealed to restrict the evaporation of water. The mass of the core, after removal of excess water, is recorded at 60 minutes (this was found to be an optimum time, beyond which some cores became saturated).

The water absorption in $ml/m^p.s$ is calculated by dividing the mass of water absorbed, by the time of absorption and the area of contact (Section C.3.3).

CHAPTER 6

EXPERIMENTAL PROGRAMME AND MATERIALS

6.1 Introduction

In the three preceeding chapters the basic scope of the research in terms of the mix designs and test methods was followed by a more detailed appraisal of each of these elements. The first part of this chapter deals with the programme of mixing and the nature and regularity of supportive testing, for example, upon the constituent materials. It is the characteristics of these materials which are covered in the latter part of the chapter.

6.2 Experimental Programme

6.2.1 Mix Notation

A summary code was devised for the mix designs, together with a number to facilitate randomisation. These are shown below for the Main Programme of research.

2S0	1	3S0	4	4S0	7
2S4	2	3S4	5	4S4	8
2S7	3	3S7	6	4S7	9
2P4	10	3P4	12	4P4	14
2P7	11	3P7	13	4P7	15

This code was extended for the complementary work to include four components in sequence:

1) 2,3 or 4 denoting the 200, 300 and 400 kg/m^ cement contents;
2) S or P denoting the slag sources Scunthorpe and Purfleet;
3) 0,4,7,10 denoting the 0,40,70 and 100% GGBS levels; and
4) L,M or H denoting the low, medium and high w/c ratios.

6.2.2 Main Programme of Research

The research has a randomised block design in which each of the fifteen different mix designs is cured under five regimes and tested at five ages, this being replicated twice.

The number of specimens made from the same batch of concrete and the number of specimens made on the two days available each week for mixing was limited by the mixer capacity, number of cube moulds, and accumulation of hardened concrete testing.

The author decided that in order to comply with these restrictions, and reduce the logistical problems associated with simultaneous use of a large number of regimes the work should be split into two parts. In Part 1 of the Main Programme each of the fifteen mix designs were made in a randomised order and cured underwater at 40°C and 20°C, and cured in air (60% relative humidity) at 20°C. This procedure was then repeated to give two independent blocks of results. In Part 2, these medium curing temperatures were replaced by low temperature curing underwater at 10 C and 5°C. This design is represented in Tab 6.2.a.

The need to be able to demould the cubes following the first mix each week, to release more moulds and curing tank space for the second mix, meant full randomisation of the mix designs was impractical. Instead the designs were divided into higher and lower strength mixes and randomised within these groups. Higher strength mixes were produced first each week, followed by the lower strength mixes.

The initial programme of mixing is shown is shown in Tab 6.2.b. Unfortunately, there was a loss of specimens during the work. Specimens from six mixes were lost due to the failure of an electrical relay serving the 40°C tank, and four beams cured at 5°C were broken during stripping. Replacement specimens were manufactured at the end of Parts 1 and 2 of the work respectively.

6.2.3 Complementary Work

In Chapter 3 it was mentioned that was provision for complementary work outside the rigid factorial experimental design (Tab 3.5).

The 100% slag mixes were produced at the end of Part 2 of the

Tab 6.2.a : The Experimental Design.

Cm 1 Cm 2 Cm 3

Ty 1 Ty 2 Ty1 Ty 2 Ty 1 Ty 2

Bk Rp3 Rp2 Rp1 Rp2 Rp3 Rp3 Rp2 Rp1 Rp 2 Rp3 Rp3 Rp2 Rp 1 Rp2 Rp3 Bk

(10) (12)

Cm - Cement Content (200,300,400 kg/m3)
Rp - Replacement Level (0,1(0,70% GGBS)
Ty - Slag Type
Bk - Block Number
0 - Common OPC Control Mix Results

Tab 6.2.b : Initial Programme of Mixing

MIX DESIGNS

Part 1 - 1986		Part 2 - 1987	
Block 1 (July)	Block 2 (September)	Block 1 (February)	Block 2 (April)
* 13	15	8	4
* 4	7	1	1
* 9	5	12	13
* 8	10	! 3	12
* 5	2	4	6
* 7	8	15	14
6	13	11	9
12	12	7	6
14	3	6	11
11	6	14	7
1	11	9	3
2	4	5	! 15
10	14	! 13	2
15	1	2	! 5
3	9	10	10

* specimens incorrectly cured
! specimens broken

Month of starting each block is shown in parentheses

Main Programme. The aim was to confirm the trends observed up to the 70$ GGBS level, and discount the OPC source. Three cementitious contents were considered, giving rise to six mix designs. Only workability was assessed, because of the low rate of strength development likely in such mixes.

A Secondary Study was started in late 1987 to determine the effect of adjusting the water content. The 300 and 400 kg/m^ cementitious content mixes were produced at three water-cement ratios; the medium ratio corresponding with that adopted in the Main Programme. These 30 mixes used new deliveries of OPC and fine aggregate and the results were considered separately from those of the Main Programme. The workability, strength and elasticity were assessed.

6.2.4 Supportive Testing

These tests included calibrating the apparatus, testing the materials used and monitoring the curing regimes. The nature and frequency of the testing is indicated in Tab 6.2.c.

The practical nature of the work made it undesirable that all factors should be rigorously controlled. However, care was taken to ensure any variation in curing temperature, for example, remained within commonly accepted limits.

6.3 Materials

6.3*1 General

The cements and aggregates were sampled and tested according to BS 4550 and BS 812 respectively. In the case of the cementitious materials the samples were randomly selected from the drums, and each tested to produce an average result, representative of the whole. In the case of the aggregates an unbiased result was formed by testing a representative test portion of the aggregates formed by random sampling and riffling.

Tab 6.2.c : The Nature and Frequency of Supportive testing.

Nature		Methodology	Frequency
CALIBRATION			
Two-point Apparatus		Spring Balance	start/end
Temperature Monitoring System		Mercury Thermometer	start/end
Compression Testing Machine		Proving Ring	yearly
CHECKS			
Speedy Moisture Meter		Oven-drying*	start/end
Electrodynamic Materials Tester		Aluminium Bar	every 3 months
Underwater Pulse Velocity Rig		Cubes in air	start/end
Split Cube Platen Dimensions		Vernier Calipers	every 2 months
MATERIALS			
Aggregates			
Particle Size Distribution		Sieving	every 8 months
Relative Density		Gas Jar	2 samples
Free Moisture Content		Speedy Moisture Meter	each mix
Cementitious Material !			
Fineness		Rigden	12 samples
Consistence,Setting,Soundness		0,40,70% GGBS blends	2 samples
Chemical Composition		X-ray fluorescence	3 samples
Particle Size Distribution		Sedimentation	1 sample
TEMPERATURE			
Fresh Concrete		Electronic Thermometer	each mix
Regimes	40°C wet	Temperature	start/end
	20°C wet	Monitoring System	once
	20°C dry	Casella Hygrometer	continously
	10°C wet	Electronic Thermometer	daily
	5°C wet	Control Thermometer	weekly

! Cementitious materials tested to BS 4550:Part 3

* Aggregates tested to BS 812:Parts 2 and 103

The water used throughout the investigation was freshly drawn tap water supplied by the Yorkshire Water Authority.

6.3.2 Cementitious Component

Ordinary Portland Cement to BS 12 and two types of ground granulated blastfurnace slag complying with BS 6699 were supplied in single consignments at the start of the work by Castle Cement Limited, Ketton and the collaborating establishments respectively. They were stored in airtight drums until needed. Samples for physical and chemical testing were taken randomly from the numbered drums. The results of these tests are summarised in Tab 6.3.a.

It canbe observed that the GGBS type 2 has the highest specific surface area, followed by the GGBS type 1, and then the OPC. The GGBS type 2 also has the higher chemical modulus, and therefore potential reactivity, of the two slags.

The particle size distributions shown in Fig 6.3 were obtained by x-ray sedigraph. Determinations by two other laboratories using both sedimentation and elutriation techniques displayed a consistent ranking of the materials (Tab A.1.a) but differed by up to eight percentage points in the cummulative percentage passing. In accordance with the specific surface area values the type 2 GGBS has particles which are finer and of a single size. The type 1 GGBS has a particle size distribution similar to the OPC.

The distributions can be summarised in terms of the Rosin-Rammler constants xQ and N (66)in the relationship

$$\ln \ln \frac{100}{R} = N\ (\ln x - xQ),$$

where R is the percentage greater than the particle size x in microns, and xQ is the particle size for R equal to 36.79%.

	%	£
OPC	22.9	1.18
GGBS type 1	21.3	0.96
GGBS type 2	12.3	1.32

Tab 6.3.a : Properties of the Cementitious Materials.

PHYSICAL		OPC	Slag Type 1		Slag Type 2	
Colour		grey	white (greyish)		white (pinkish)	
Rigden Fineness (m2/kg)		378 (375-381)	406 (402-409)		452 (450-456)	
Median Particle Size (microns)		16.5	13.0		9.0	
Oven-dried Relative Density		3.14	2.89		2.91	
Moisture Content (%)		0.4	0.3		0.4	
% GGBS in blend		0	40	70	40	70
Standard Consistence (%)		24.0	24.0	27.8	27.8	31.1
Setting Time (minutes)	Initial	100	145	170	160	195
	Final	150	180	250	210	275
Expansion (%)		1	1	2	0	0

CHEMICAL	OPC	Slag Type 1	Slag Type 2
Major Oxides (%)			
CaO	64.5 - 66.0	38.1 - 39.1	38.6 - 39.5
SiO_2	21.3 - 21.6	35.1 - 36.0	32.7 - 33.4
Al_2O_3	4.9 - 4.9	10.4 - 10.6	11.1 - 11.3
MgO	2.7 - 4.0	9.4 - 9.6	8.9 - 9.2
Fe_2O_3	2.8 - 2.9	0.4 - 0.4	1.2 - 1.3
BS 6699 :1986 Chemical Modulus		1.65	1.79

Tab 6.3-b : Supplementary Data from the Manufacturers.

PHYSICAL

		Slag Type 1	Slag Type 2
BS 4550 :1978 Compressive Strength (MPa) of 70% GGBS blend	3-day	6.5	9.0
	7-day	13.0	20.0
	28-day	36.5	42.0

CHEMICAL AND MINERALOGICAL

		Slag Type 1	Slag Type 2
Major Oxides (%)	CaO	40.7	40.5
	SiO_2	36.7	34.5
	Al_2O_3	9.8	11.5
	MgO	9.2	8.5
BS 6699 :1986 Glass Content (%)	Pure	90	95
	Glassy	100	100

j®IIDLUg •£ ©Ai^D|nujno

Fig 6.3 : Particle size distribution of the cementitious materials (Sedigraph).

The lower value of xQ and higher value of N for the GGBS type 2 confirms its finer and narrower particle size distribution. The lower value of N for the GGBS type 1 compared to the OPC indicates a wider distribution. The difference in the particle size distributions of the GGBS types could account for their differing water demands for standard consistence.

The lime to silica ratio of GGBS type 1 is 1.08 compared to 1.18 for GGBS type 2. No mineralogical tests were carried out by the author. Work by others (30) on slags with similar lime to silica ratios indicates that GGBS type 1 will contain Melilite inclusions, whilst the type 2 will contain Merwinitic inclusions. The Merwinitic inclusions have the effect of promoting the reactivity of the surrounding glass (Section 2.5). It would be expected that the GGBS type 2 would, by virtue of its physical, chemical and possibly mineralogical properties, have a higher rate of strength development. Indeed, the standard strength data supplied by the manufacturers in Tab 6.3.b indicate this (although different sources of OPC were used).

6.3.3 Aggregates

One consignment of fine aggregate and two consignemts of coarse aggregate were used during the investigation. The fine aggregate is a Trent Valley sand conforming to a BS 882:1983 zone fMf or a BS 882:1965 zone 3. It was obtained from Newark,Nottinghamshire. The coarse aggregate is a graded Trent Valley gravel from Blaxton, South Yorkshire. It has a 20-5 mm grading, which is slightly deficient in 10 and 5 mm particles.

Although the source of the second delivery of coarse aggregate was the same as the first, some sieving to remove oversize material was carried out. The consistent grading of the coarse aggregate is witnessed by the small range in the cummulative percentage passing shown in the Tab 6.3*c.

The aggregates were stored in enclosed bunkers in an approximately saturated surface-dry condition. Local drying at the surface of the fine aggregate was prevented by a polythene cover.

Tab 6.3.c : Physical Properties of the Aggregates.

GRADING

Fine Aggregate			Coarse Aggregate		
	% Passing Blocks 1 - 4			% Passing	
Sieve Size	Mean	Range	Sieve Size	Blocks 1 - 3	Block 4 *
5.00 mm	96.4	95.5 - 96.9			
2.36 mm	84.4	82.6 - 85.8			
1.18 mm	75.2	72.9 - 77.3	20 mm	99.4	94. 1 (99.6)
600 microns	62.3	60.9 - 65.8	14 mm	63.8	58.3 (61.7)
300 microns	12.0	9.6 - 17.6	10 mm	28.7	26 .4 (28.0)
150 microns	1.5	1.2 - 1.7	5 mm	1.8	0.9 (0.95)

BS 882 : 1965		BS 882 : 1983	
Sieve Size	Zone 3 Limits on % Passing	Sieve Size	20 - 5mm Limits on % Passing
5.00 mm	90 - 100	20 mm	90 - 100
2.36 mm	85 - 100	14 mm	
1.18 mm	75 - 100	10 mm	30 - 60
600 microns	60 - 79	5 mm	0 - 1 0
300 microns	12 - 40		
150 microns	0 - 1 0		

DENSITY CHARACTERISTICS

	Fine Aggregate	Coarse Aggregate	
		Blocks 1 - 3	Block 4
Saturated Surface-Dry Relative Density	2.65	2.63	2.63
Water Absorption (%)	0.8	0.6	0.7

* Values in parentheses are adjusted fractions when oversize material has been removed

7.1 Introduction

The previous two chapters dealt with the tests methods and the experimental programme. This chapter describes the daily procedure, from batching the fresh concrete through to testing the hardened concrete specimens. Particular attention is paid to the sequence and timing of tests. Any changes in procedure are indicated.

7.2 Batching and Mixing

The mixes were batched in a clean and dry 0.1m^3 capacity mixer pan on 250 kg capacity Avery Scales. The total mass of solids batched was approximately 150 and 100 kg in Parts 1 and 2 of the Main Programme respectively. The batch masses per cubic metre are shown in Tab 7.2. Each constituent was added until the required cummulative mass was obtained to the nearest 0.2 kg. To improve the efficiency of the mixing the cementitious component was batched between half quantities of the aggregates.

In the Secondary Study the mass of solids was reduced to approximately 50 kg and the the cement was weighed separately to the nearest 10 g.

Tab 7.2 : Batch Masses for the Main Programme Mixes.

Mix Design Number		Batch Quantities kg per cubic metre						
		WATER	BLENDED CEMENT		AGGREGATES		GGBS	
Slag type 1	Slag type 2	Free	OPC ! 3.15	GGBS 2.90	Fine 2.65	Coarse 2.65	level (%)	
1		165	200	___	855	1160	0	* W/C = 0.83
2	10	165	120	80	855	1160	40	A/C = 10.0 %Firies= 42.5
3	11	165	60	140	855	1160	70	%Paste=22.9-23.2
4		165	300	___	770	1160	0	W/C = 0.55
5	12	165	180	120	770	1155	40	A/C = 6.4 %Fines= 40.0
6	13	165	90	210	770	1155	70	%Paste=26.1-26.6
7		165	400	___	690	1160	0	W/C = 0.41
8	14	165	240	160	685	1155	40	A/C = 4.6 %Fines= 37.3
9	15	165	120	280	685	1150	70	%Paste=29.3-29.8

* W/C=Free Water/Total Cementitious Content
A/C= Aggregate/Total Cementitous Content
! Assumed oven-dried and saturated surface-dry relative densities

The design shown in Tab 7.2 assumes 1^ entrained and the relative densities indicated. No adjustment of the batch masses of the aggregates for their moisture content was deemed necessary. However, the free moisture content of the fine aggregates was allowed for when calculating the water to be added (the coarse aggregate was assumed to be saturated surface-dry). Accurate allowance for the moisture content of the aggregates and the true relative densities of the materials gives rise to the proportions in Tab A.1.b.

The water to be added was weighed to the nearest 10 g and mixed with the solids for two minutes in a Liner Cumflow rotating pan mixer, with a forced impeller action. The concrete was allowed to stand for approximately 10 minutes before samples were taken for the workability tests.

7.3 Fresh concrete testing

The nominal time of the workability tests was 15 minutes after the addition of water. The actual timing is given below.

slump	- first determination at 13 to 15 minutes and second determination at 15 to 18 minutes
compacting factor	- 15 to 18 minutes
two-point test	- idling pressures measured before and after the test at 13 and 20 minutes

In Part 2 of the Main Programme an additional speed setting of 6 (1.1 Hz) was inserted at the end of the normal sequence of speeds in the two-point test to determine the change in resistance of the concrete, brought about by the period of shearing.

The concrete from the workability tests was returned to the mixer and subject to half a minute remix. Samples for vacuum flask calorimetry and pulse velocity measurement at very early ages were taken before and after casting the hardened concrete test specimens. Monitoring the temperature and pulse velocity started 30 minutes and around 60 minutes after mixing respectively.

7.4 Specimen Manufacture, Curing and Handling

The casting of specimens started 30 minutes after mixing. In the Main Programme, twelve cubes and a beam were manufactured per regime. In the Secondary Study six cubes were produced for each mix, and an additional beam and cylinder were manufactured from the medium water-cement ratio mixes.

The 100mm cubes and 100x 100 x 500 mm beams were cast in two layers, each receiving 20 seconds of vibration. The 150 mm diameter by 300mm long cylinder was cast in six layers with its axis vertical. A cover plate was then attached to its upper rim and it was vibrated with its axis horizontal. It was stored in this position till stripping.

In order to reduce the time taken for the specimens to reach the nominal curing temperature some moulds were preconditioned by heating to 40°C or cooling to 10° C, as appropriate. After casting the specimens were immediately transferred to their undemoulded curing conditions (Fig 7.4). The temperature at the centre of specimens was found to be within 10^ of the nominal curing temperature 100 minutes after mixing.

Demoulding of the specimens normally took place 16 to 24 hours after casting. Each specimen was marked with: the date of mixing; the mix number prefixed by letters to indicate the origin; and a curing code consisting of the temperature and the letter W or D to denote wet or dry curing respectively. After marking, the specimens were placed in the main curing regimes.

7.5 Hardened Concrete Testing

The hardened concrete tests were carried out at 1, 3, 7, 28 and 91 days, within a tolerance of a sixtieth of the nominal age, as follows:

a) pulse velocity (cubes) - two cubes underwater at each age

b) compressive strength - two cubes at each age

c) pulse velocity (beam) - one beam used at each age

CASTING | PLACED IN REGIME | UNDEMOULDED CONDITIONS | DEMOULDED CONDITIONS

Fig 7.4 : Specimen curing.

d) dynamic elastic modulus - one beam used at each age

e) splitting strength - two cubes at 28 days

f) flexural strength - one beam at 91 days

g) equivalent cube strength- two ends of each beam at 91 days

h) water absorption - one core at 95 days.

i) density - each specimen at testing

In the Secondary Study compressive strength was determined at 1,7 and 28 days, and the dynamic and static elastic moduli were determined at 7 and 28 days.

The cubes were immersed in 20°C water for 15 minutes after removal from their respective regimes to standardize the temperature and surface saturation. Two pulse velocity measurements underwater were carried out through each cube and its mass in air was recorded to the nearest 10 g. The cubes were then tested in compression. In Part 2 of the Main Programme the more sensitive transverse unit of the compression machine was used where strengths less than 2 Mpa (corresponding to a pulse velocity of 3-5 km/s) were anticipated.

The beam was removed from its curing regime. Three pulse velocity measurements were made along the beam, 25,50 and 75mm below the trowelled face using 200 kHz transducers. Where the transit time using this frequency of transducer was over 200 microseconds (corresponding to a velocity of 2.5 km/s) a single measurement was made using 50 kHz transducers instead. Without delay the beam was weighed in air and its dynamic elastic modulus determined. The beams was returned to their regimes within 30 minutes of removal.

To avoid inappropriate testing, no pulse velocity measurement was made on a beam when the corresponding pulse velocity through cubes was less than 3*3 km/s, and no electrodynamic measurement was made when a compressive of less than 1 Mpa was recorded.

After the non-destructive tests at 91 days all beams were placed in water at 20°C for 24 hours to standardize the temperature and surface saturation. At 92 days (nominally 91 days) each beam was weighed in air and water to the nearest 1 g. After removal from the water each beam was immediately tested in flexure. The two portions of the failed beam were retained and tested in compression as equivalent cubes. The longest unbroken section of beam remaining at this time was drilled through its width to provide a 75mm diameter water absorption specimen. This specimen was tested at 95 days after drying.

In the Secondary Study the static modulus cylinder was fitted with demec spots *2k* hours prior to testing using dental cement. After four cycles of stressing up to a third of the compressive strength, obtained from cubes, the cylinder was loaded to failure.

Although most specimens were stripped and tested without difficulty, some delays were experienced in low cementitious contents mixes and under low curing temperatures. These delays to testing are indicated in Tab 7.5.

Tab 7.5 : Effect of Curing on Hardened Concrete testing at 1 day.

Mix Design	Slag Type	Cementitious Content (kg/m) OPC	GGBS	Curing Code 40W	20W	20D	10W	5W
7	–	400	0					
4	-	300	0					
14	2	240	160	--				
8	1	240	160					
1	-	200	0					E V
12	2	180	120					E V
5	1	180	120					E V
15	2	120	280					E V
9	1	120	280	--	-	-	E V	E V
13	2	90	210	--	-	--	E V	E V
6	1	90	210	-	--	-	E V	E V
10	2	120	80	--	--	-	E V	E V C
2	1	120	80	--	--	--	E V	E V C
11	2	60	140	--	E	E	E V	E V C
3	1	60	140		E	E	E V	E V C

Letters indicate tests not carried out
E - Dynamic Elastic Modulus
V - Pulse Velocity (beam)
C - Compressive Strength

8.1 Introduction

This chapter has two main sections; the first deals with the results from the Main Programme , the second part relates to the Secondary Study. In each section there is a graphical account of the results, followed by a tabulated summary of the regression analyses. The strength and elasticity data from the Main Programme has been arranged into a comparison of medium curing temperatures (40 and 20°C), different curing humidities (100/6 and 65% RH at 20°C), and low curing temperatures (10 and 5°C)

In general the graphs adopted solid, broken and dashed lines for the low, medium and high cementitious contents or GGBSlevels, respectively. The slag type was indicated by the number of dots breaking a line or by shading of the symbols. The symbols corresponding to the low, medium and high cementitious contents were a circle, square or cross, and triangle or asterix, respectively.

8.2 Analysis of the results

It is worthwhile at this point to reiterate the three main objectives of the study:

1) To determine the practical and statistical significance of the effects of mix design factors (particularly GGBS type and level) upon the workability, strength and elastic properties of concrete.
2) To develop, where practically appropriate, predictive functions for the behaviour of slag cement concretes in the fresh and hardened states.
3) Examine the relationship between the assessment methods for the workability, strength and elastic properties.

To accomplish these objectives the raw test data was first processed to give the test parameters, which were then analysed. The analysis included graphical presentation, summary statistics, and where appropriate, regression analysis and analysis of variance.

An account of the processing of the results is given in Tab

8.2. Most of the calculations are adequately covered in the British Standards, however further explanation of the processing of the two-point test, underwater pulse velocity, water absorption and vacuum flask calorimetry data is given in Appendix C. For brevity raw test data is not supplied, however the processed results are detailed in Appendix A. A brief explanation of the statistical summary parameters and analyses are given in Appendix B.

Individual block results were used when plotting or regressing the relationships between test parameters. The effects of experimental factors were generally indicated using block means, with the block range giving a measure of the residual variation.

Some data was plotted on logscales or logarithmically transformed prior to statistical analysis. One consequence of transforming a variable is that associated residuals are effectively weighted according to their proportion of the variable. Transformation of data is discussed in Sections B.2 and B.3 of the Appendices.

Three maturity functions summarising the combined effect of age and curing temperature have been employed in this work. A limited comparison of two of them,the Sadgrove and Nurse-Saul functions (Section C.2.1) is given in Fig 8.3.3*k. Unless otherwise stated equivalent ages at 20°C were calculated using the Sadgrove function. The Arrhenius function was used to estimate activation energies for the different cementitious blends used (Section C.3.2).

Computers were used to store, process and analyse the experimental data. Programs were written for the BBC B+ microcomputer to control the sampling of pressure and temperature and to store and process this data. Salient elements of these program are given in Appendix D, together with examples of their output. The BBC B+ and IBM PC microcomputers were used for simple statistical analyses and for the manipulation and presentation of data. Regression analyses and anlyses of variance were carried out on the IBM 4341 mainframe computer using the Minitab and SPSSX (67 >68) packages.

Tab 8.2 : Processing the test Results

Final Parameter	Measured Quantities	Processing
WORKABILITY		
Slump to 1 mm	Length to 5 mm	mean of two determinations
CF to 2 dp	Mass to 10 g	ratio of partially and fully compacted masses
£ to 0.01 Nm	Pressure to 1 lbf/in2	calculation and regression
h to 0.01 Nms	Speed to 10 rpm	of impeller torque and speed
STRENGTH		
Compressive to 0.1 MPa	Force to 0.1 kN*	Force/10 mean of two determinations
Tensile Splitting to 0.01 MPa	Force to 0.1 kN	Force/15.7 mean of two determinations
Flexural to 0.01 MPa	Force to 0.01 kN Volume to 1 ml	Force x 1500 / Volume
ELASTICITY		
Dynamic Modulus to 0.1 GPa	Frequency to 5 Hz Mass to 10 g Volume to 1 ml	calculate density Density x (Frequency)2x 10
Pulse Velocity	Time to 0.1 ps	nominal path length (mm) divided by time
to 0.01	Beam	mean of three determinations
to 0.1 km/s	Cube	mean of two determinations
DURABILITY		
Water Absorption to 0.01 ml/m2s	Mass to 0.1 g	Mass/15.9

* transverse mode testing
dp decimal places

Results from the Main Programme

Workability

Figs	8 8 [illegible]	effect of cementitious blend
Figs	8.3.1.f-g	relationships between the test methods
Figs	8.3.1.h-l	mix stability
Tab	8.3.1.a	polynomial model
Tabs	8.3.1.b-c	relationships between the assessment methods

□ slag type 1
A slag type 2
- limits

workability
relative to
control

same o
more +
less —

160

120

80

40

T2

0-96

40% 70%

0–88

0-84

T2

40% 70%

4–s

40 % 70 %

— s — s

T2

40 70

GGBS LEVEL (%)

8.3-1-a : Effect of GGBS level upon workability in the low (200 kg/mJ) cementitious content mixes.

□ slag type 1
■Aslag type 2
- limits

workability relative to control

same O
more
less —

160

120

80 —fs

40 T2

40% 70 %

0-88

0-84 T2

40% 70%

T2 — S

40 % 70 %

(J— 4\

—

T2

40 70

GGBS LEVEL (%)

Fig 8.3.1.b : Effect of GGBS level upon workability in the medium (300 kg/m^) cementitious content mixes.

□ slag type 1 workability same O
■Asiag type 2 relative to more 4-
limits control less —

160

120 40 % 70 Vo

80
¬J

40 T2 — s — s

0-96-^—

40% 70%

0–88

0-84 T2 — s — s

(.y–

T2 — s — s

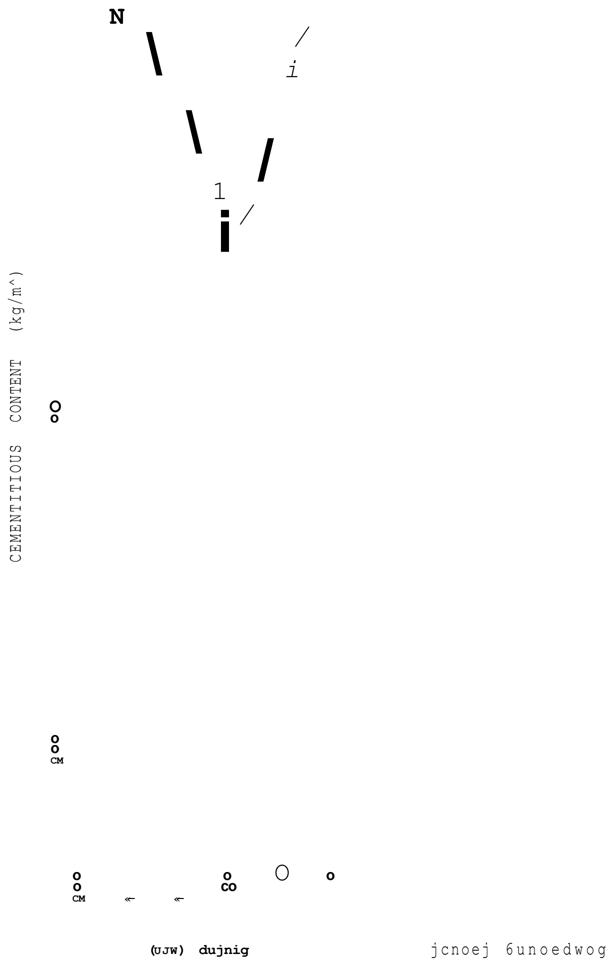
40 % 70 %

T2 — s

40 70

GGBS LEVEL (%)

Fig 8.3.1.c : Effect of GGBS level upon workability in the high (400 kg/m^) cementitious content mixes.


CEMENTITIOUS CONTENT (kg/m^)

CEMENTITIOUS CONTENT (kg/m3)

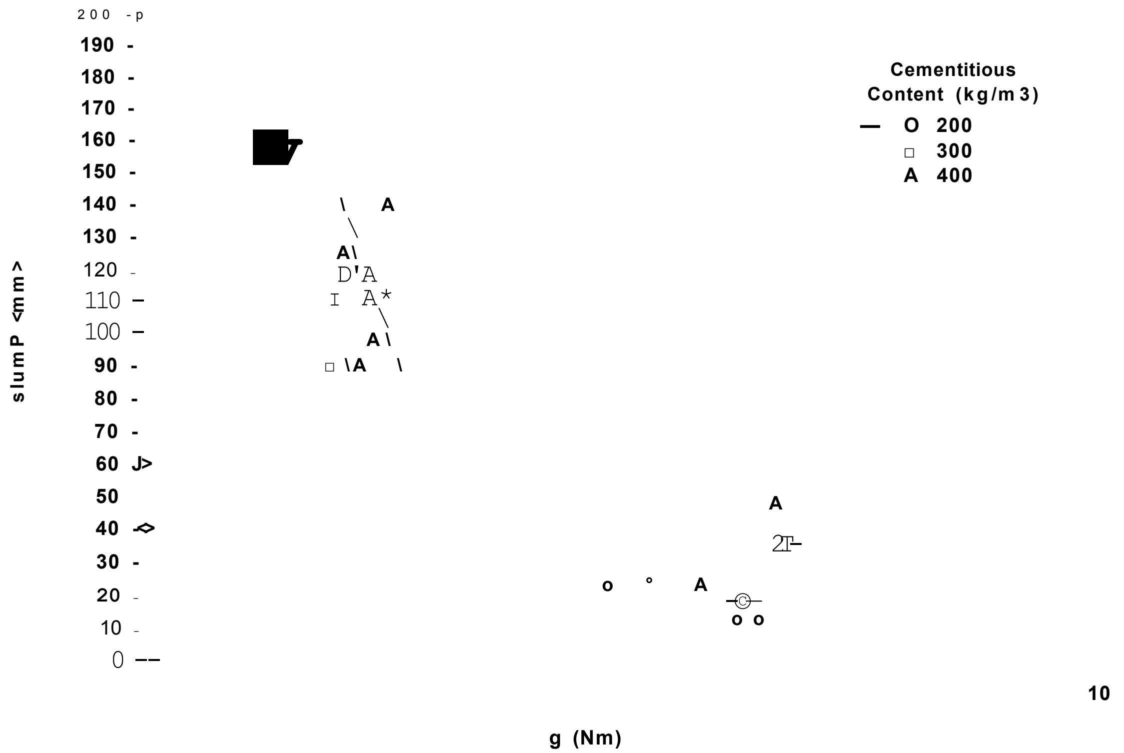


Fig 8.3.1.f : Slump against g for different cementitious contents

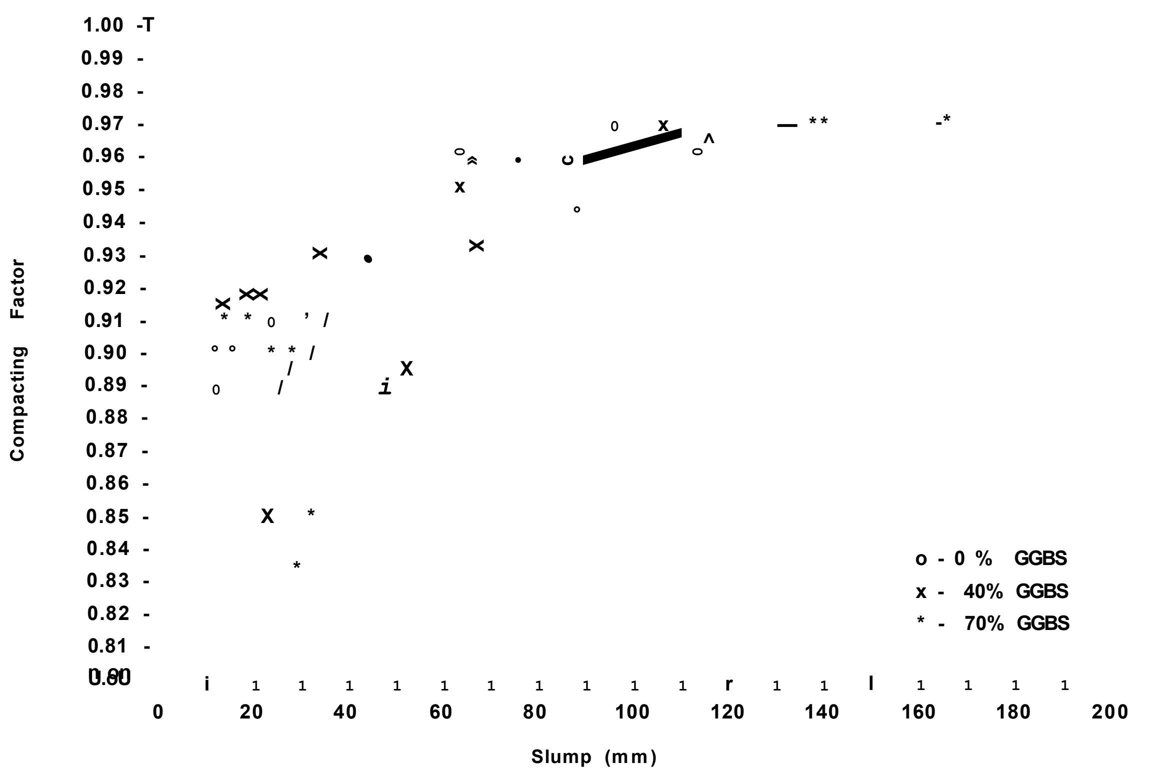


Fig 8.3.1.g : Compacting factor against slump for different GGBS levels.

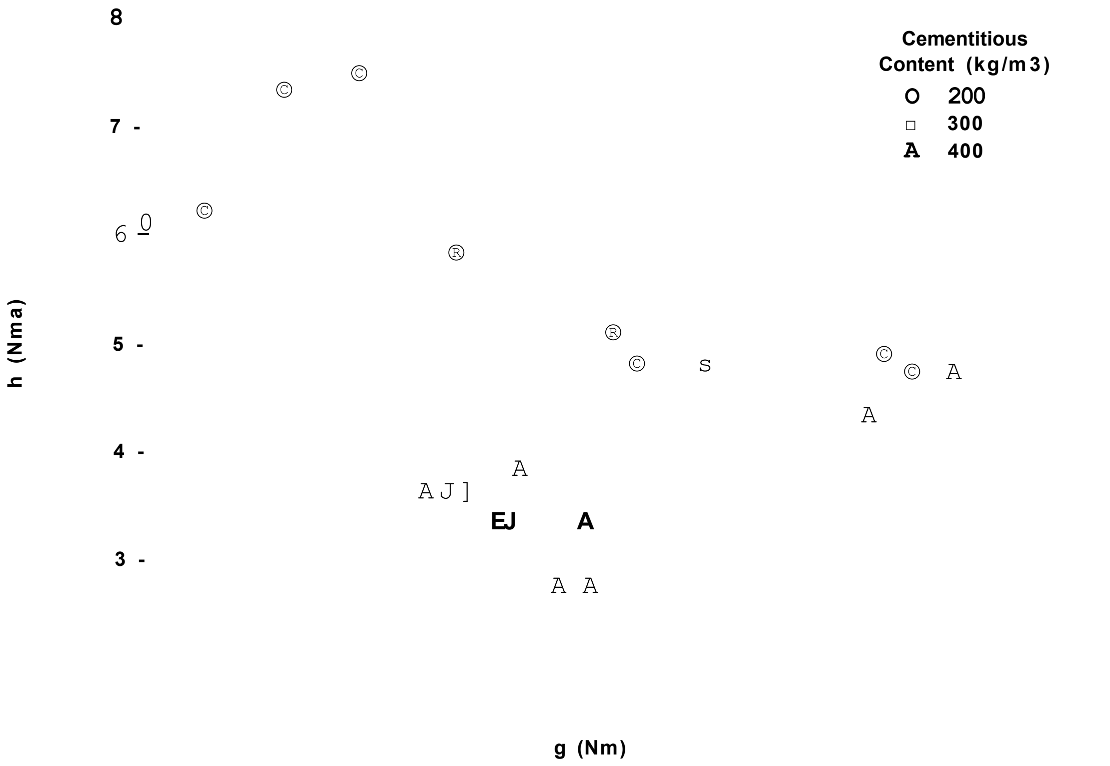


Fig 8.3-1-h : The bleeding mark located on a plot of h against g.

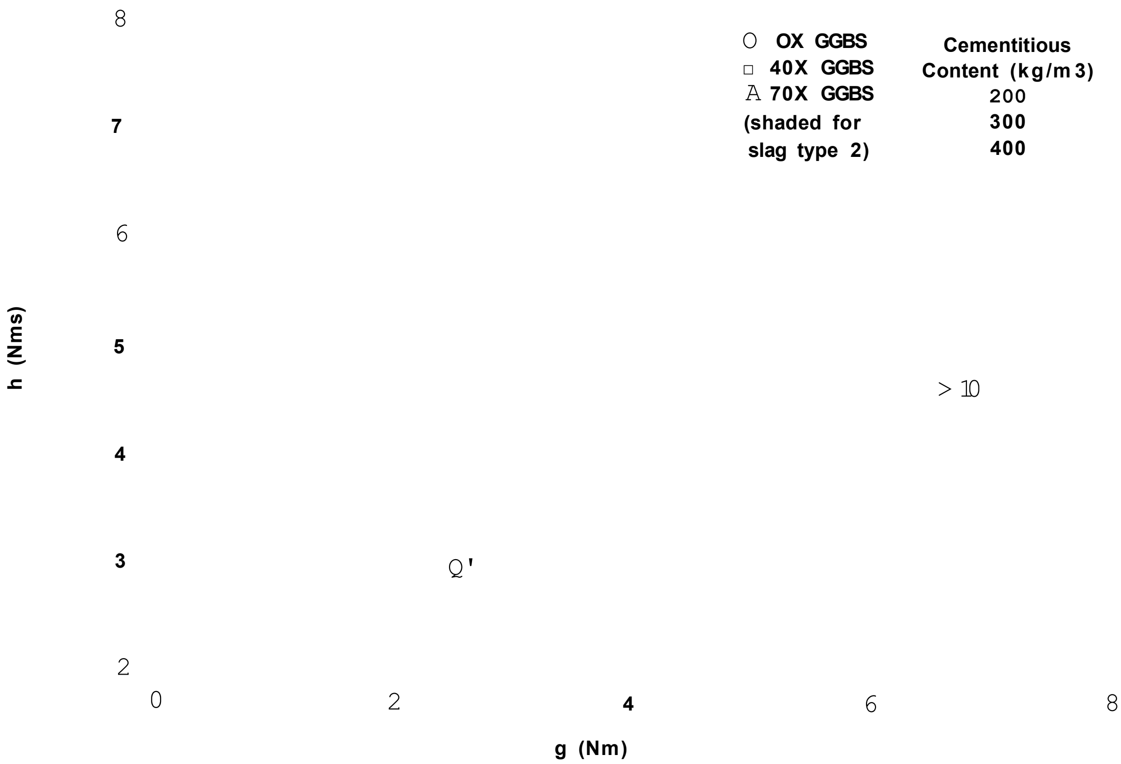


Fig 8.3.1.i : The cohesion mark located on a plot of h against g.

10

Bleeding Mark

Bleeding = 1.89 TCH - 1.60

Torque Change (Nm)

Fig 8.3.1.j : Bleeding mark against torque change

10

9 -

Cohesion = -1.05 TCH + 7.61

Cohesion Mark

00

<30

1 2 3 A 5

Torque Change (Nm)

Fig 8.3.1.k : Cohesion mark against torque change

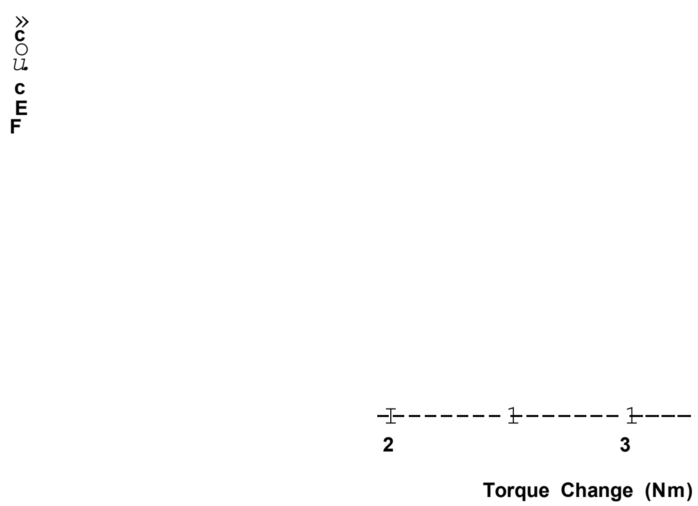


Fig 8.3.1.1 • The relationship between hardened concrete homogeneity, indicated by variation in ultrasonic pulse velocity and fresh concrete stability, indicated by torque change under shearing.

Tab 8.3.1.a : Coefficients from a polynomial model for workability.

Parameter	GGBS Type	Constant	Cm	Rp	Cm x Rp	Cm2		
Slump	1	-415	3.04	0.3 X	0.001 X	-0.005 /	0.879	22
(mm)	2	-320 i	2.36 si	1.3 si	0.005 V	-0.003 V	0.835	16
CF !	1	657	1.70 V	0.3 X	-0.001 X	-0.002 V	0.942	9
	2	503 I	2.83 V	2.3 sj	-0.009 V	0.004 si	0.894	18
g *	1	1609	-7.23 V	-13.3 i	0.035 V	0.010 si	0.884	71
(Nm)	2	1907	-9.27 sj	-15.8	0.055 v	0.013 V	0.829	108
h *	1	1871	-9.25 i	4.2 i	-0.109 X	0.013 V	0.929	65
(Nms)	2	1568	-7.34 V	0.4 V	0.038 si	0.010 V	0.849	69

72 Observations

! All values multiplied by 1000
* All values multiplied by 100
V Probability of significance 98% or higher

Cm Cement Content
Rp GGBS Level

Tab 8.3.1.b : Relationship between the workability assessment methods.

Linear y = **ax** + c

y	x	a	c	r	df	sig*
CF	Slump	0.001	0.885	0.766	58	> 99.8
Ang. CF 1	log Slump	10.77	56.50	0.803	58	> 99.8
Slump	g	-11.35	102.5	0.508	58	> 99.8
CF	h	-0.012	0.982	0.489	58	> 99.8
Slump	h	-17 .6	142.6	0.666	58	> 99.8
CF	g	-0.014	0.976	0.696	58	> 99.8

y	x	a,	a2	c	r	df	sig*
Slump	g h	-11.45	-17.72	179.6	0.841	57	> 99.8
CF	g h	-0.014	-0.012	1. 028	0.853	57	> 99.8
6	g	0. 042			0.872	59	> 99.8

Power y = **axb**

y	x	Cement Content	a	b	r	df	sig*
Slump	g	low	36.6	-0.352	0.625	18	> 99.0
		medium	177.7	-0.833	0.910	18	> 99.8
		high	268.8	-1.083	0.914	18	> 99.8

s (Slump)$^{-0.47}$

1 Arcs in0 (CF)$^{0.5}$

* Probability that correlation is significant

Tab 8.3.1..c : Relationship between the mix stability assessment methods

Linear y = **ax** + c **df = 28**

y	x	a	c	r	sig*
Bleeding Mark	Cohesion Mark	-0.86	7 .£2	0.720	> 99 .8
Cohesion Mark	TCH (Nm)	-1.05	7.61	0.564	> 99 .0
Bleeding Mark	TCH (Nm)	1.89	-1.60	0.692	> 99 .8
TTR (km/s)	TCH (Nm)	1.15	0.71	0.771	> 99. 8

* percentage probability that the correlation is significant
TCH Torque change during two-point testing, measured at 1.1 Hz
TTR Transit time range in the beam, measured at 28 days.

8.3.2 Hydration

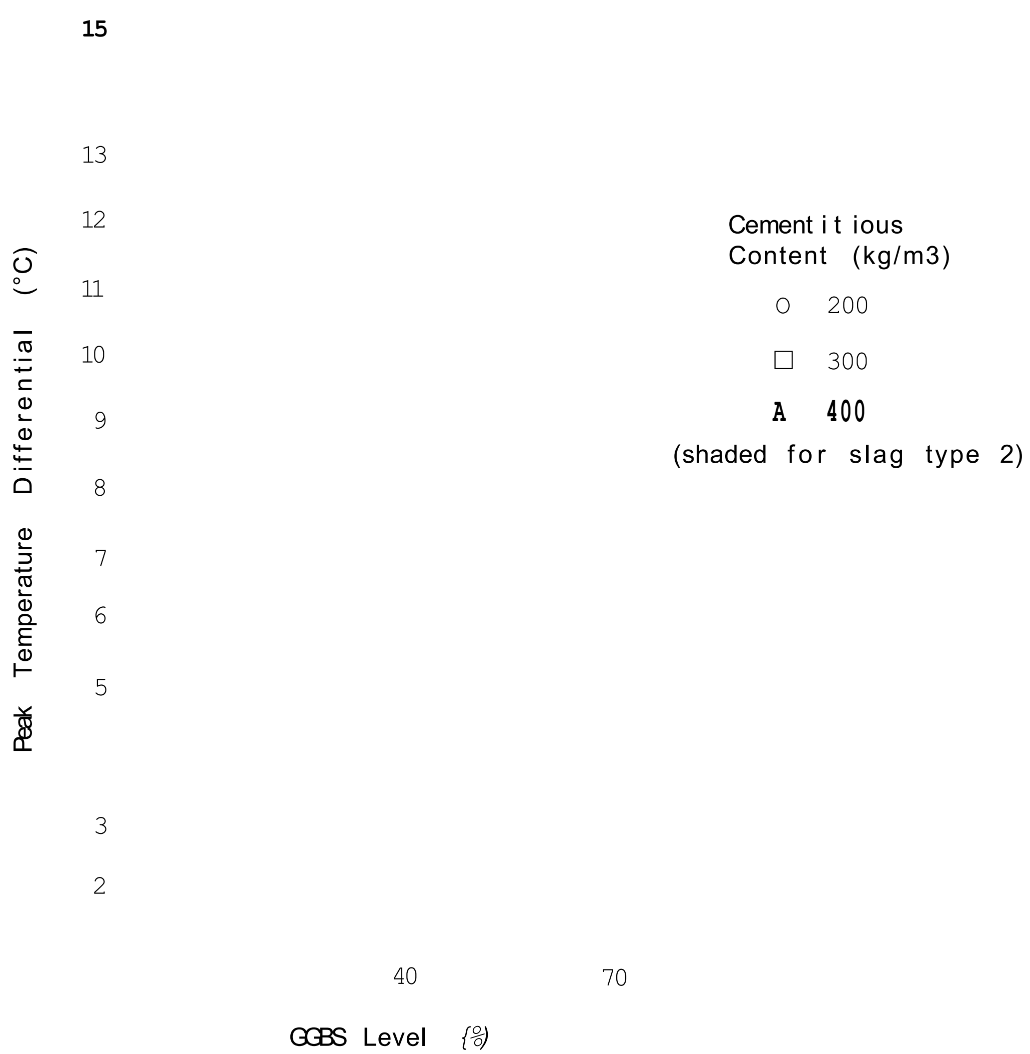


Fig 8.3.2a : Effect of GGBS level and type on the magnitude of the peak temperature differential at different cementitious contents.

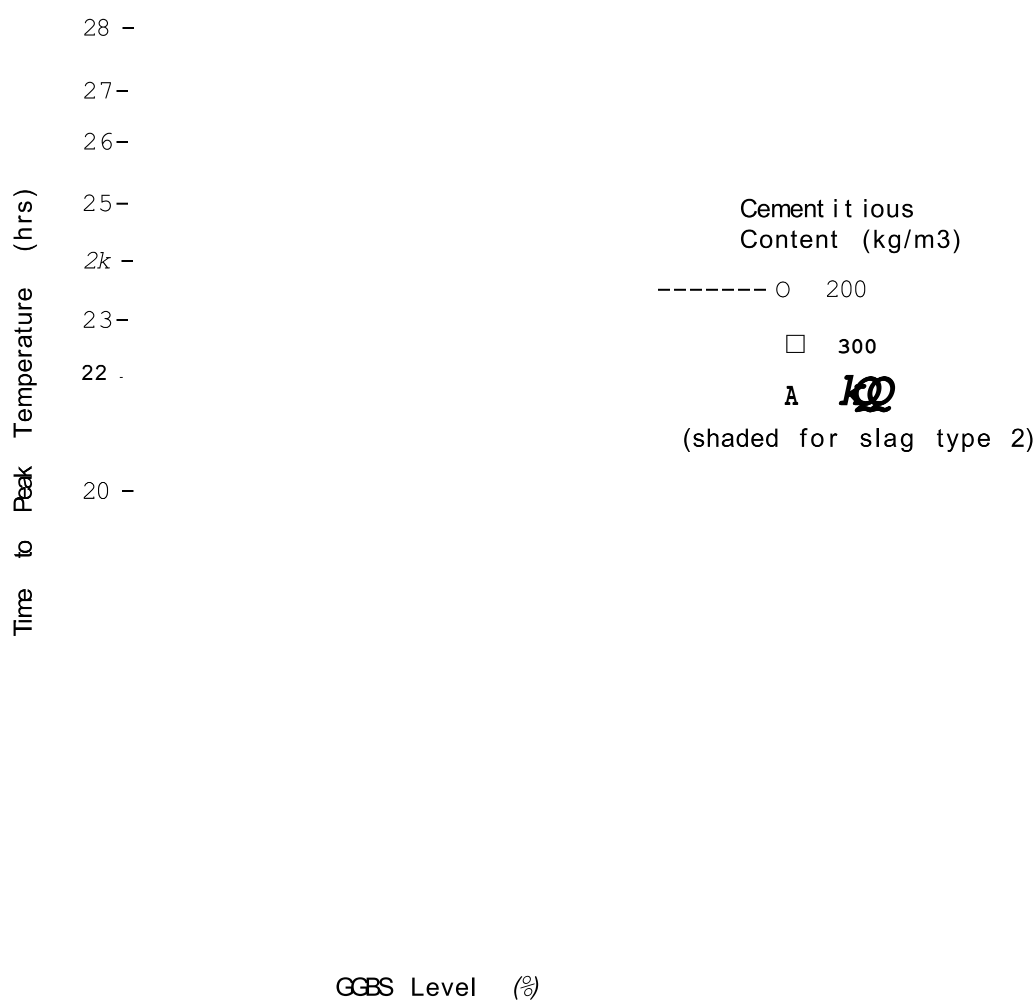


Fig 8.3.2b : Effect of GGBS level and type on the time to the peak temperature at different cementitious contents.

8.3.3 Compressive Strength

Figs	8.3.3.a-c	development with age
Figs	8.3.3*d-h	pseudo three-dimensional plots
Fig	8.3.3.i	relative to the control mixes
Fig	8.3- 3-J	relative to standard curing
Fig	8.3-3.k	relationship with equivalent age
Tab	8.3*3	relationship with equivalent age

CEMENTITIOUS CONTENT

200 kg/m3 | 300 kg/m3 | 400 kg/m3

AGE (days): 0 - 1, 1 - 3, 3 - 7, 7 - 28, 28 - 91

(i) 40°C wet curing

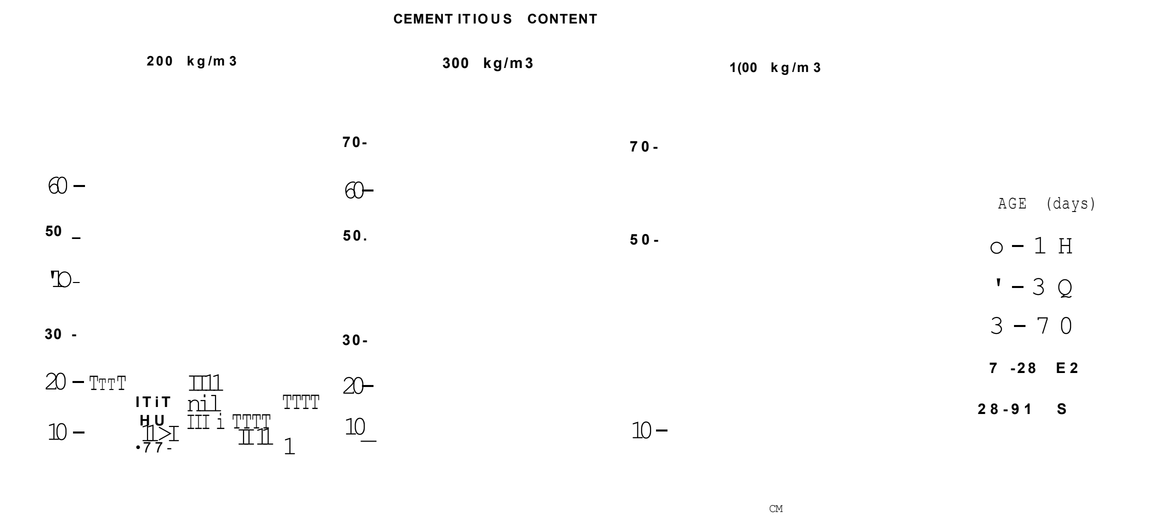
(ii) 20°C wet curing

CEMENTITIOUS CONTENT

200 kg/m3 | 300 kg/m3 | 400 kg/m3

AGE (days): 0 - 1, 1 - 3, 3 - 7, 7 - 28, 28 - 91

Fig 8.3-3.a : Development of compressive strength at medium curing temperatures.



(i) 20°C wet curing

(ii) 20°C dry curing

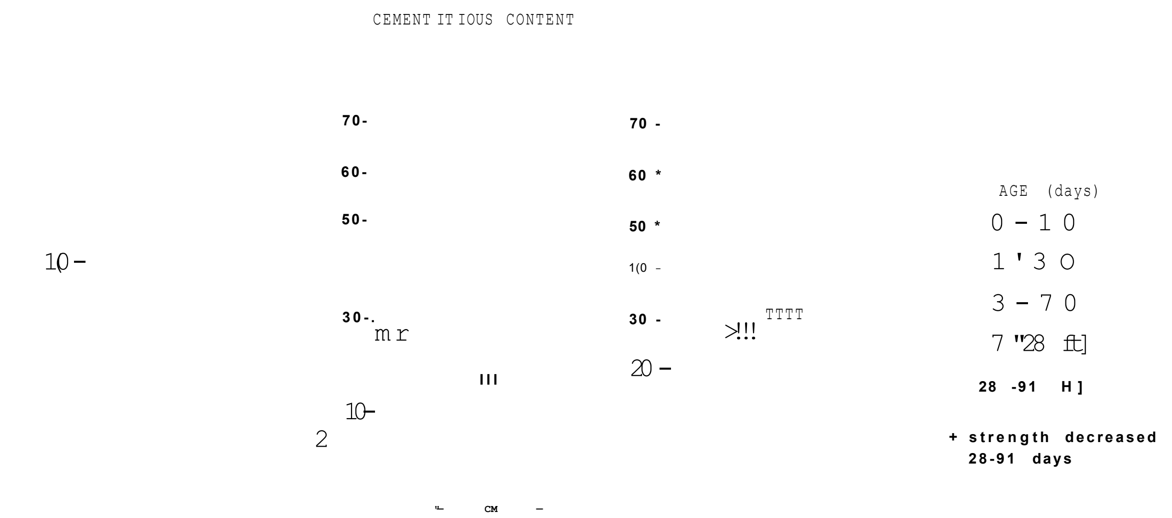
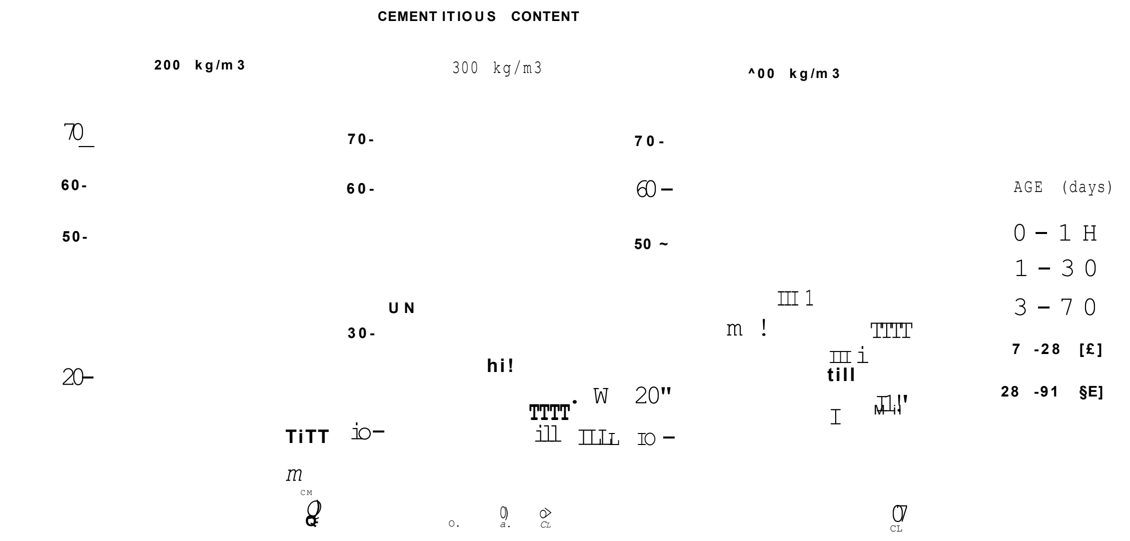


Fig 8.3.3.b : Development of compressive strength at different curing humdities.



(i) 10°C wet curing

(ii) 5°C wet curing

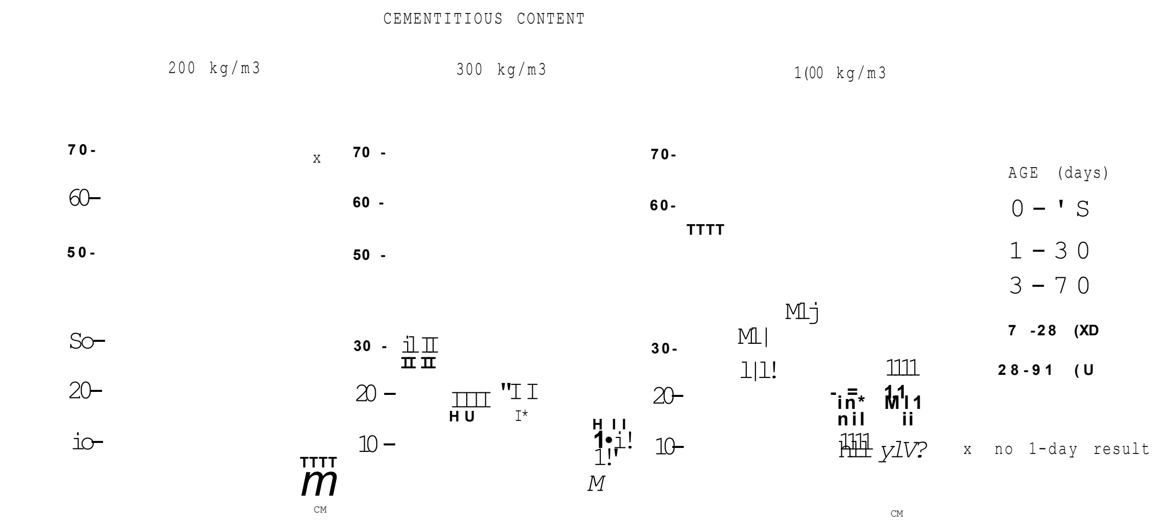


Fig 8.3.3.C : Development of compressive strength at low curing temperatures

CEMENTITIOUS CONTENT

(PdW) H10N3dlS 3AISS3ddW03

under 40 C wet curing.

CEMENTITIOUS CONTENT

CEMENTITIOUS CONTENT

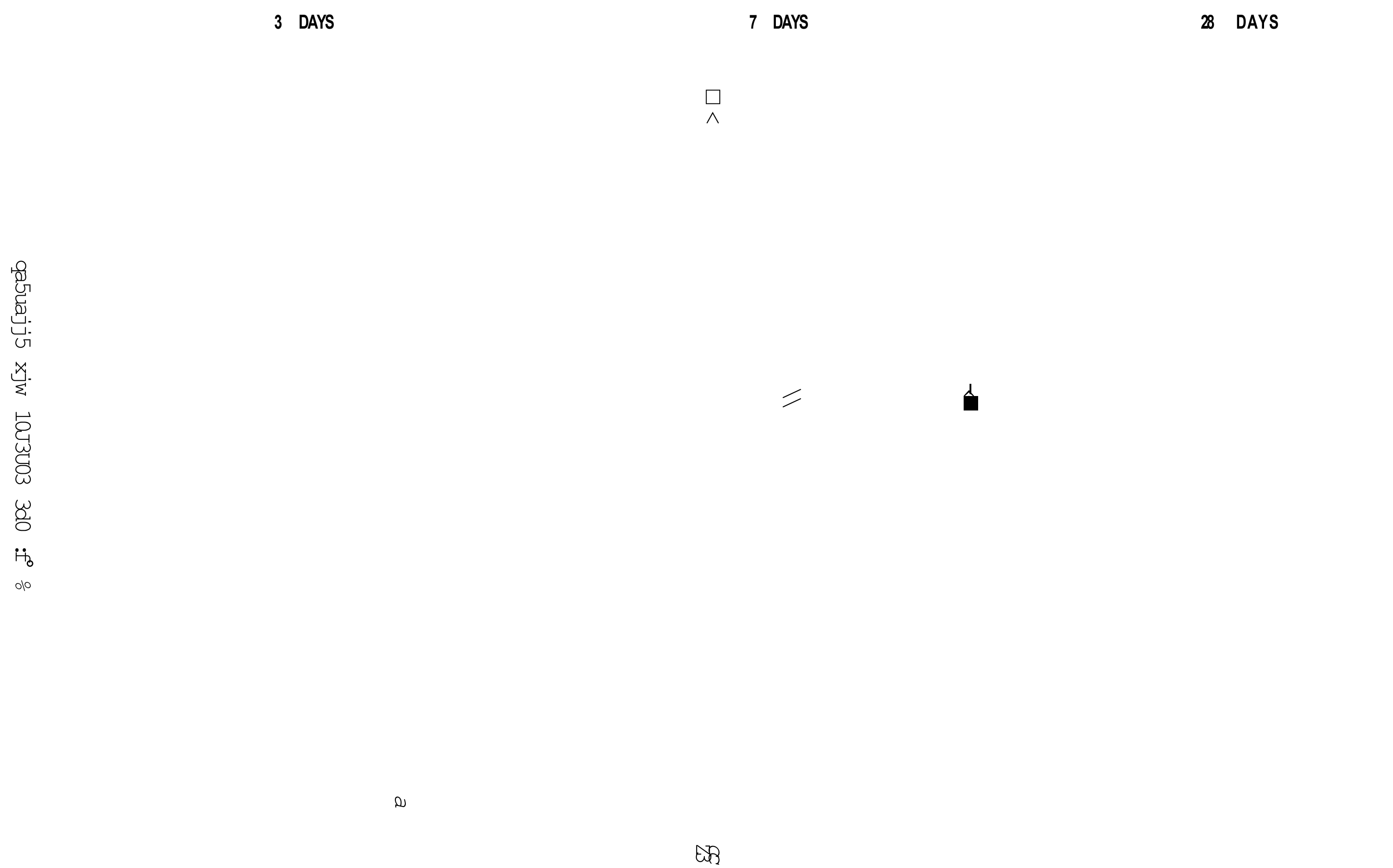
COMPRESSIVE STRENGTH (MPa)

CEMENTITIOUS CONTENT

10 C wet curing.

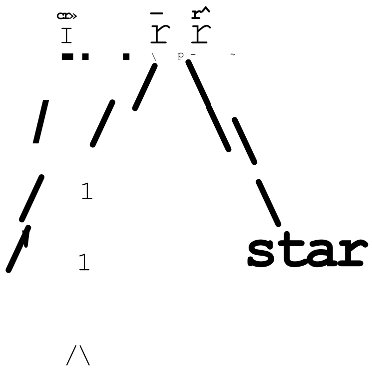
CEMENTITIOUS CONTENT

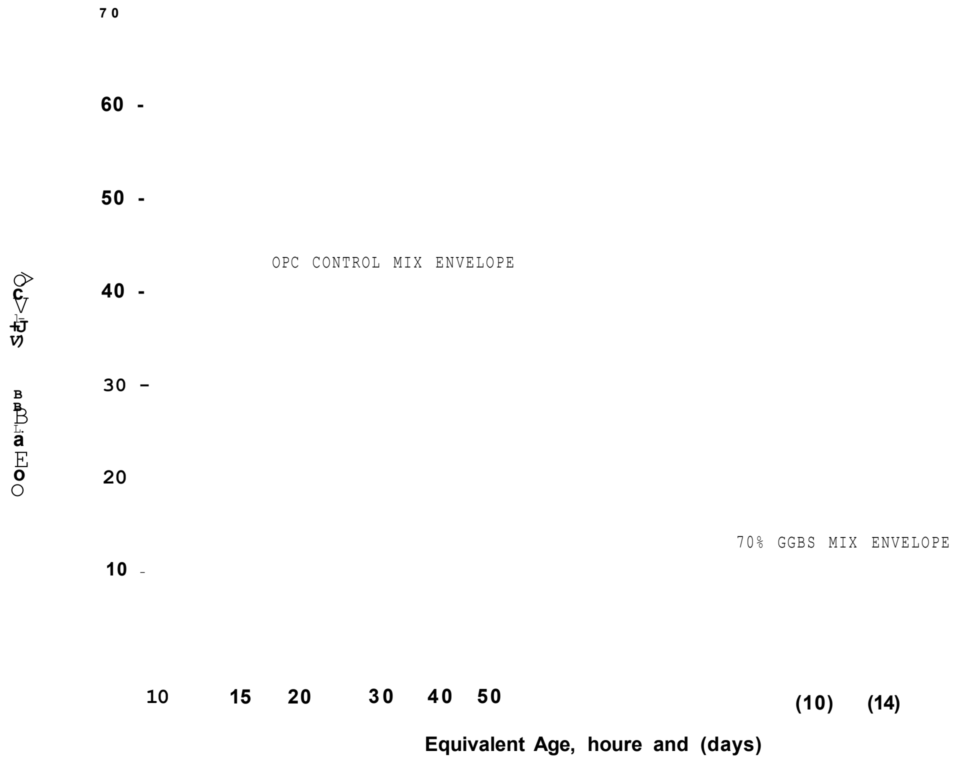
(BdW) H1DNSdlS 3AISS3ydWOO



at different ages.

CURING CODE





(i) Effect of blend

(ii) Effect of function

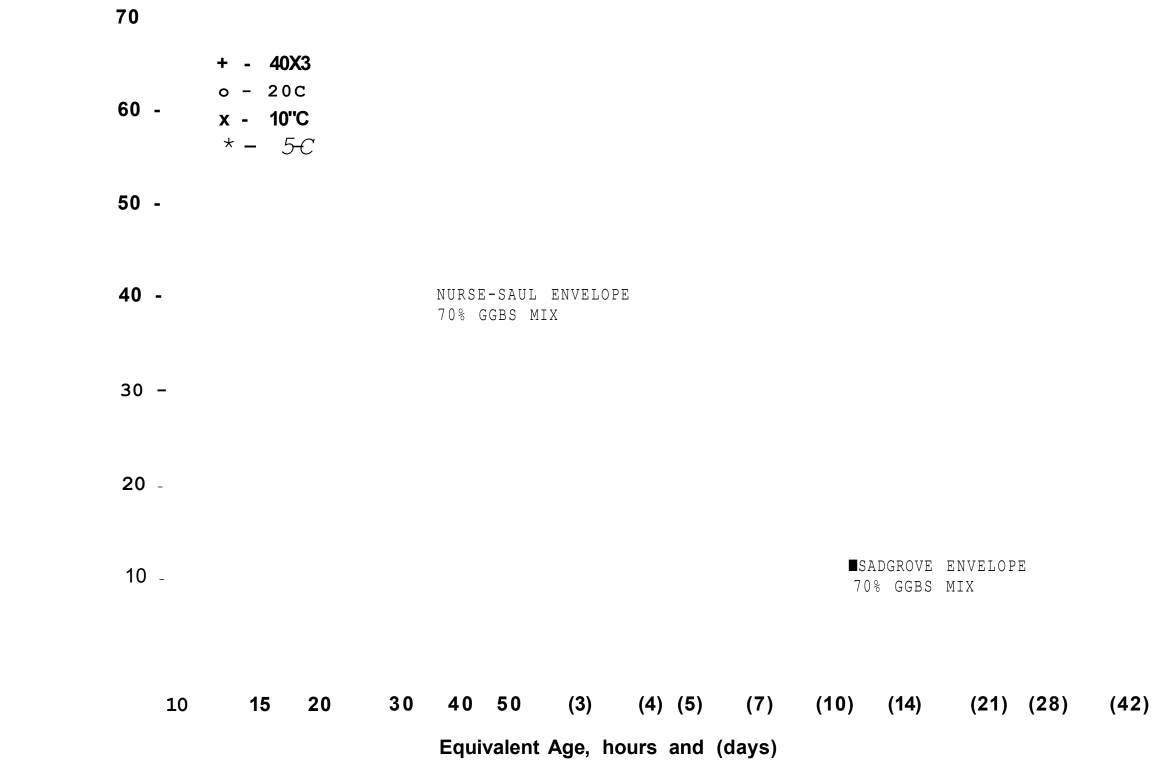


Fig 8.3.3.k : Typical relationships between compressive strength and equivalent age (logscale) for OPC and GGBS concretes.

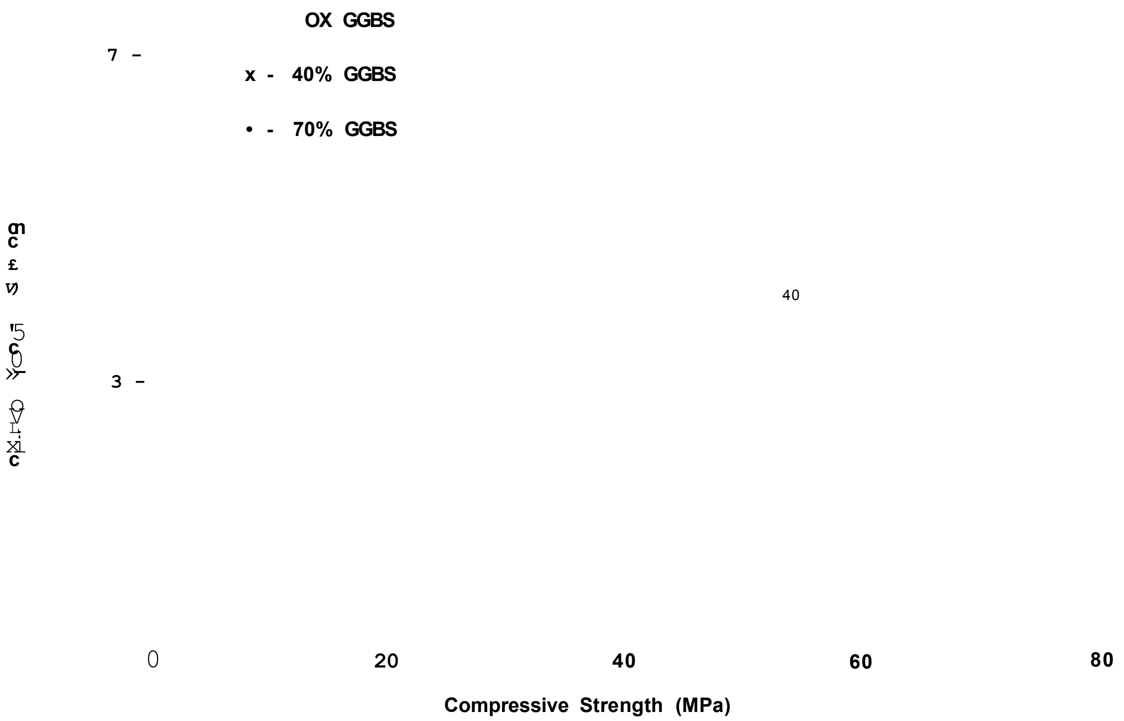
Tab 8.3.3 : Coefficients from the regression analysis of Compressive Strength and Equivalent Age.

[illegible]

Indirect Tensile Strength

Figs	8.3.^.a-d	relationship with compressive strength
Tab	8.3.^	relationship with compressive strength

(supplementary results included).



(i) 40°C wet curing

(ii) 20°C wet curing

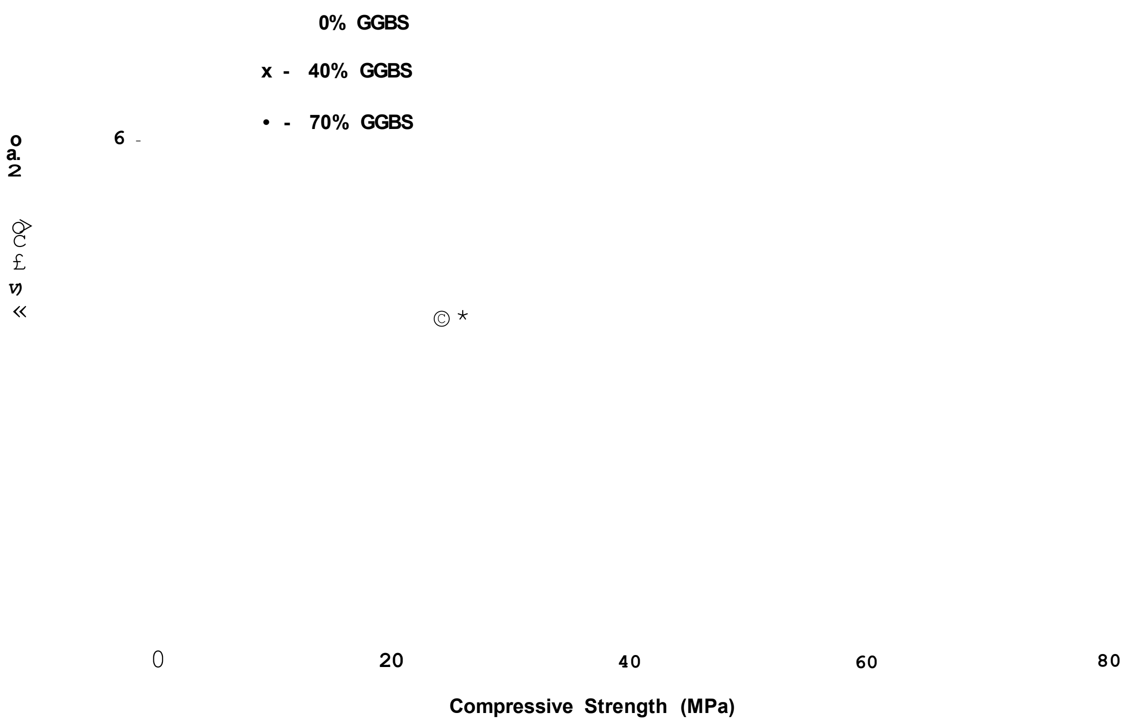
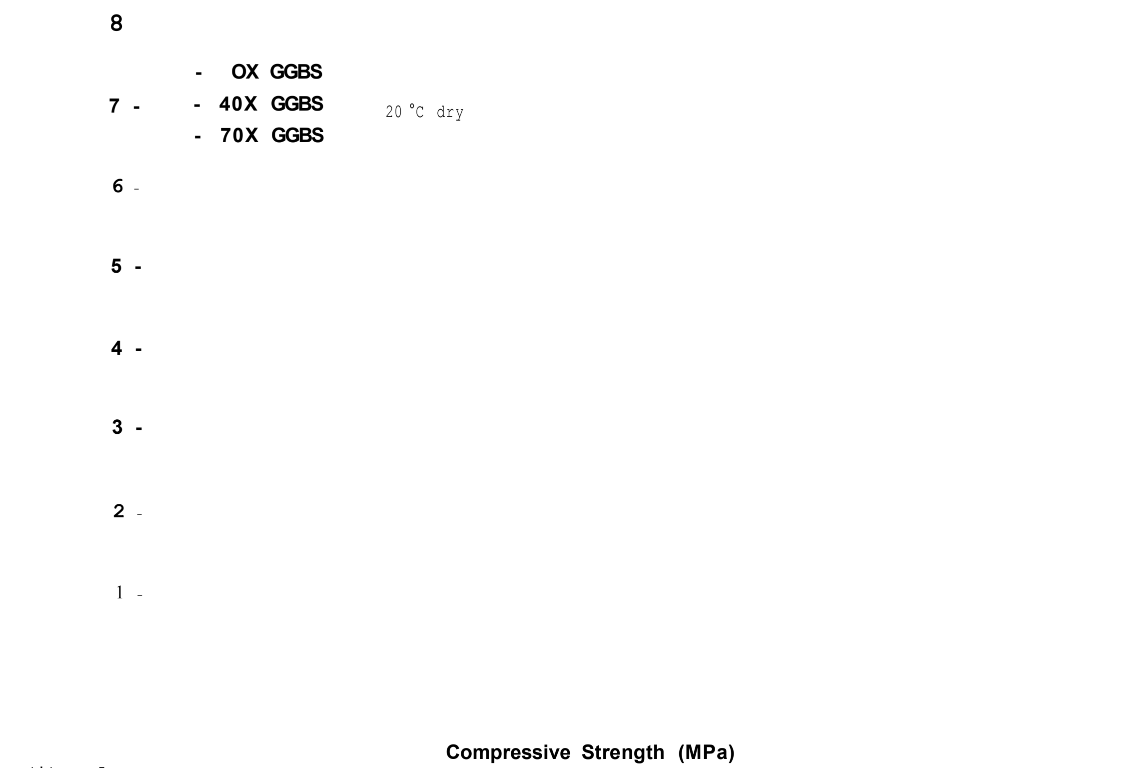


Fig 8.3.*1.b Indirect tensile strength, in flexure and splitting, against compressive strength at medium curing temperatures.



(i) Flexure

(ii) Splitting

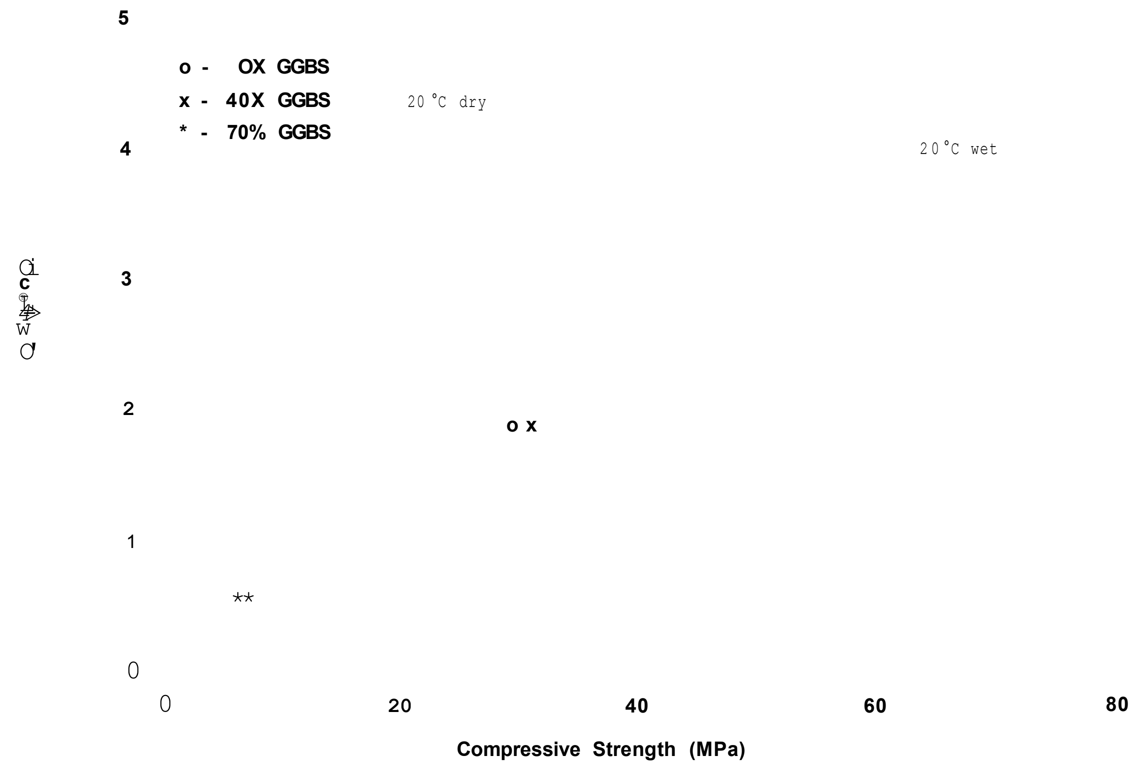
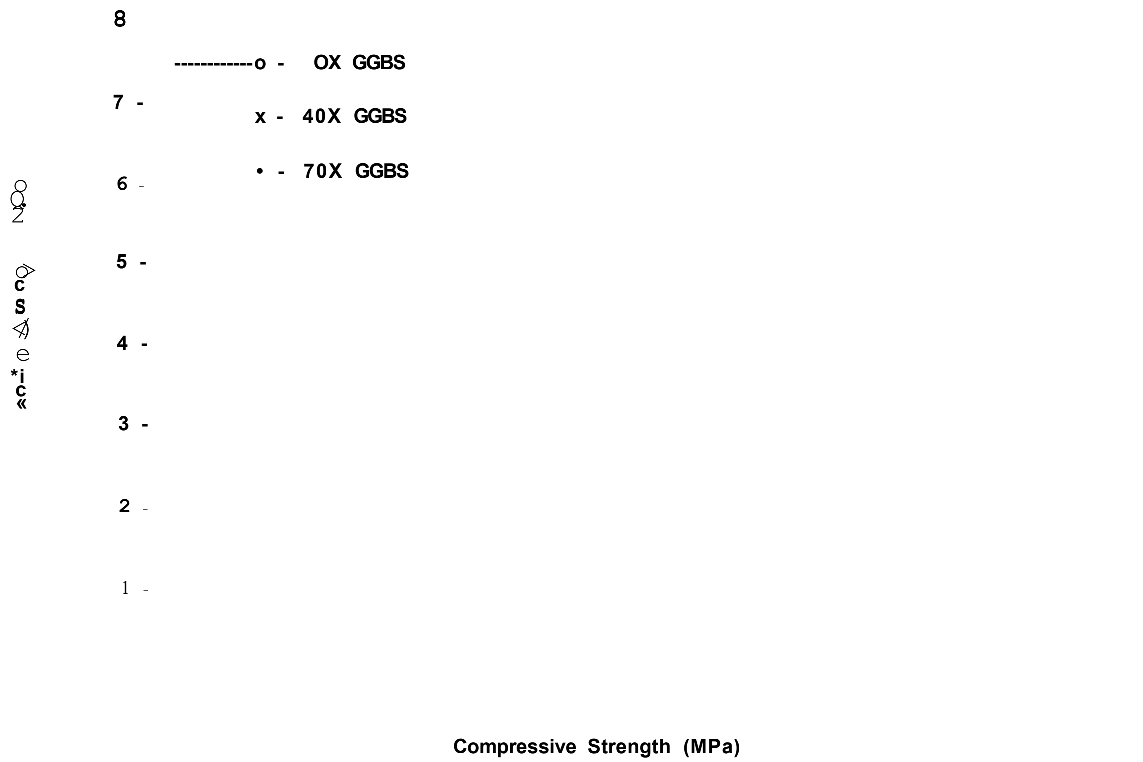


Fig 8.3.^.0 : Indirect tensile strength, in flexure and splitting, against compressive strength at different curing humidities.



(i) 10°C wet curing

(ii) 5 C wet curing

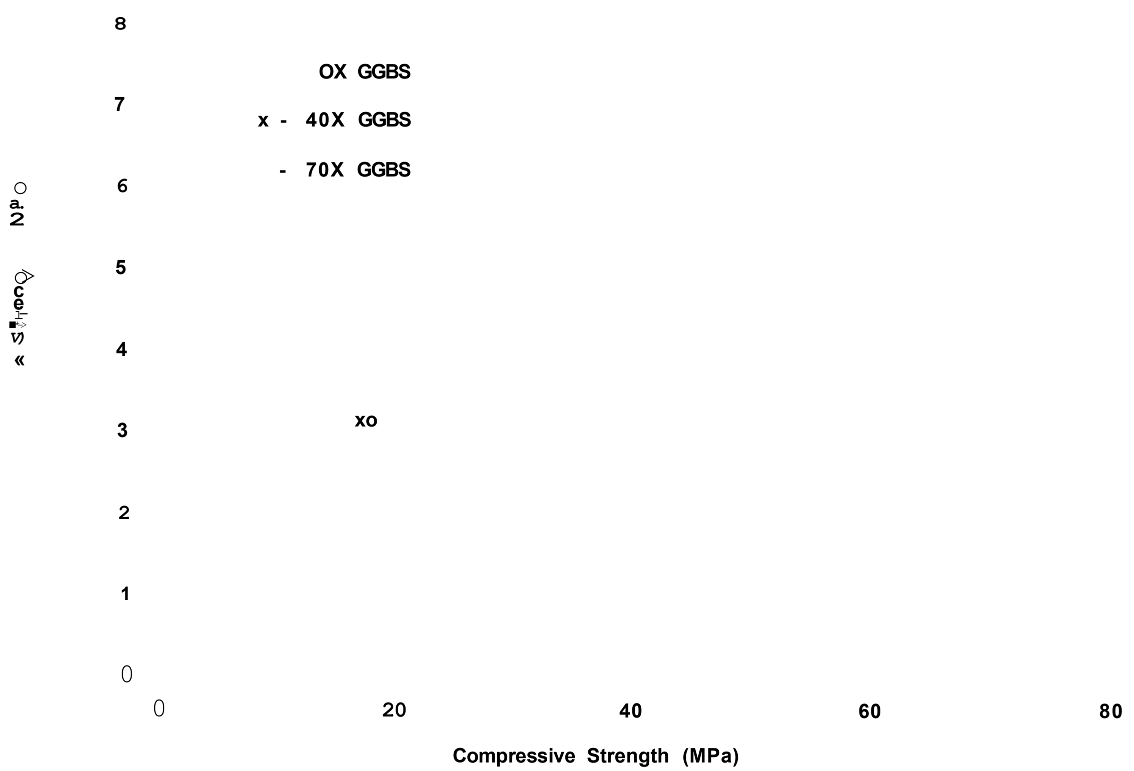


Fig 8.3.4.d : Indirect tensile strength, in flexure and splitting, against compressive strength at low curing temperatures.

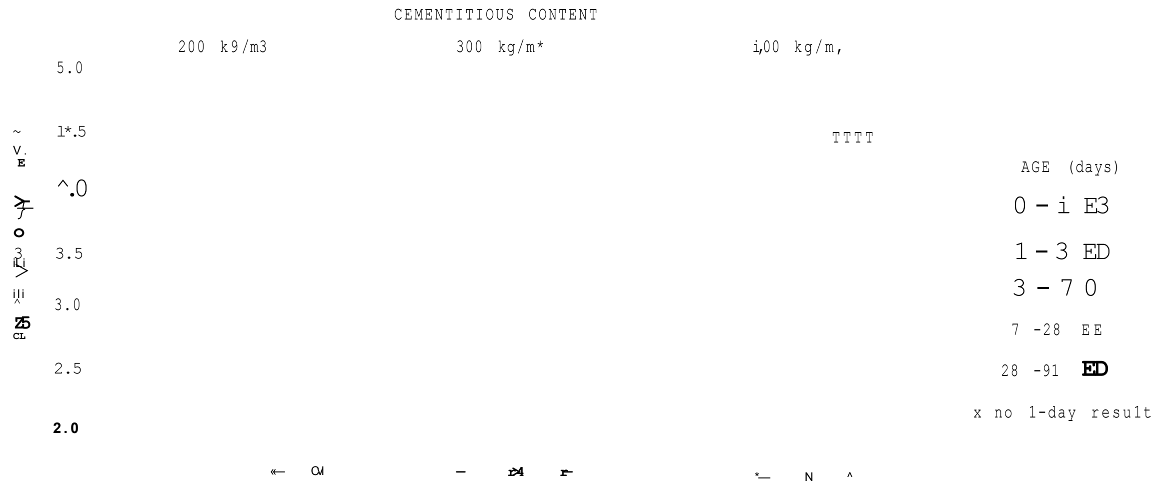
Tab 8.3.4 : Coefficients in the regression analysis of Compressive Strength and Indirect Tensile Strength.

Relationship	se	a	b	r	df	Note
y = Splitting Strength (MPa) x = Compressive Strength (MPa)						
		0.395	0.882	0.971	28	40°C wet
Power		0.543	0.821	0.982	28	20°C wet
y = axb		0.143	1.101	0.947	28	20°C dry
		0.629	0.921	0.976	28	10°C wet
		0.242	0.964	0.982	28	5°C wet
		0. 377	0.892	0.980	118	wet
y = Flexural Strength (MPa) x = Compressive Strength (MPa)						
		0.113	0.681	0.965	28	40°C wet
Power		0.142	0.594	0.912	28	20°C wet
y = axb		0.052	0.863	0.942	28	20°C dry
		0.109	0.553	0.960	28	10°C wet
		0. 094	0.822	0.898	28	5°C wet
		0.114	0.693	0.926	118	wet

Note:- The compressive strength was assumed to be the dependent variable when regressing.

8.3.5 Ultrasonic Pulse Velocity

Fig	8.3.5.a	development with age
Figs	8.3«5.b-e	relationship with compressive strength
Tab	8.3*5	relationship with compressive strength



(i) 10°C wet curing

(ii) 5°C wet curing

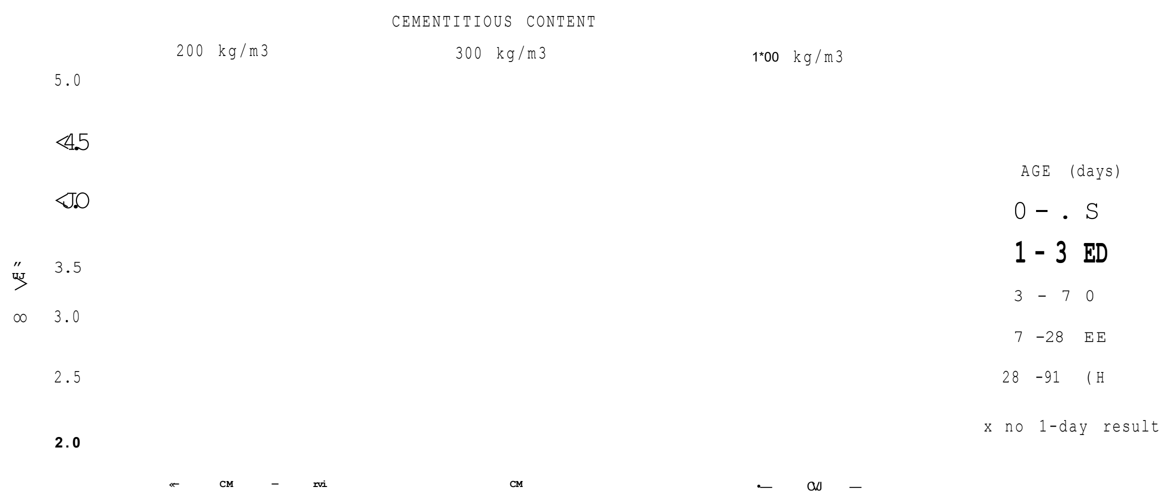


Fig 8.3.5.a : Development of ultrasonic pulse velocity at low curing temperatures.

100
80

OX GGBS
40% GGBS
70% GGBS

50
40
30
20
10

K'M1/

90% CONFIDENCE INTERVAL ON OBSERVATIONS

2.0 2.4 2.8 3.2 3.6 4.0 4.4 4.8

Ultrasonic Pulse Velocity (km/s)

(i) 40°C wet curing

(ii) 20°C wet curing

100
80

- 0% GGBS
- 40% GGBS
- 70% GGBS

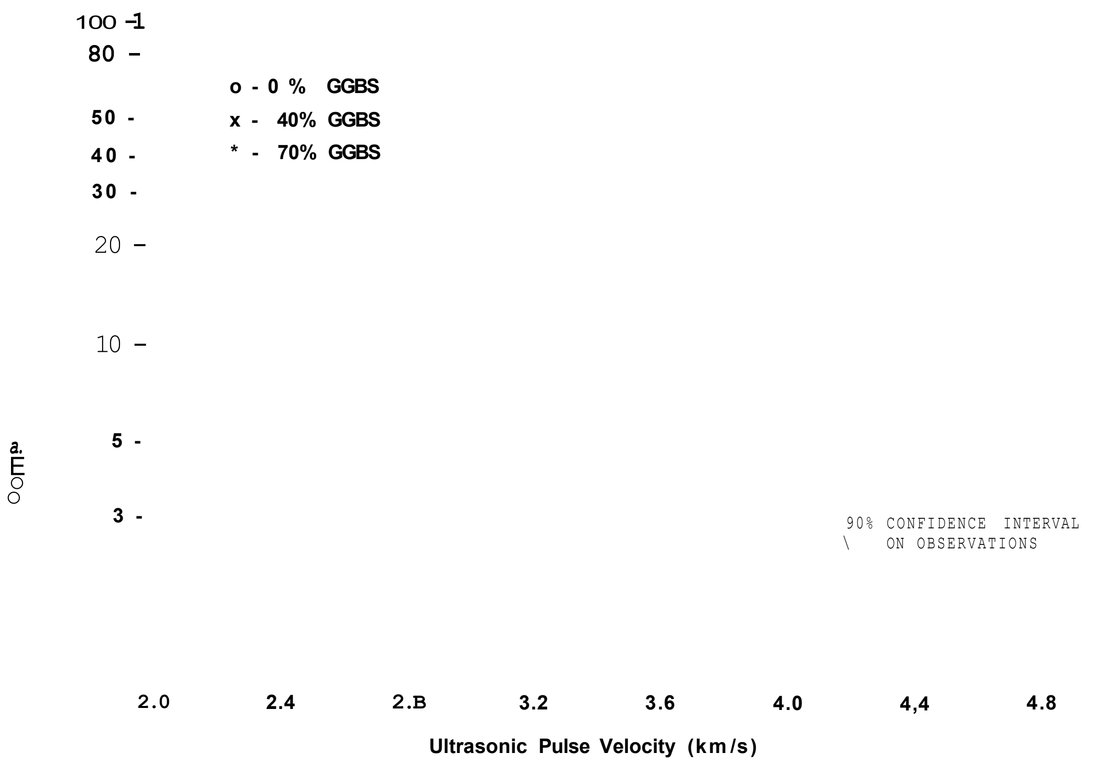
50
40
30
20
10

90% CONFIDENCE INTERVAL ON OBSERVATIONS

2.0 2.4 2.8 3.2 3.6 4.0 4.4 4.8

Ultrasonic Pulse Velocity (km/s)

Fig 8.3.5.b : Compressive strength (logscale) against pulse velocity at medium curing temperatures.



(i) 20°C wet curing

(ii) 20 C dry curing

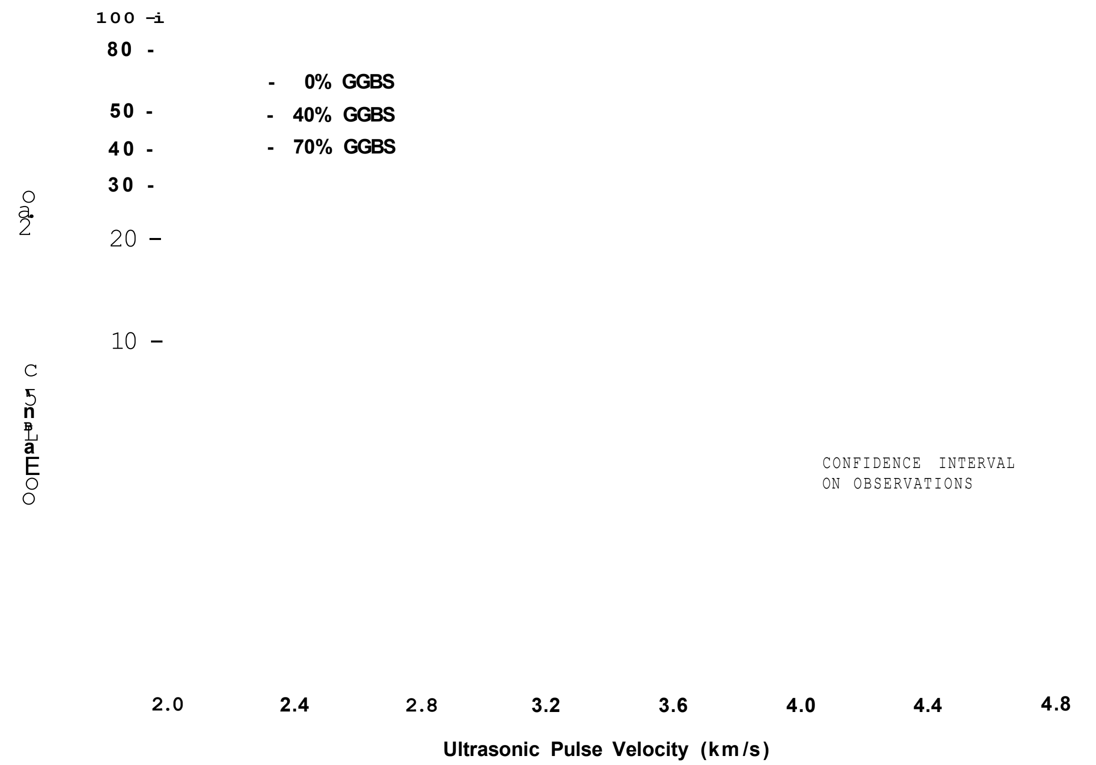
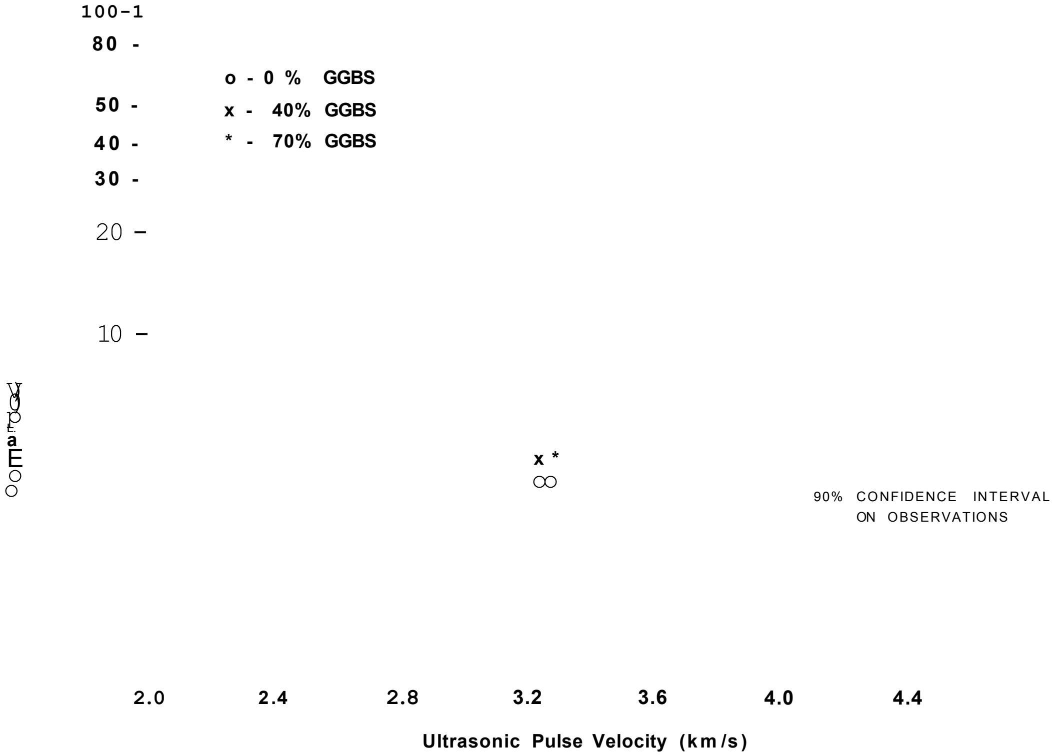


Fig 8.3.5.C : Compressive strength (logscale) against pulse velocity at different curing humidities.



(i) 10°C wet curing

(ii) 5°C wet curing

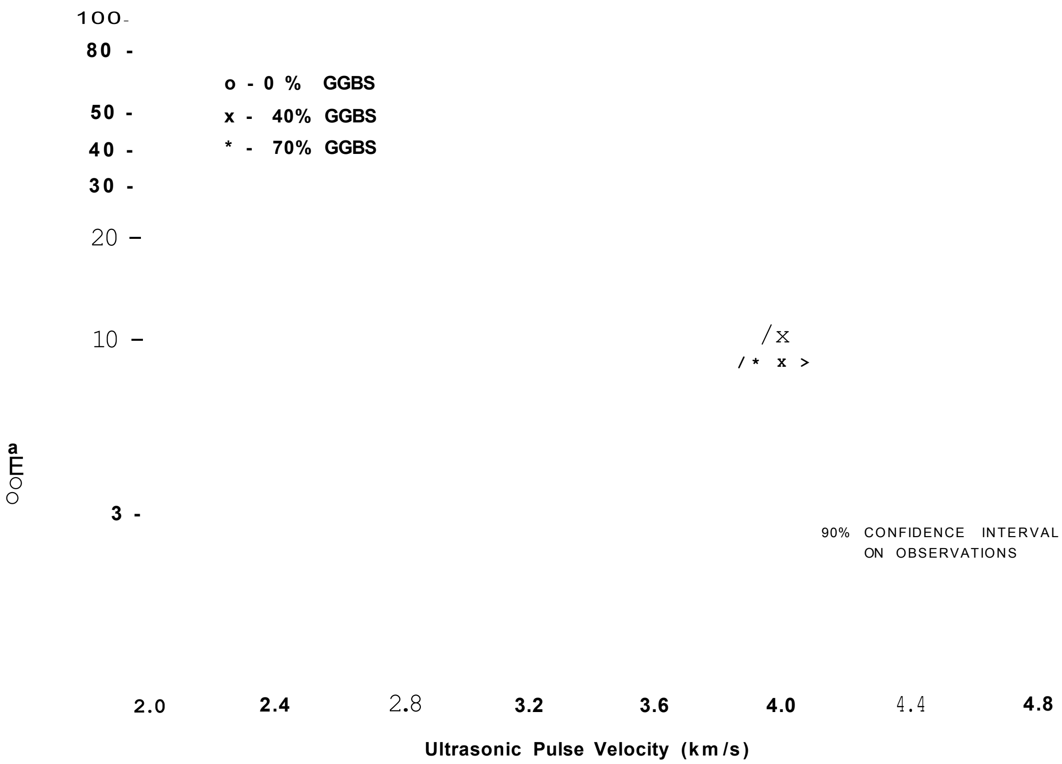


Fig >.3-5-d : Compressive strength (logscale) against pulse velocity at low curing temperatures.

Tab 8.3.6 : Coefficients from the regression analysis of Strength and Ultrasonic Pulse Velocity.

Relationship	se	a	b,c	r	df	Note
y = Compressive Strength (MPa) x = Pulse Velocity (km/s)						
		(Upper portion, UFV > 3.5 km/s)				
		2.30	2.09	0.961	144	40*C wet
		0.87	2.31	0.985	128	20"C wet
		13.64	1.76	0.964	103	20*C dry
		1.17	2.24	0.977	103	10*C wet
		0.85	2.29	0.969	98	5°C wet
		(Lower portion, UPV < 3.5 km/s)				
		0.266	0.78	0.995	2	40'C wet
Exponential		0.151	0.92	0.887	9	20-C wet
y = aebx		0.041	1.45	0.931	36	20*C dry
		0.102	1.02	0.872	30	10"C wet
		0.181	0.75	0.754	22	5*C wet
		(OPC Control Mixes, upper portion)				
		1.14	2.25	0.991	28	40°C wet
		1.54	2.18	0.975	28	20®C wet
		22.45	1.63	0.981	28	20-C dry
		2.77	2.04	0.974	24	10'C wet
		1.12	2.23	0.982	22	5°C wet
		(Slag Mixes, upper portion*)				
		0.79	2.34	0.983	98	40 °C wet
		2.45	2.08	0.958	114	20'C wet
		22.93	1.63	0.980	111	20*C dry
		0.81	2.33	0.979	77	10°C wet
		0.75	2.32	0.963	74	5*C wet
y = Splitting Strength (MPa) x - Pulse Velocity (km/6)						
Linear	0.42	4.24	-16.66	0.913	118	wet
y r ax + c	0.26	1.77	-5.79	0.930	28	dry
y = Flexural Strength (MPa) x = Pulse Velocity (km/s)						
Linear	0.67	7.35	-29.37	0.847	118	wet
y = ax + c	o.28	1.86	-5.53	0.942	28	dry

* Includes the lower portion results for 20'C dry curing.
Note:- Coefficient a multiplied by 1000 for the upper portion.

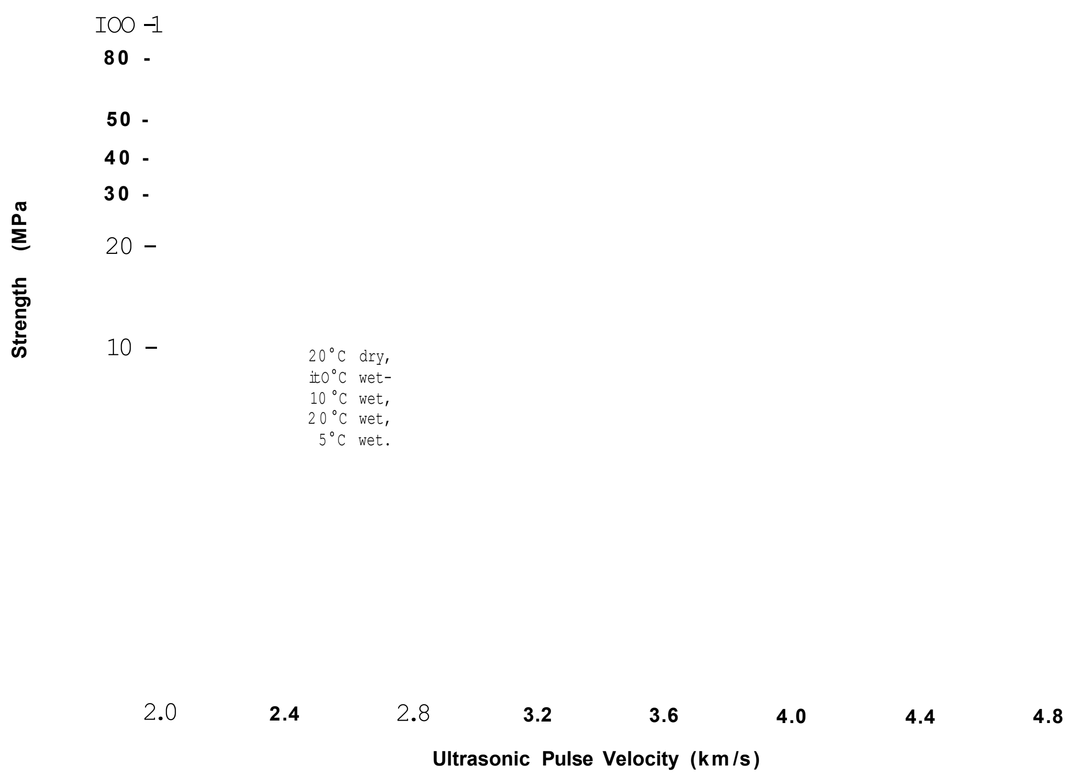


Fig 8.3.5.e : Compressive strength (logscale) against pulse velocity showing the regression relationships (upper portion).

8.3.6 Dynamic Elastic Modulus

Figs	8.3.6.a-c	development with age
Figs	8.3.6.d-g	relationship with compressive strength
Figs	8.3*6.h-i	relationship with stiffness constant
Tab	8.3.6.a	relationship with compressive strength
Tab	8.3*6.b	relationship with stiffness constant

CEMENTITIOUS CONTENT

200 kg/m3 300 kg/m3 ^00 kg/m3

AGE (days)

0 - 1

1 - 3

3 - 7

7 - 28

28 - 91

(i) 40°C wet curing

(ii) 20°C wet curing

CEMENTITIOUS CONTENT

AGE (days)

0 - 1

1 - 3

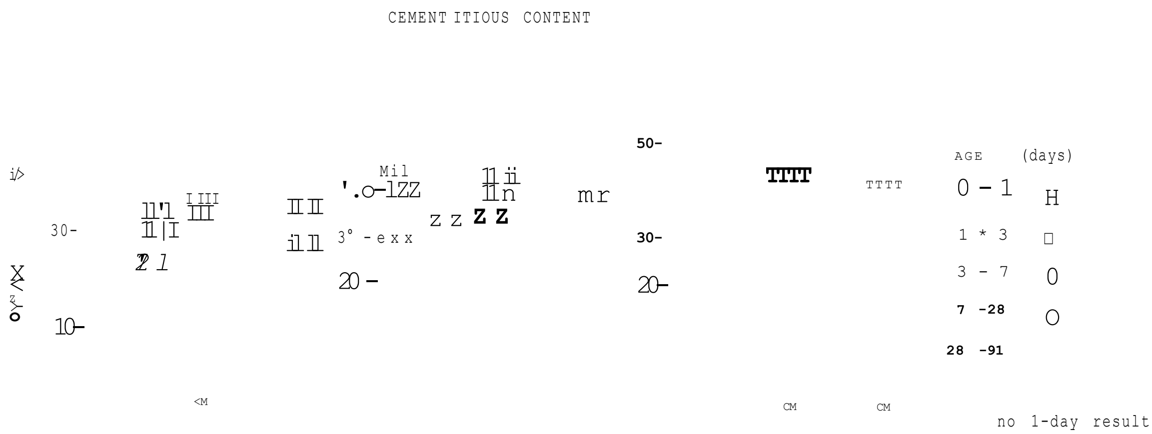
3 - 7

7 - 28

28 - 91

x no 1-day result

Fig 8.3*6.a : Development of dynamic elastic modulus at medium curing temperatures.



(i) 20°C wet curing

(ii) 20°C dry curing

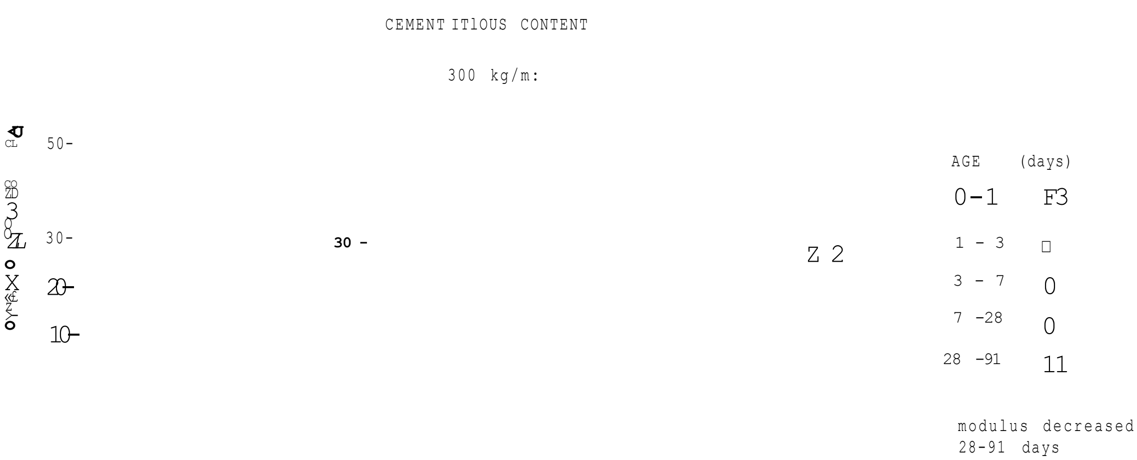


Fig 8.3.6.b : Development of dynamic elastic modulus at different curing humdities.

CEMENTITIOUS CONTENT

50-

30 -

20*

10-

AGE (days)

0 - 1

1 - 3

3 - 7

7 -28

28 -91

x no 1-day result

(i) 10°C wet curing

(ii) 5°C wet curing

CEMENTITIOUS CONTENT

200 kg/m3

300 kg/m3

1*00 kg/m3

60.

50-

Ao-

30-

20-

10-

0-

AGE (days)

0 - 1

1 - 3

3 - 7

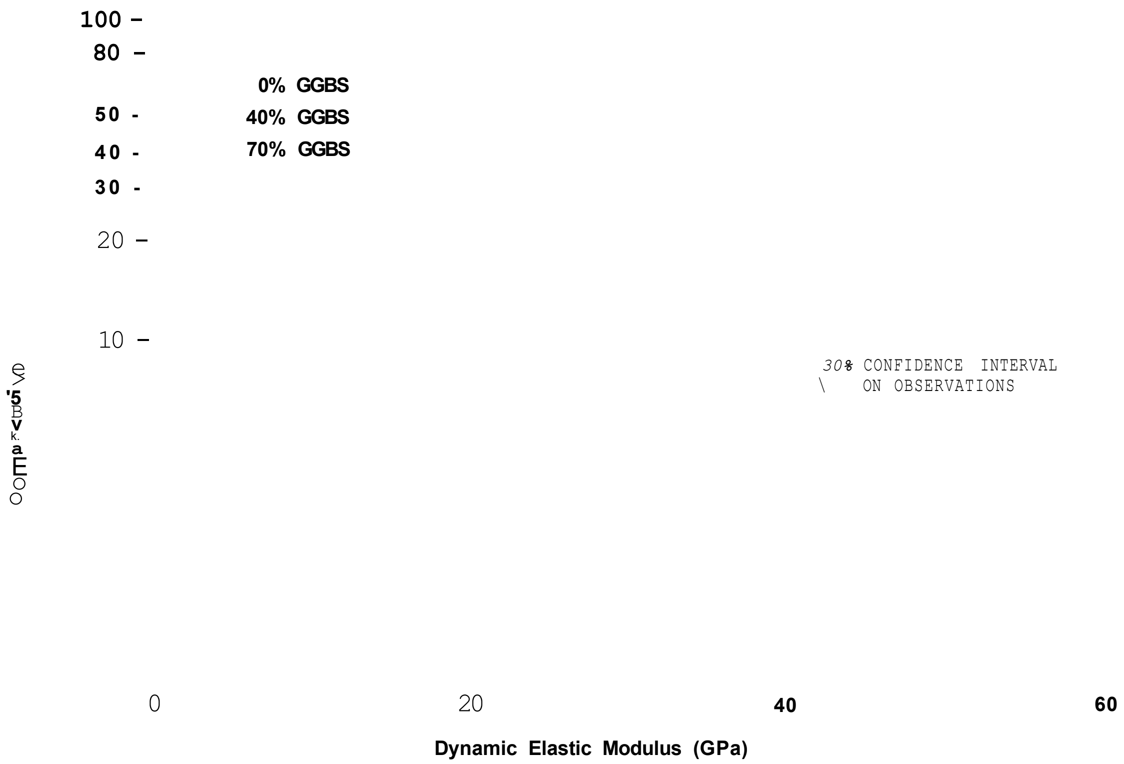
7 -28

28 -91

x no 1-day result

* no 3"day result

Fig 8.3.6.C : Development of dynamic elastic modulus at low curing temperatures.



(i) 40°C wet curing

(ii) 20°C wet curing

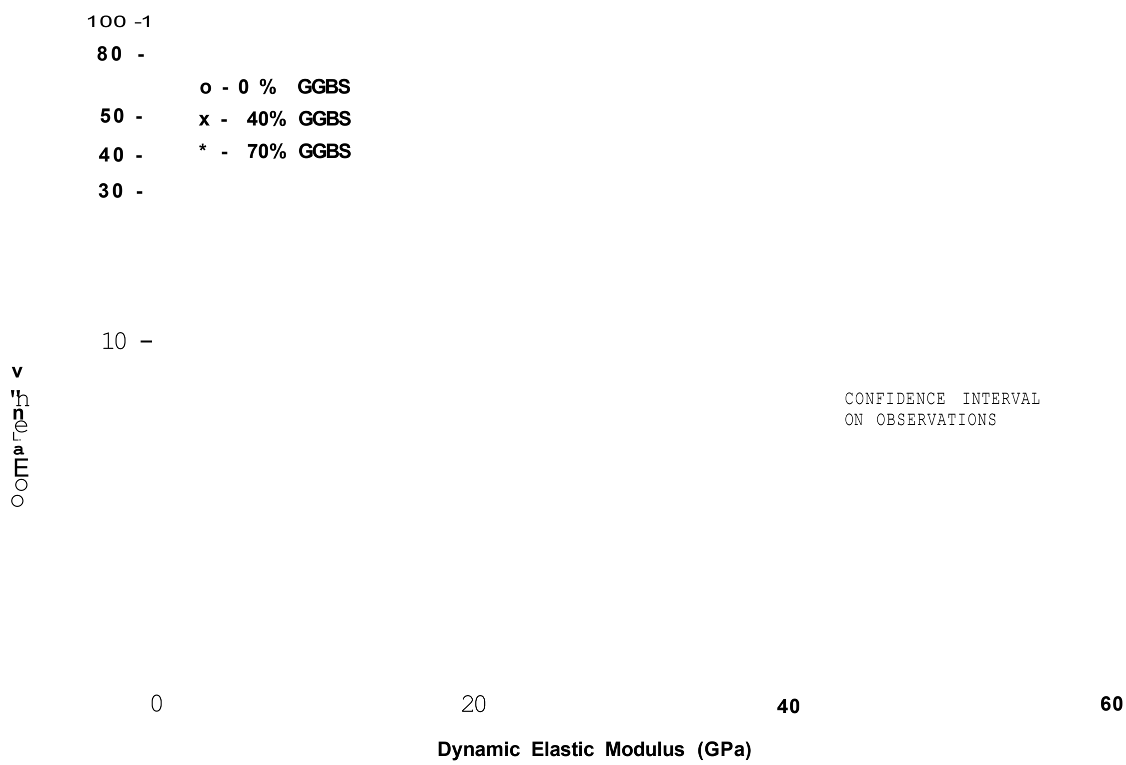
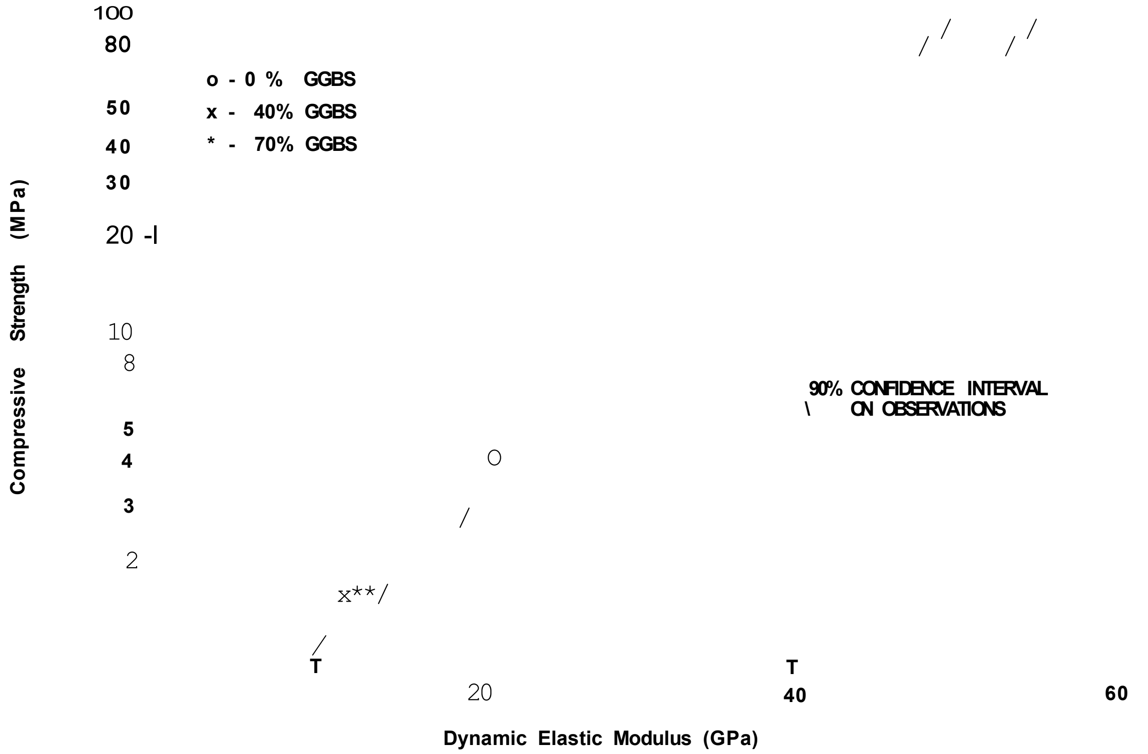


Fig 8.3*6.d : Compressive strength (logscale) against dynamic elastic modulus at medium curing temperatures.



(i) 20°C wet curing

(ii) 20°C dry curing

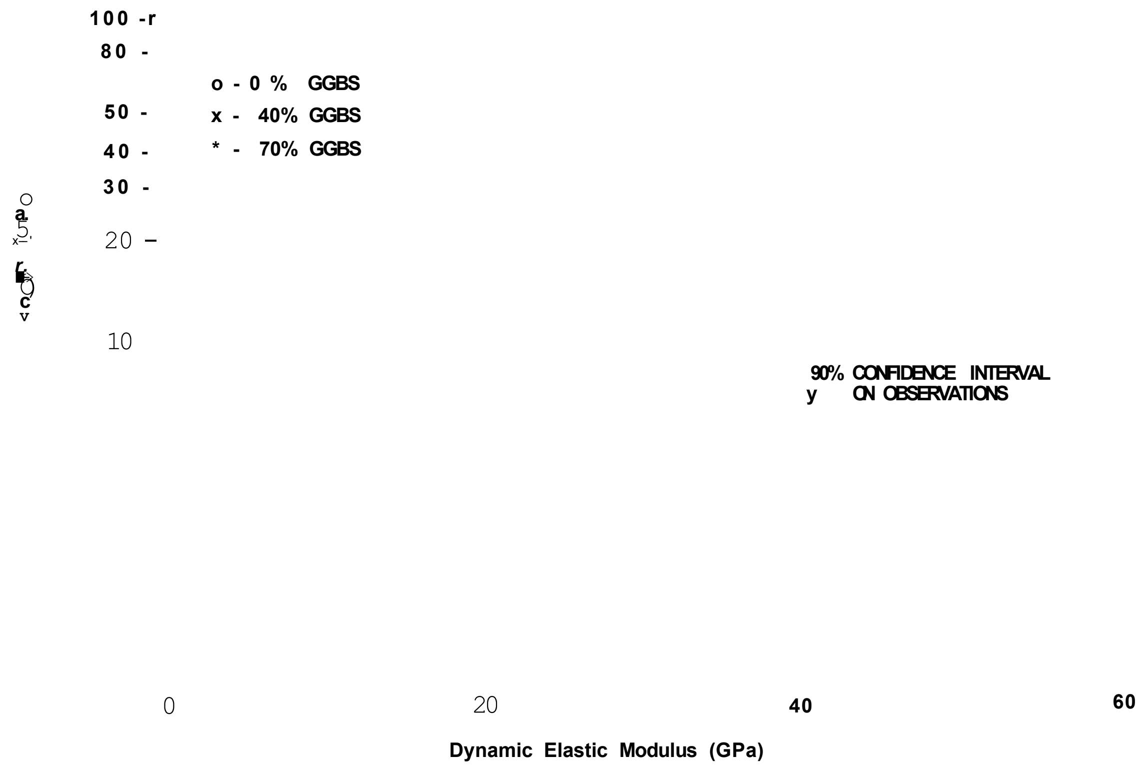
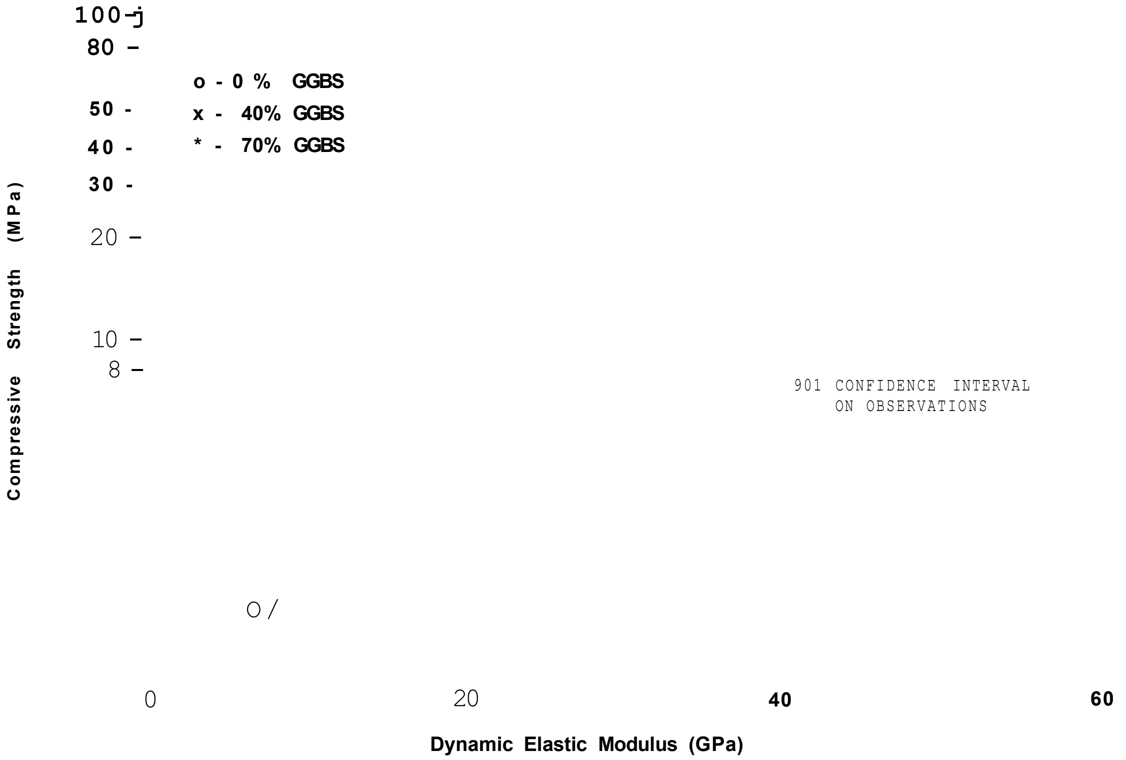


Fig 8.3.6.e : Compressive strength (logscale) against dynamic elastic modulus at different curing humidities.



i) 10°C wet curing

ii) 5 C wet curing

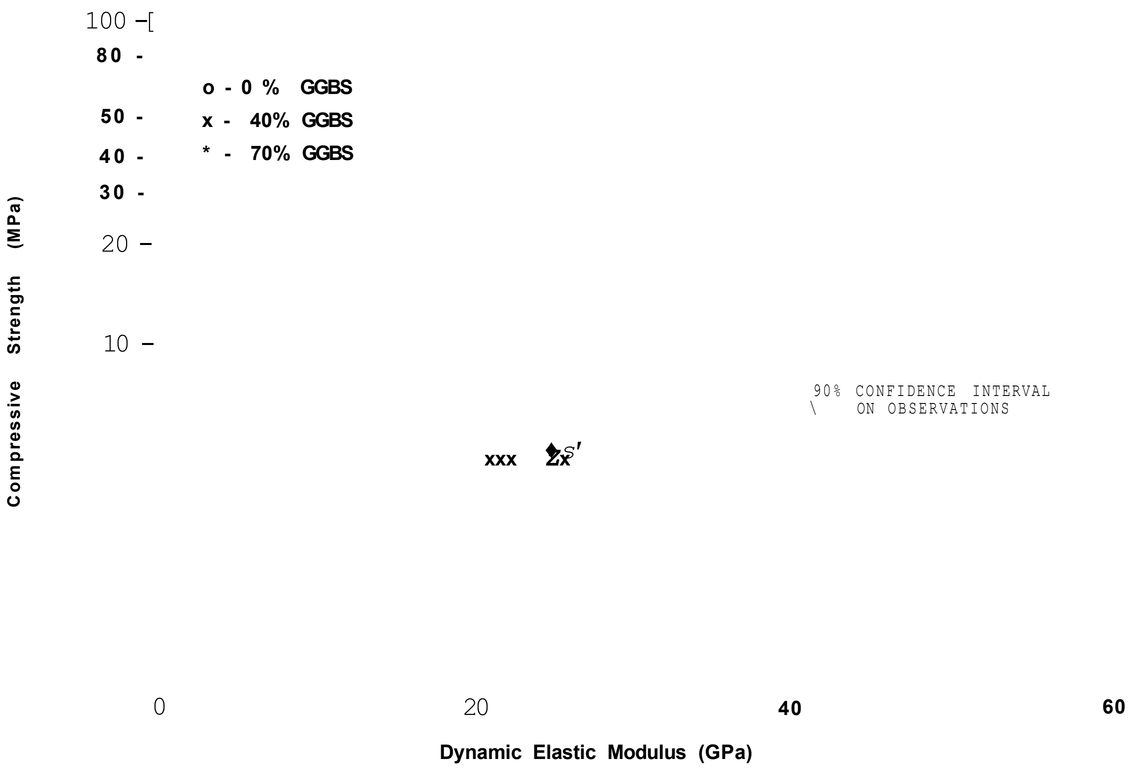


Fig 8.3.6.f : Compressive strength (logscale) against dynamic elastic modulus at low curing temperatures.

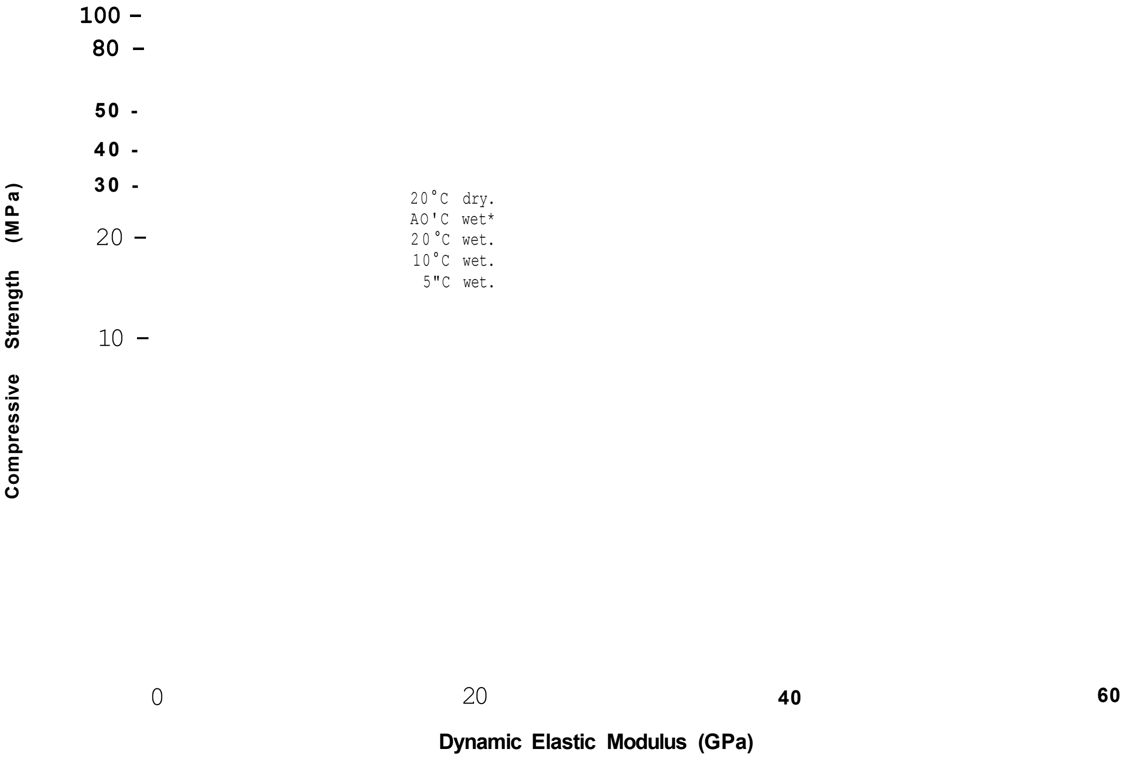
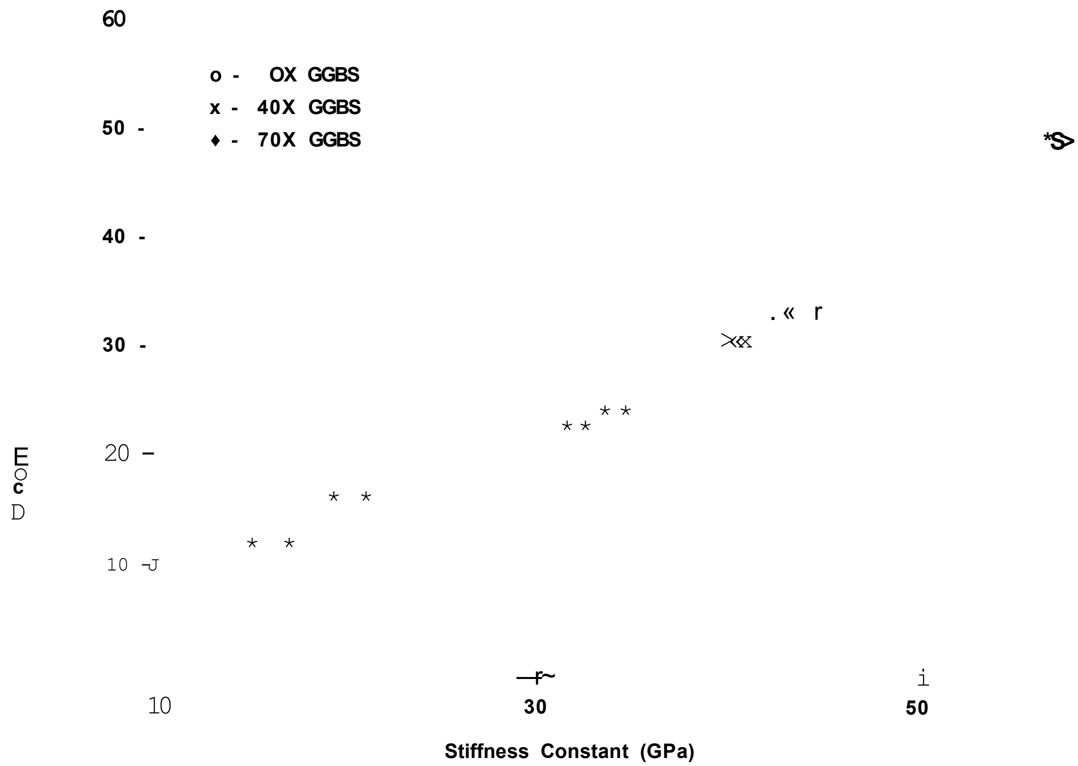


Fig 8.3.6.g : Compressive strength (logscale) against dynamic elastic modulus showing the regression relationships.



(i) 20°C wet curing

(ii) 20°C dry curing

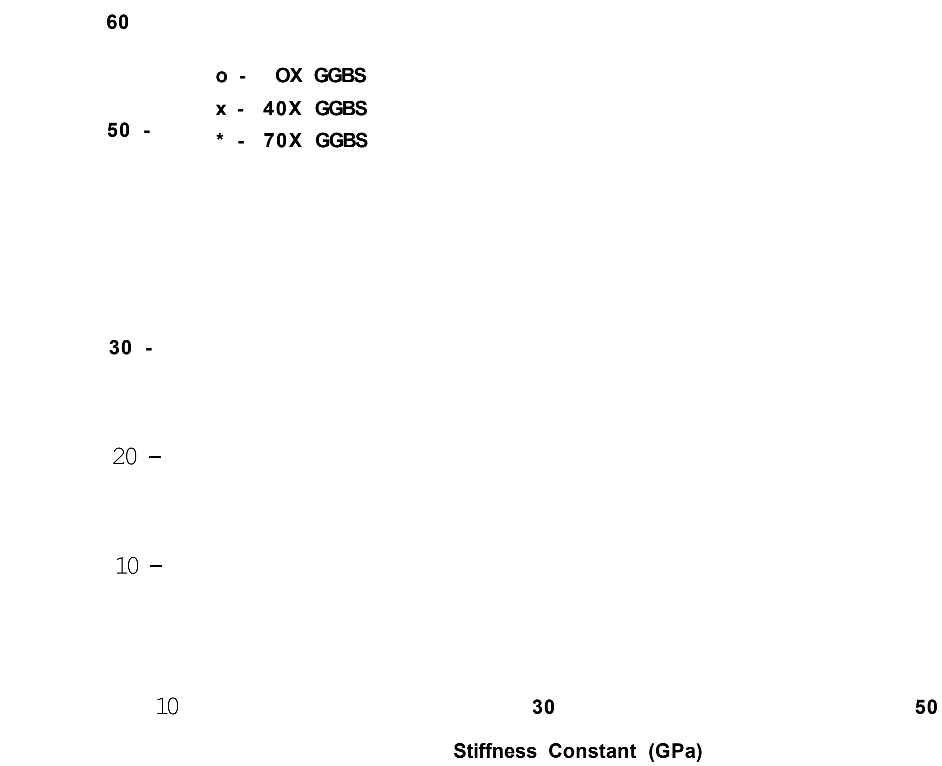


Fig 8.3*6.h : Dynamic elastic modulus against the stiffness constant at different curing humidities.

70

60

50

40

30

D
c
Q 20

10

0

Stiffness Constant (GPa)

(i) Linear portion

(ii) Power relationship and Poisson's ratio

70

60 -

50

40 -

30 -

DRY

20 –

10 – WET

o 20 40 60

Stiffness Constant (GPa)

Fig 8.3.6.i : Dynamic modulus against stiffness constant, showing the regression relationships.

Tab 8.3-6.a : Coefficients from the regression analysis of Strength and Dynamic Elastic Modulus.

Relationship	se	a	b,c	r	df	Note
y = Compressive Strength (MPa) x = Dynamic Modulus (GPa)						
	8.2	1.76	-38.7	0.874	148	40°C wet
Linear	9.3	1.66	-33.2	0.880	142	20°C wet
$y = ax + c$	4.1	1.13	-17.7	0.922	146	20°C dry
	8.1	1.32	-23.0	0.877	132	10°C wet
	8.7	1.16	-18.7	0.844	121	5°C wet
(All Mixes)						
		0.762	0.089	0.976	148	40°C wet
Exponential		0.524	0.099	0.991	142	20°C wet
$y = ae^{bx}$		0.509	0.106	0.964	146	20°C dry
		0.516	0.098	0.989	132	10°C wet
		0.542	0.095	0.987	121	5°C wet
(OPC Control Mixes)						
		0.632	0.094	0.983	28	40°C wet
		0.513	0.099	0.993	28	20°C wet
		0.895	0.088	0.981	28	20°C dry
		0.724	0.089	0.992	27	10°C wet
		0.608	0.092	0.993	25	5°C wet

Tab 8.3.6.b : Coefficients from the regression analysis of Dynamic Elastic Modulus and Stiffness Constant.

Relationship	se	a	b,c	r	df	Note
y = Dynamic Modulus (GPa) x = Stiffness Constant (GPa) (upper linear portion, Stiffness Constant > 20 GPa)						
	0.86	1.09	-12.8	0.994	146	40°C wet
Linear	0.78	1.05	-11.2	0.996	134	20°C wet
$y = ax + c$	0.72	0.91	-2.6	0.996	141	20°C dry
	1.17	0.99	-8.1	0.994	131	10°C wet
	1.47	1.04	-10.8	0.992	120	5°C wet
(all results)						
	1.30	1.02	-9.5	0.992	544	wet
Power $y = ax^b$		0.219	1.34	0.984	544	wet

8.3*7 Water Absorption

Fig	8.3*7*a	summary of the data
Fig	8.3* 7*b	relationship with compressive strength
Fig	8.3.7-c	relationship with BS absorption
Tab	8.3*7	regression relationships

CURING CONDITIONS

(SziD/iw) uoiqdjosqv jsiefl

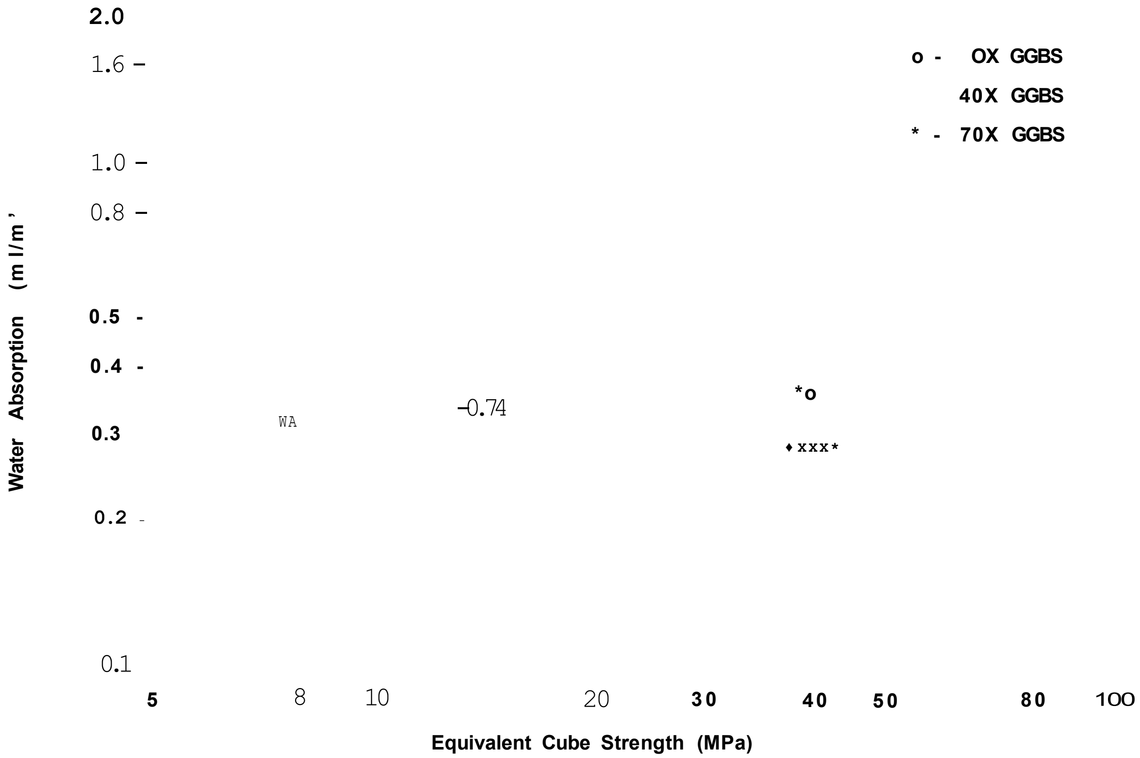


Fig 8.3.7.b : Water absorption (logscale) against equivalent cube strength, showing regression relationship.

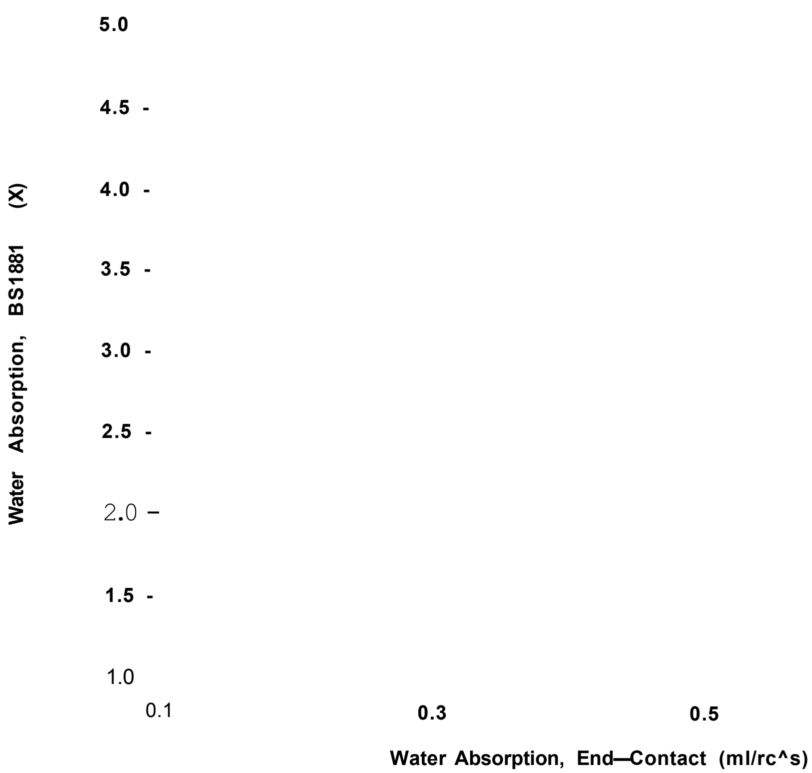


Fig 8.3*7.c : A comparison of BS 1881 water absorption under full immersion and water absorption under end-contact.

Tab 8.3*7 : Coefficients from the regression analysis of the water absorption data.

Relationship	se	a	b,c	r	df	Note
y = Water Absorption (ml/m2s)				**x = Equivalent Cube Strength (MPa)**		
Power		2.35	-0.577	0.868	28	40°C wet
y = axb		4.46	-0.709	0.911	28	20°C wet
		6.93	-0.815	0.943	27	20°C dry
		2.04	-0.516	0.858	26	10°C wet
		1.51	-0.435	0.831	27	5°C wet
		4.65	-0.735	0.905	144	All Regimes
y = BS 1881 Water Absorption under immersion (%)				**x = Absorption under end-contact (ml/m2s)**		
Linear y = ax + c	0.29	4.49	0.835	0.939	19	

Results from the Secondary Study

Figs 8.4.a-b	workability assessment
Figs 8.4.c-e	pulse velocity profiles
Figs 8.4.f-g	compressive strength
Fig 8.4.h	relationship between strength and slump
Figs 8.4.i-k	static modulus
Tab 8.M	regression relationships

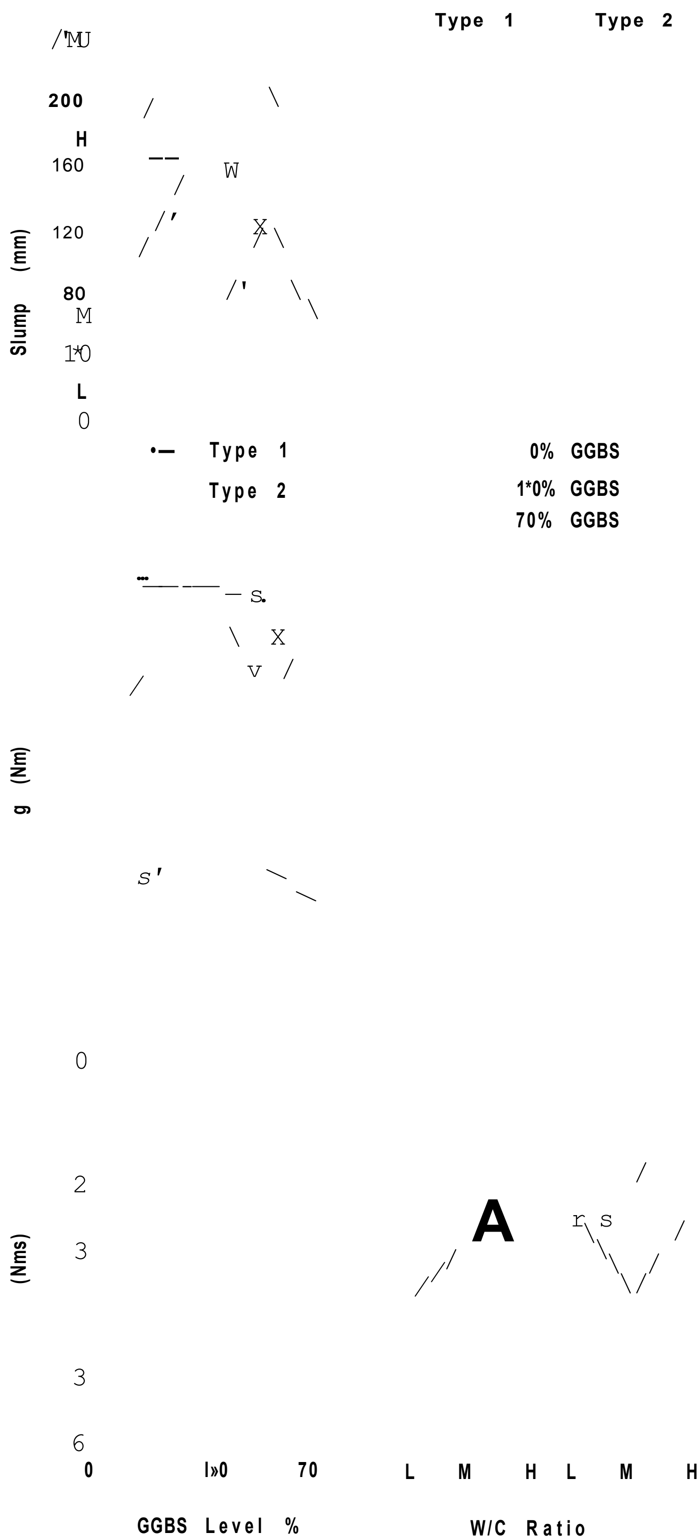


Fig 8.4.a : Workability assessment on normalised scales against GGBS level and W/C ratio (L=0.50, M=0.55, H=0.60) for the 300 kg/m^3 cementitious content mixes.

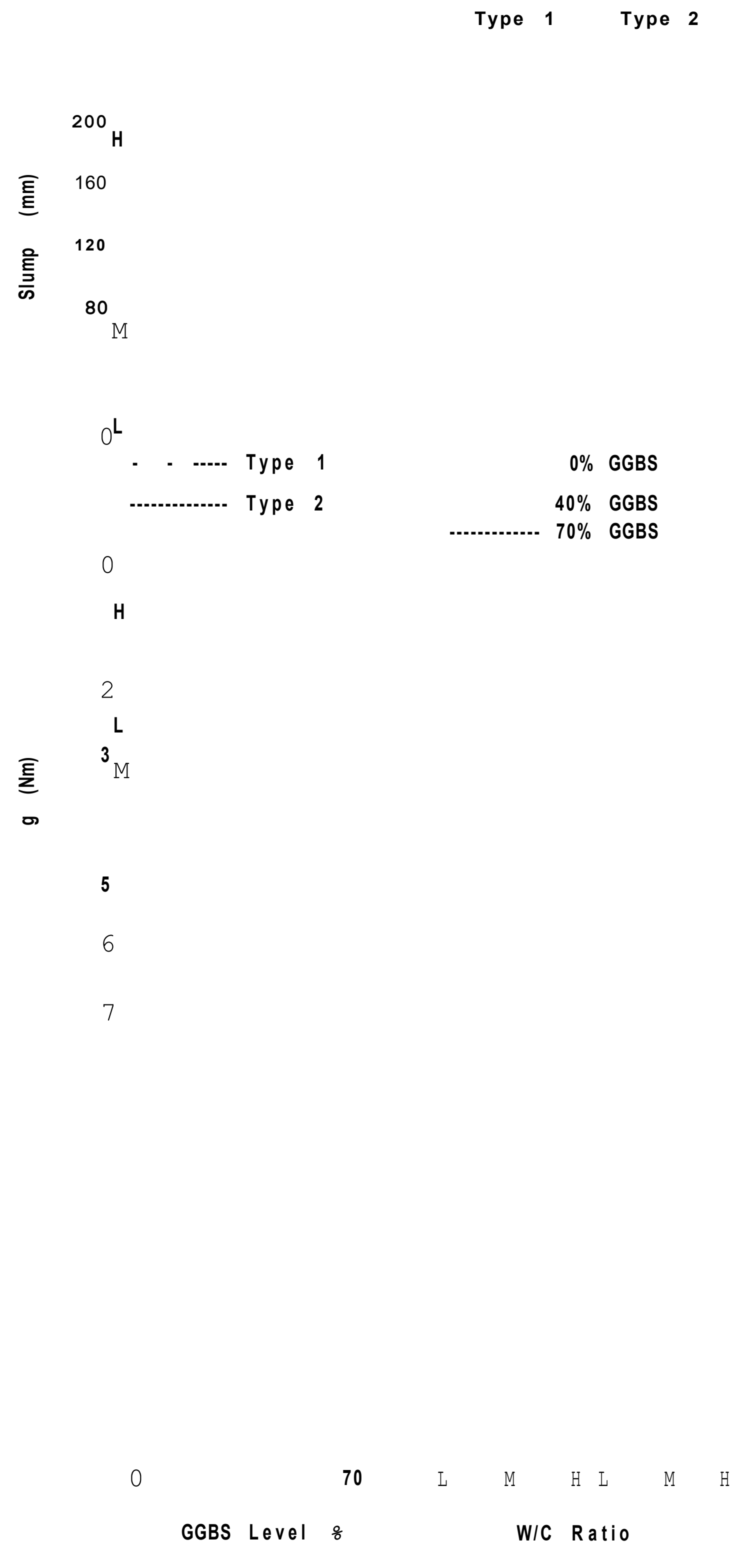


Fig 8.4.b : Workability assessment on normalised scales against GGBS level and W/C ratio (L=0.36, M=0.4l, H=0.46) for the 400 kg/m" cementitious content mixes.

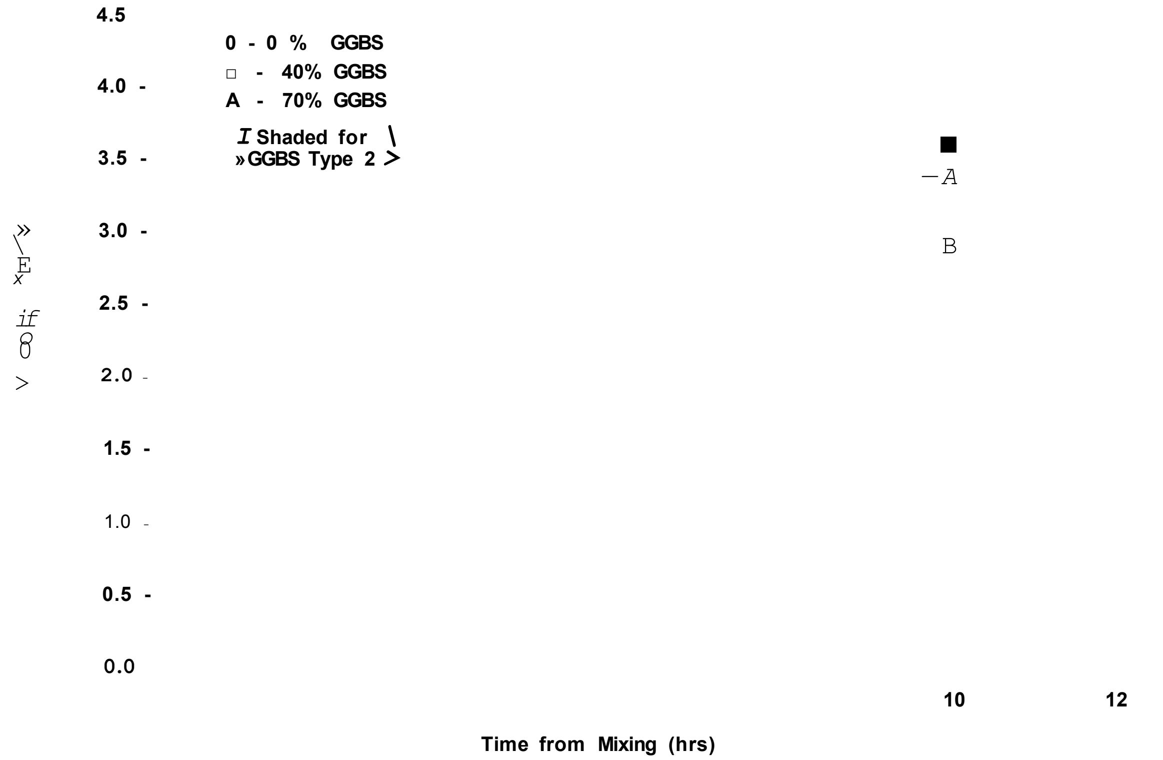


Fig 8.4.c Profiles of pulse velocity at very early ages against time for the 300 kg/m^ cementitious content mixes.

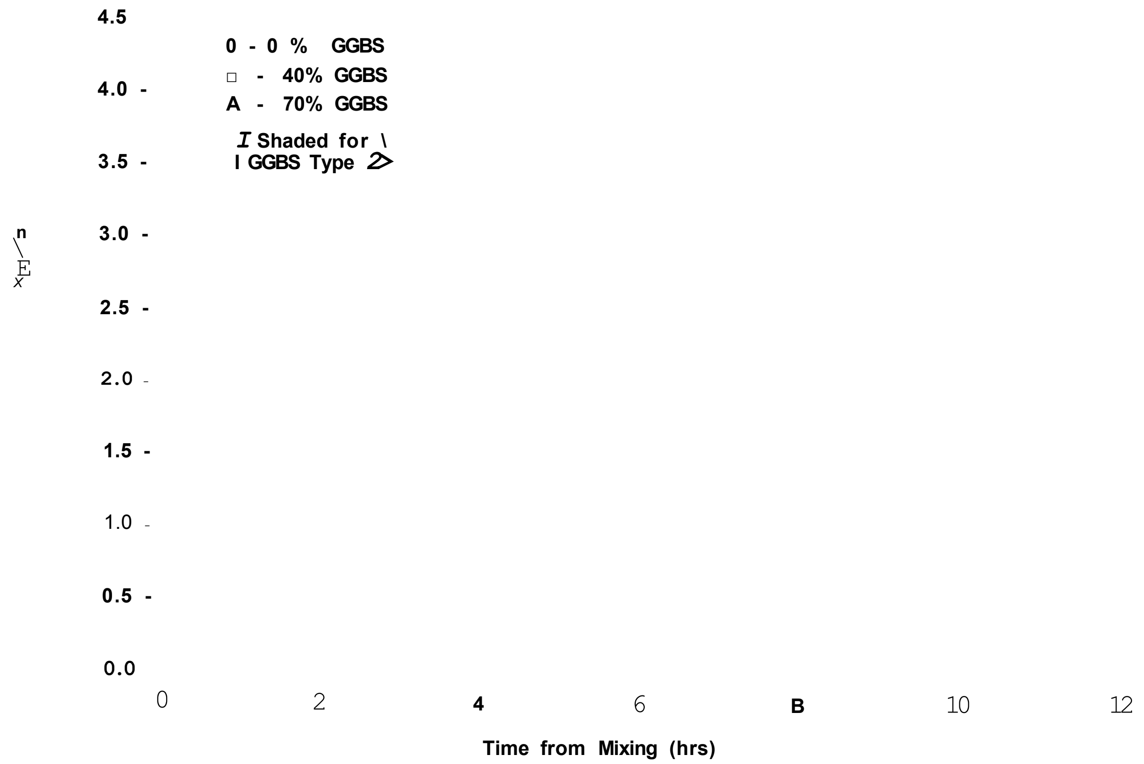


Fig 8.4.d : Profiles of pulse velocity at very early ages against time for the 400 kg/m^ cementitious content mixes.

■ O
I/) *if)* C5 *U)* *if)*
n *tn* po

(S / U I>J) ><ij.po|©A © sjnd

Type 1 Type 2

Type 1

— Type 2

– 0 % GGBS

■ 40% GGBS

70% GGBS

0 70 L M H L M H

GGBS Level % W/C Ratio

Fig 8. .f : Compressive strength against GGBS level and W/C ratio for the 300 kg/m^ cementitious content mixes at different ages.

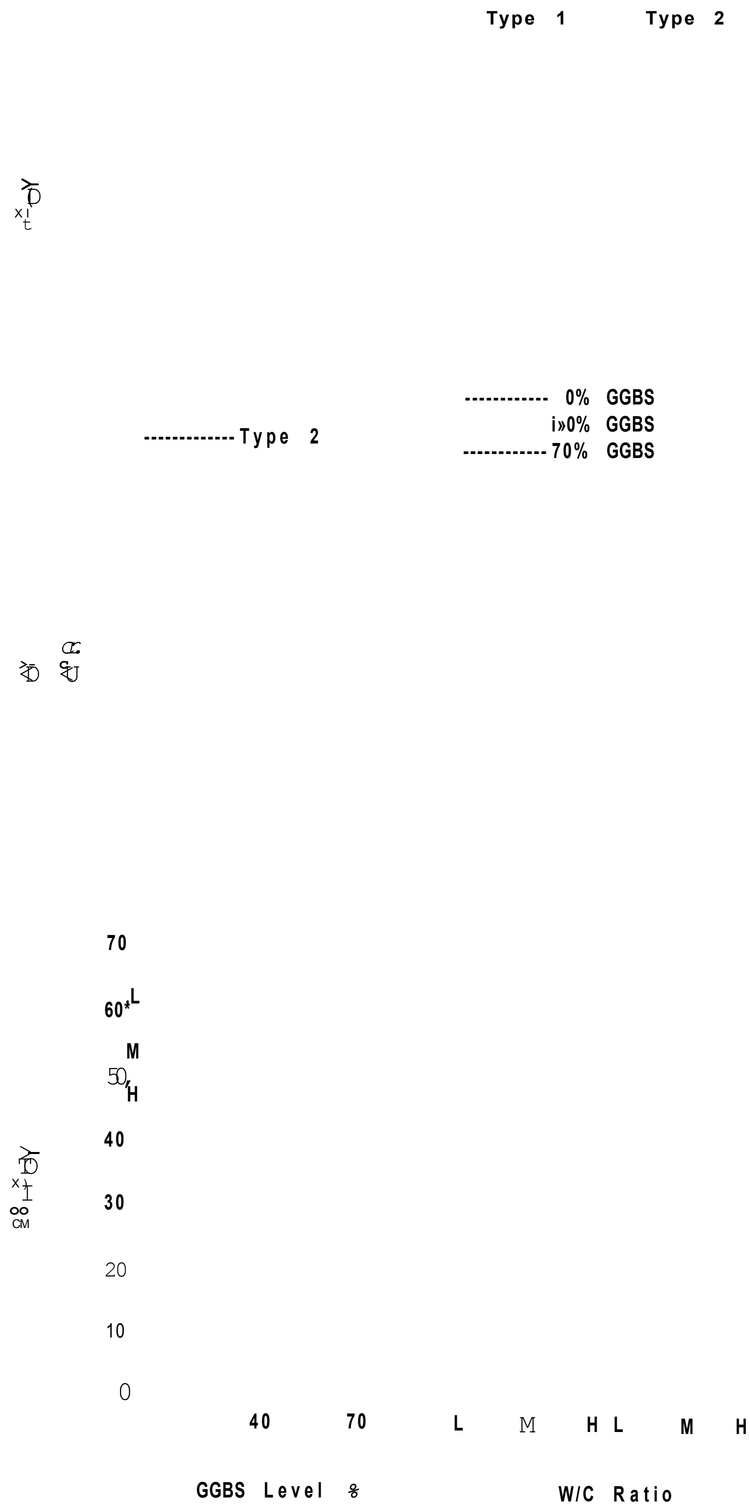


Fig 8.4.g : Compressive strength against GGBS level and W/C ratio for the 400 kg/m3 cementitious content mixes at different ages.

70% GGBS

GGBS

0 % GGBS

(edW) H1DN3B1S 3AISS3ddW03

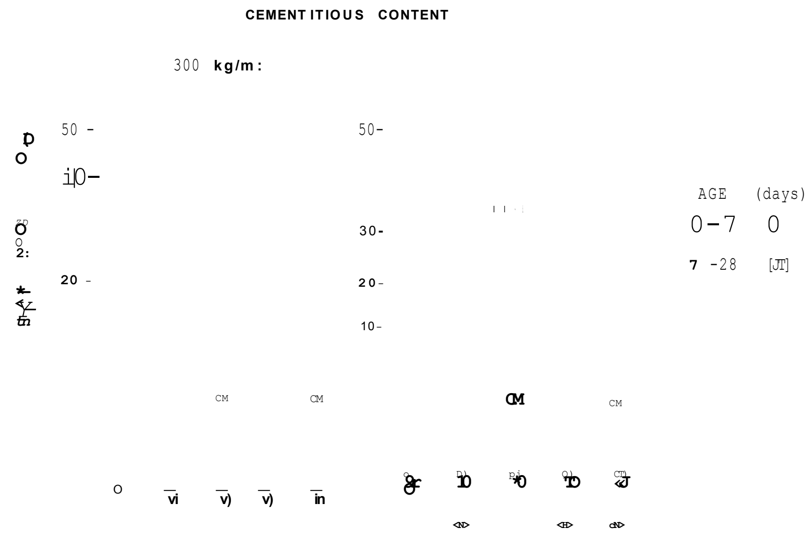


Fig 8.4.i : Development of static modulus with age.

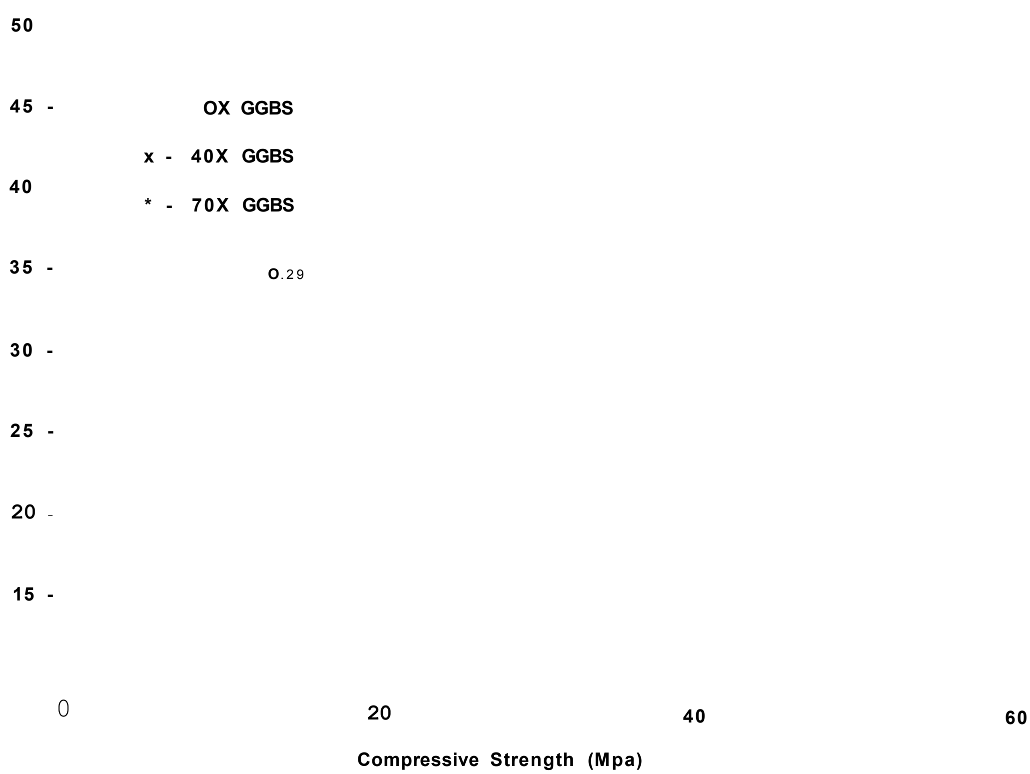


Fig 8.4.j : Static elastic modulus against compressive strength, showing the regression relationships.

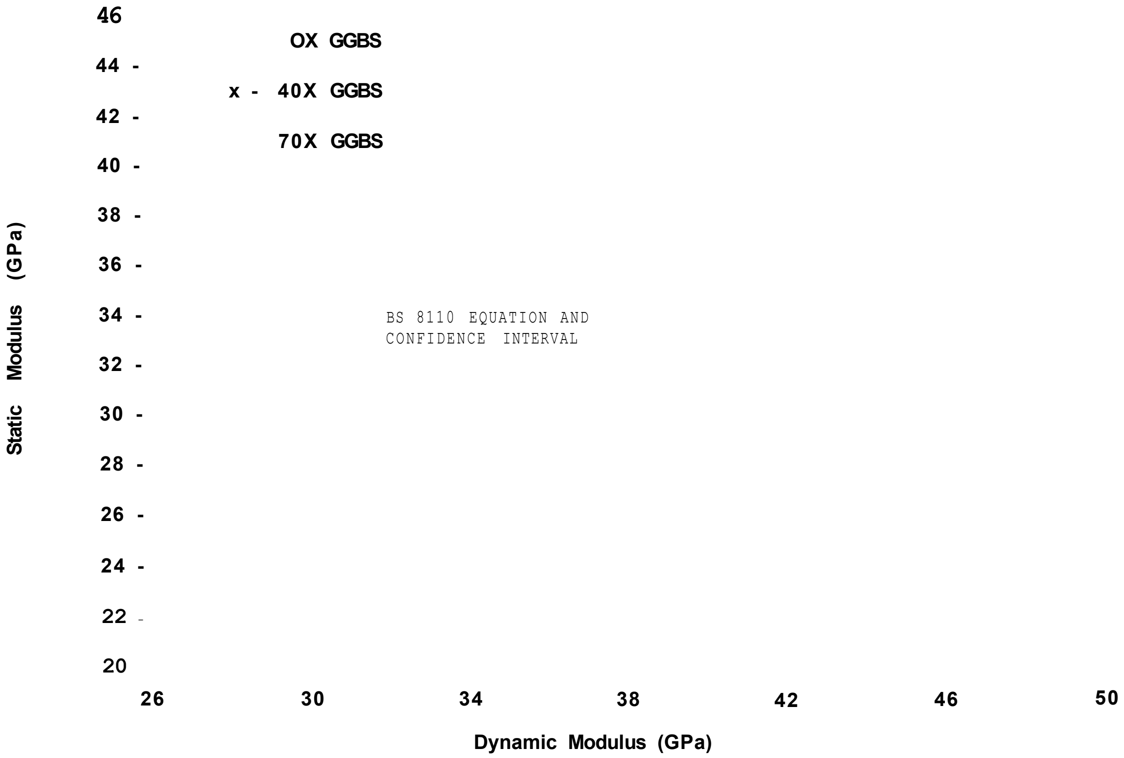


Fig 8.4.k : Static elastic modulus against dynamic elastic modulus, showing the BS8110 relationship and its confidence limits

Tab 8.4 : Coefficients from the regression analysis of the Elastic Moduli and Compressive Strength data.

Relationship	se	a	b ,c	r	df	Note
y = Static Modulus (GPa)			x = Compressive Strength (MPa)			
Linear	2.70	0.284	20.4	0.833	18	All mixes
y = ax + c	2.97	0.280	20.3	0.811	14	Slag Mixes
Power b		10.97	0.291	0.852	18	All mixes
y = Static Modulus (GPa)			x = Dynamic Modulus (GPa)			
Linear	2.09	0.951	-9.15	0.940	18	All mixes
y = ax + c	2.30	0.998	-10.86	0.892	14	Slag Mixes

9.1 Introduction

This chapter follows the logical sequence of reporting the results adopted previously, that is: workability, hydration, compressive strength, indirect tensile strength, ultrasonic pulse velocity, dynamic elastic modulus, and water absorption. The first part of the chapter discusses the results arising from the Main Programme of research, the latter part the results from the Secondary Study. Within each of the seven sections consideration of the effect of the experimental factors on the various test parameters is followed by an appraisal of the relationship between these parameters.

9.2 General

In discussing the results it should be bourne in mind that a constant water content was adopted throughout the work and that, in practice, mixes incoporating GGBS would be designed to have the same workability as their OPC equivalents.

The author, where possible, has considered both the statistical significance of the changes occuring, relative to those occuring by chance, and the practical significance of the changes, relative to levels which are significant, either economically, or when allowing for inherent variability, perhaps introduced by factors deliberately excluded from the work.

A factorial design was adopted for the Main Programme of research. Unfortunately both the design and data are flawed. The failure of the 40°C wet regime and the breakage of some specimens meant that eleven mixes were produced outside the original randomised order, to replace missing data. Significant block effects, whilst justifying the choice of a randomised block design, cast doubt both on the validity of replacing missing results and the adequacy of control of time-related factors. The design is distorted by the provision for a non-existent slag type effect at the 0$ GGBS level, and the use of duplicate results from the common OPC control mix.

For the sake of brevity some of the discussion is limited to selected ages and cementitiouscontents, or average trendsover the two GGBS types. Unless otherwise stated the trendsdiscussed will be representative of the whole of the data.

9.3 Main Programme

9.3*1 Workability

Workability is a general term covering a number of properties which for the purpose of this study may be summarised as : flowability, compactability and stability. The first part of this section deals with the flowability and compactability as assessed by the slump, compacting factor and two-point tests. The subjective assessment of stability, and its link with objective measurements on fresh and hardened concrete, is discussed in the later part of this section.

Figs. 8.3.1.a to 8.3.1.c show the changes in workability, as assessed by the four workability parameters, with GGBS level and type, for the three cementitious contents respectively. The arithmetic mean and range of the four blocks of available results are indicated by the lines and symbols respectively. The dotted lines above and below the OPC control mix results are BS 5328 tolerance limits for the British Standard tests, or equivalent rule-of-thumb limits for the two-point test (Section C.1.2). When the mean value of the results from the GGBS mixes falls outside these limits a practically significant change in workability from that of the OPC control, is assumed, indicated by an 's' in the adjoining table.

9.3.1.1 Effect of GGBS level and type

At the low (200kg/m^) cementitious content both slag types have a similar effect upon workability. Slump and compacting factor rise consistently with GGBS level. This trend in workability is repeated in the g values which decrease significantly to approximately a third of the control mix value in the 70$ GGBS mixes. The difference in the g values of the two GGBS types is small, compared to the range present between the blocks of results. This range could be ascribed to the large amount of bleeding observed in the concrete prior to sampling. The value of h increases with GGBS level indicating, in contrast to the other workability assessment parameters, a decrease in workability. This increase in h, which is significant for GGBS type 1, suggests that at higher shear rates any beneficial effect of GGBS level would diminish.

At the medium (300 kg/m^) cementitious content some divergence in the performance of mixes made from the two slag types becomes apparent. At the 40$ GGBS level, workability, as assessed by the four parameters, increases slightly with slag type 1, and decreases slightly with slag type 2. At the 70% GGBS level the workability of the slag type 1 mixes is, according to all the parameters, greater than that of the control; significantly so in the case of slump and g. In contrast the slag type 2 mixes have a a lower workability than the control for all the assessment parameters; significantly so in the case of g.

In the high (400kg/m^) cementitious content mixes the divergent effect of the two slag types upon workability becomes more pronounced. Slump and compacting factor increase for slag type 1, but signficantly decrease for slag type 2 relative to the control, at both the 40% and 70$ GGBS levels. The latter effect is particularly marked for compacting factor, the mean value of which decreases from approximately 0.96 in the OPC control, to 0.84 in the 70$ GGBS type 2 mixes. The two-point parameters confirm this trend in workability for slag type 2, but indicate that slag type 1 has little effect upon workability.

It was mentioned in Section 6.3.2 the particle size distribution of slag type 2 is finer and narrower than that of slag type 1. Sumner et al (66) investigated the influence of a narrow partice size distribution in OPC, due to more efficient grinding, upon the water demand of pastes and concrete. By grinding GGBS to normal and narrow particle size distributions they showed that, at least in pastes, the changes in water demand arose from a physical effect. A narrower distribution of particle sizes results in increased voidage, which in turn requires more water before lubrication is achieved.

9.3*1.2 Effective Fines Ratio

Figs 8.3-1.d and 8.3*1.e show the trend in the mean values of British Standard and two-point parameters respectively, with GGBS level and cementitious content. One block of results at the 100$ GGBS level have been included.

The trends in workability observed up to the 70$ GGBS level are generally maintained at the 100$ GGBS level. Increasing the levels of both slag types has a beneficial effect upon workability at the low cementitious content. At the high cementitious content, increasing the proportion of slag type 2 in the blend results in a decrease in workability. Lower than expected values of g and h in mixes of low workability may be attributed to the formation of a stable annulus of conrete adjacent to the impeller orbit, and a consequent reduction in the volume of concrete being sheared.

One possible explanation for the effect of GGBS level upon workability is the increase in the volume of paste in the mix when OPC is replaced, on a mass basis, by slag of a lower relative density. This change can be described in terms of the effective fines ratio (EFR), that is the combined volume of fine aggregate and cement divided by the volume of coarse aggregate.

The percentage paste and EFR are shown at the bottom of Fig 8.3. I.e. It can be observed that the value of the EFR is the same in the OPC control mixes, but rises from 88.5 to 91.2$ as a result of GGBS inclusion. Tattersall has suggested that replacement of OPC by GGBS may be sufficient to take the EFR through an optimum value for workability, thus explaining a transition in the effect of GGBS upon workability as the cement content changes (17). In the case of slag type 2 the optimum value of the EFR appears to be around 89.3$*

The effect of using 70$ GGBS upon workability is summarised below in terms of the water content adjustment in the OPC control mix, in litres per cubic metre, to produce a similar change in slump. The adjustments were obtained by applying the mean slump values to Fig 4.4.a.

	Cementitious Content (kg/m^)		
	200	300	400
Slag type 1	+5	+6	+7
Slag type 2	+7	-2	-9

The maximum benefit of using slag is equivalent to an addition of about seven litres of water, whilst the maximum difference between the slag types is equivalent to 16 litres (approximately 10$) per cubic metre. The former value is in accord with the equivalent 5$ increase in water content suggested by Tattersall (Section 2.6.2), but is much smaller than the water reduction obtained by Moss (19) working at a constant nominal compacting factor, and employing slag from the same sources. His values confirm the extra water demand of the GGBS type 2, and indicate a 15$ difference in water demand between the two slags.

9.3*1.3 Statistical Deductions

As expected from the transition in the effect of GGBS level with GGBS type and cementitious content, the analysis of variance produced a significant interaction between these three factors (Section B.2.3). It was necessary to split the analysis by one of the terms present in the interaction, in this case cementitious content. The results of these analyses are summarised in Tab 9.3.1. The differences between the result of the analyses of variance on the transformed and untransformed data are small, and only the latter will

Tab 9.3.1 : Summary of the 3-factor Analysis of Variance of the Workability data, split by cementitious content.

Factor	Cement Content	Slump (mm)	log	CF	angular	g (Nm)	h (Nms)
Rp	Cm1	■	■	|	I	A	A
	Cm2	0	0	0	0	0	0
	Cm3	0	0	|	I	|	1
Ty	Cm1	0	0	0	0	0	0
	Cm2	|	I	I	|	I	0
	Cm3	I	|	|	|	|	1
Bk	Cm1	0	o	0	0	0	0
	Cm2	0	o	■	■	0	A
	Cm3	0	o	0	0	0	0
Rp x Ty	Cm1	0	o	0	0	0	0
	Cm2	■	■	A	A	A	A
	Cm3	□	□	A	A	A	□
Rp x Bk	Cm1	0	0	□	□	0	0
	Cm2	0	0	0	0	0	0
	Cm3	0	0	0	0	0	0
Ty x Bk	Cm1	0	0	0	0	0	0
	Cm2	0	0	0	0	0	0
	Cm3	0	0	0	0	0	0
RpxTyxBk	Cm1	0	0	0	0	0	0
	Cm2	□	A	0	0	0	0
	Cm3	▲	A	0	0	0	0

	Probability Level (%)	Significance Attributed
o	> 2.5	None
O	^ 2.5	Just
A	^ 1.0	Moderate
M	^ 0.5	Very
A	^ 0.1	Extremely

I indicates where main effects are high but not proven because of significant interaction terms be discussed further. GGBS replacement level is the most persistently significant factor, both as a main effect and through interactions with slag type and block. A main effect of GGBS type could not be proven because of significant interactions. The prevalance of significant interactions vindicates the choice of a factorial experimental design.

At the low cementitious content, there is a single main effect of GGBS level in the slump, g and h data. A least significant difference follow-up study, equivalent to multiple t-tests, was carried out to determine whether the data from the GGBS levels were grouped in any way. The study (Section B .2. *0 indicates that significant differences only existed between the extreme GGBS levels in the slump data, whilst the g data from all three replacement levels was significantly different. It could be expected from the diverging effects of GGBS level for the two slag types, in the medium and high cementitious content mixes, that the Rp x Ty interaction would be significant. Indeed, this is so across all the parameters, even when tested against a significant Rp x Ty x Bk interaction.

At the medium cementitious content a significant block effect was detected in the compacting factor and h data. This indicates a systematic time-related effect upon the results. A least significant difference study indicates that mixes in block 3 were significantly less workable than those in the other blocks. This difference may be connected with the use in block 3 of coarse aggregate, near to the base of the stockpile, with a raised dust content, or the lower mix temperatures (Fig A.1.e).

The analysis of variance confirms that consideration must be given to the cementitious content, GGBS level and slag type when judging the probable effect of GGBS replacement of OPC upon workability. A more extensive consideration of the analysis is given elsewhere (69).

It seemed likely from a visual appraisal of the results , and from the work of others (70), that a polynomial model could be fitted to the workability data. A model was formed using the quadratic, linear and interaction components of cement content and GGBS level (Tab 8.3*1.a). The slag types were considered separately, since it was felt that this qualitative term was unsuitable for incorporation into the model. The Rp^2 term was not significant, and was therefore removed from the model, to yield equations such as that below .

slump = 2.36 Cm + 1.3 Rp + 0.005 (Cm x Rp) - 0.003 Cm^

The standard error on the observed workability parameters were small when taking into consideration BS 5328 tolerance limits on slump and compacting factor of 25 mm and 0.06 respectively, and standard error estimates for g and h of 0.9 and 0.6 respectively, from the analysis of variance. It can be observed that the linear Cm (cementitious content) and Rp (GGBS level) terms act to increase the workability, whilst their quadratic and interaction terms decrease it. As expected the Cm x Rp term is much more important in the model for slag type 2 than slag type 1.

Verifying the model with independent data is necessary, but outside the scope of this thesis.

9.3.1.4 Relationship between the British Standard and two-point test parameters.

Tattersall (71), has suggested that a good relationship should hold between slump and g because both parameters relate to a state of zero shear rate. Fig 8.3.1.f seems to indicate that a single relationship will only be applicable over a limited range of cementitious contents. At low g values the points separate out, reflecting an increase in slump, at any value of g, with increasing cementitious content. This effect could arise from a transition in the relative importance of paste viscosity and particle interlock in determining slump and g, as cementitious content changes.

Fig 8.3-1 -g shows the relationship between compacting factor and slump. An approximately exponential relationship exists between these parmeters; slump becomes more sensitive at high values, compacting factor shows a reverse trend. The presence of a wide spread of results, particularly attributable to the high cementitious content slag type 2 mixes, indicates that a unique relationship between the parameters is unlikely. Logarithmic and angular transformation of the slump and compacting factor data improves their correlation, (Tab 8.3.1.b), and supports the adoption of these transformations in the analyses of variance.

Regression of the British Standard test parameters upon g and h indicates that the correlation between mixed shear rate tests, such as CF and g is unexpectedly higher than that between parameters with associated shear rates, such as slump and g (Tab 8.3.1.b).

The three curves obtained for the different cementitious contents in the relationship between slump and g may be described by power expressions (Tab 8.3*1.b). As the cementitious content increases the correlation coefficient of the relationship also increases, and there is a transition between an inverse relationship, with a power index of -1.08, to an approximately inverse square root relationship, with an index of -0.35. The latter is consistent with a parameter "S”, equal to slump proposed by Tattersall (71). Regression of this parameter against g gave rise to the expression

$$S = 0.042 g,$$

with a much higher correlation coefficient than using slump, or by multiple regression of slump upon both g and h. Multiple regression of compacting factor upon g and h produced the relationship

$$Cf = -0.014g -0.012h + 1.028.$$

The constant term is similar to that obtained by Tattersall, but the coefficent differs. The latter can be easily ascribed to differences in the apparatus used.

There is no indication in Fig 8.3.1.h of a relationship between g and h, even within the cementitious contents. This confirms the power of the test, in that neither parameter is redundant. However, the similarity of the g and h values for the low cementitious content OPC control mixes and high cementitious content mixes incorporating *10%* GGBS type 2 illustrates that these parameters, whilst independent, are not unique to a single mix design.

9.3.1.5 Mix Stability.

As stated previously (Section 5.2.3) an assessment of the bleeding and cohesion of each mix were made in blocks 2 to 4 of the Main Programme. Figs 8.3. 1.h and 8.3.1.i show the subjective assessment marks for each mix located on a plot of h against g.

Considering bleeding first we observe that the highest and lowest marks were observed in the low and high cementitious content mixes respectively. There appears to be a slight tendency at the low cementitious content, towards higher bleeding marks in mixes with a high h and low g value; these mixes, containing 70 % GGBS, were from a practical viewpoint adjudged to be bleeding excessively.

The assessment of cohesion was made during the slump test. Cohesion marksnear to ten indicate mixes that were felt to be over-cohesive, whilst marks near to zero indicate instability. It can be observed in Fig 8.3.1.i that a region of assessment marks around the ideal value of five is centred on g and h values of about 2.5 and 3.5 respectively. The lowest cohesion marks were awarded to the low cementitious content mixes. The high cementitious content mixes displayed a trend to higher g values and cohesion marks with an increasing proportion of GGBS type 2; the 70% GBBS type 2 mixes were adjudged to be over-cohesive.

Similar findings to the above were made for flowing concrete containing superplasticizer, by Edmeades (72). He suggests that over-cohesion and segregation in flowing concrete is associated with high and low g values respectively.

Although the subjective assessment marks provide some additional information upon the mixes, which was not immediately apparent from any of the objective workability tests, it was recognised that they have the disadvantage of being very dependent on the assessor, the range of workabilities encountered, and the shear rate and time of the assessment. It was observed that some mixes segregated in the two-point test, and that this segration was accompanied by a a decrease in the resistance of the concrete to shearing, at a given speed. It was therefore logical to explore this phenomenon as a possible objective method of assessing the stability of mixes to segregation and bleeding (60).

Figs 8.3.1.j and 8.3.1.k show the subjective assessment marks of cohesion and bleeding respectively, against the torque change, at an impeller speed of 1.1 Hz, during a prolonged period of shearing. It appears that bleeding increases linearly with torque change, whilst cohesion displays a corresponding non-linear decrease, or inverse relation, with torque change. Regression analyses of bleeding and cohesion upon torque change produced significant correlations, at greater than the 99- 8% probability level in the former case.

The above suggests a link between objective and subjective assessments of mix stability. However, it was hoped that a confirmatory connection with the hardened concrete properties could be found. Tomsett suggests that the variation in UPV, for example in a column, provides some measure of mix bleeding and segregation (73)• During the Main Programme three measurements were made on each beam at different depths from the casting face. The author tried several methods to summarise this data, the range in the transit time of the ultrasonic pulse at the top and bottom of the beam being considered the most efficient. The mean value of this range at 28 days under 10°C and 5°C curing is shown plotted against the torque change in Fig 8.3.1.1. A relationship is suggested by this plot, and confirmed by the significant correlation coefficient in Tab 8.3*1.c. Thus links have been established between a subjective and objective assessment of fresh concrete stability, and an objective measure of hardened concrete homogeneity.

9.3.2 Hydration

The temperature within a vacuum flask was recorded over a period of several days. From these measurements conclusions about the hydration characterisitics of each mix were drawn. Several statistics were used summarise the profiles:

a) time to peak temperature from casting;
b) peak temperature rise above that at casting;
c) peak temperature differential (27) relative to the ambient;
d) temperature rise coefficient, calculated as the rise per 100 kg of cementitious material (26);
e) arithmetic mean temperature over the first 24 hours; and
f) adiabatic temperature gain at 24 hours, corrected for heat losses from the flask (Section C.3.1).

9.3.2.1 The peak temperature

In the vacuum flask calorimetry work the ambient temperature was 20°C (Section 5.3.1),and the casting temperature varied between 20 and 16°C; consequently the temperature differential is generally higher than the temperature rise . The temperature rise values are not discussed further, but are presented in Tab A.2.3*a, together with the other summary statistics.

Fig 8.3.2.a shows the peak temperature differential plotted against the GGBS level. As the GGBS level increases the temperature decreases almost linearly. The temperature differential in the *10%* GGBS mixes is approximately a third of that of the corresponding OPC control, at all three cementitious contents. The temperature rise coefficients in the 0, 40 and 70% GGBS mixes are approximately 4.4, 3.0, and 2.1°C per 100 kg of cement.

In addition to reducing the peak temperature, the use of GGBS delays the peak. In the OPC control mixes the peak temperature occurs 13 to 14 hours after casting (Fig 8.3.2.b). The time to the peak temperature appears to be constant or increase slightly in the 405& GGBS mixes. In the 7056 GGBS mixes the peak occurs 15 to 20 hours after casting at the medium and high cementitious contents. This delay to the peak in the 70$ GGBS mixes is more pronounced in the low cementitious content mixes, with the peak occuring 27 to 29 hours after casting.

No systematic effect of GGBS type upon the magnitude or time of the peak temperature could be detected. There were, however, some indications of slightly higher temperatures being generated in the slag type 2 mixes at the 70$ GGBS level.

This widely reported effect of using high levels of slag (16,, 24, 26 ,62) means that the temperature gradients both in time and through the section are reduced because of the lower heat generated, the increased time to the peak, and the greater opportunity for heat dissipation. The peak temperature differential values, and the substantial reduction in these values with GGBS level, indicate section sizes less than 300 mm according to CIRIA Report 91 (27). In larger concrete sections the beneficial effects of GGBS, in reducing the risk of thermal cracking, may be absent.

9.3.2.2 The arithmetic mean and adiabatic temperatures

The effect of GGBS on the temperature profile is both to broaden, and lower the peak (Figs A.2.3.a to A.2.3»c). Thus, although the peak temperature is reduced by up to 10°C in the GGBS mixes compared to the corresponding OPC mixes, the mean temperature over the first 24 hours is only reduced by 6°C.

The first-order corrected adiabatic temperature gains in the OPC control mixes are approximately 19 ,27 and 38°C in the low, medium and high cementitious content mixes respectively. The latter value, and the temperature gain of 12.5°C in the corresponding 70$ GGBS type 1 mix, are in general agreement with first-order corrected values of 43 and 11°C, obtained by Atwell for a 390 kg/m^ cementitious content mix containing OPC and a blend of 70$ GGBS respectively (16).

9.3.3 Compressive Strength

9.3.3.1 General Observations

Figs 8.3.3.a to 8.3.3.C are multiple bar charts summarising the compressive strength development at each of the cementitious contents, under the five curing regimes. Each column in the charts relates to a particular GGBS-OPC blend. The compressive strength is represented by the height of the bars, which have been overlain for the different ages to show the gain in strength for the increments in time, indicated in the key.

Several trends are immediately apparent:

a) Compressive strength rises almost linearly with cementitious content. The strength values at the high cementitious content are approximately three times those at the low cementitious content.

b) At 1 day the compressive strength decreases almost linearly with GGBS level. With increasing age and curing temperature this linearity breaks down, the 40% GGBS mixes showing a disproportionally high strength.

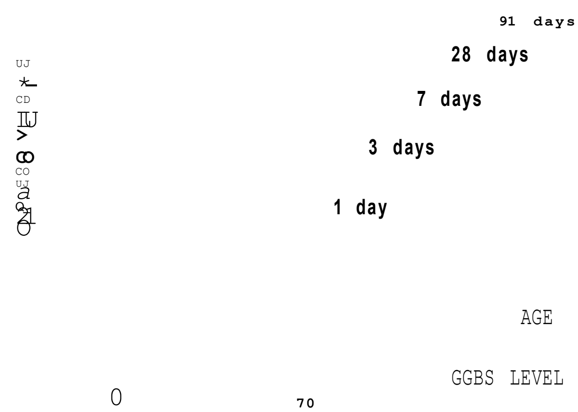
c) GGBS type has no consistent effect on strength across the curing regimes at 1 day. At the other ages the GGBS type 2 mixes are predominantly stronger than the corresponding type 1 mixes.

d) The development of compressive strength at early ages increases with curing temperature. At later ages the increments in strength under low curing temperatures equal or exceed those under medium curing temperatures. The 91-day compressive strength values increase with curing temperature up to 20°C, but fall slightly at 40°C.

e) At 1 day there is no consistent effect of curing humidity upon the compressive strength. The gain in strength at the other ages is much smaller under 20°C dry curing than under 20°C wet curing, leading to a substantial reduction in the

91-day strength.

To show graphically the effect of several factors and their interactions upon a chosen variable the results may be presented in a pseudo three-dimensional form proposed by McIntosh (74). In the following example compressive strength is plotted conventionally on the y-axis against age on the x-axis. The third dimension is created by shifting the origin along the x-axis a distance proportional to the levels of of the second factor; in this case GGBS level. The effect of age for each GGBS level is indicated by a solid curve. Dashed lines linking the results from the same age on each of these curves show the GGBS level effect. The GGBS level effect lines are approximately parallel at each of the ages. Converging or intersecting lines would signify a change in the GGBS level effect with age; or interaction between the two factors.



Additional factors could be accommodated in the graph by repeated shifts along the x-axis proportional to the factor levels, followed by the linking of corresponding points in each of the shifted groups.

Figs 8.3.3«d to 8.3*3.h show the pseudo three-dimensional technique applied to the compressive strength data. In these Figures there are five independent variables: age (logscale), cementitious content, GGBS level, GGBS type, and block. To avoid overcomplication the different cementitious contents have been segregated, and each of the curing regimes are shown separately. The x-axis has not been scaled; numbers and symbols on the graph indicate the factor levels. Individual block results are shown except where they differ by less than 0.5 MPa. Under wet curing the greatest range between the two blocks of results is less than 5 MPa.

9.3.3.2 Medium curing temperatures

The compressive strength data under 40°C wet and 20°C are shown in Figs 8.3.3.d and 8.3.3-e respectively. It can be observed that the compressive strength-log age relationships are approximately linear. In OPC mixes the upper end of the relationship deviates towards a lower compressive strength at later age. In GGBS mixes this curvature is lessened, but an additional curvature is introduced at the lower end of the relationship, due to a low initial rate of strength development.

At early ages the effect of GGBSlevel is an approximately linear reduction in compressive strength. The 1-day compressive strength values in the 70$ GGBS mixes are approximately a third and a fifth of those of the OPC control mixes at 40 and 20°C respectively. At later ages the linear GGBS level effect breaks down, the 40$ GGBS mixes displaying a disproportionally high compressive strength. Increasing cementitious content and curing temperature appear to promote the development of this peak. In addition to the peak, the GGBS effect lines are reduced in slope with age, particularly at the higher curing temperature. This effect of age can be described as an anticlockwise rotation of the GGBS level effect lines about the OPC control mix result. The rate of rotation is higher in the slag type 2 mixes and this results in their lines being displaced above those of the type 1 mixes by up to 7 MPa. The differential rotation described indicates an interaction between GGBS level, GGBS type, and age.

The higher rotation of the GGBS effect lines for slag type 2 leads to all the mixes, attaining strength parity with the OPC control mix by 91 days (at only 7 days at the low cementitious content), under 40°C wet curing. In contrast, the corresponding slag type 1 mixes are lower in strength than the OPC control, at all ages. This effect if slag type is consistent with the work of others (19,30).

9.3.3.3 Different curing humidities.

Figs 8.3.3«e and 8.3»3.f show the compressive strength data under 20°C wet and 20°C dry curing respectively. At 1 day the compressive strength values and trends are very similar under 20°C wet and 20°C dry curing, viz: an almost linear reduction in compressive strength with increasing GGBS level, and no apparent effect of slag type. The variability of the compressive strength data for dry curing was found to be great in relation to the strength levels; there is a maximum difference of 7.3 MPa (18$) between the two blocks of results.

The compressive strength-log age relationships under dry curing differ significantly from those associated with wet curing in a much more rapid decrease in the rate of strength development, at later ages. In two, low cementitious content, mixes the strength at 91 days was actually less than that at 28 days. Pomeroy reported a similar fall in strength, which he attributed to surface shrinkage cracking (75). At 91 days the compressive strength values in the 40$ and 70$ GGBS mixes only about a half and quarter respectively, of those obtained under wet curing. This reduction in compressive strength under dry curing is much greater than is suggested by data, for mixes of a constant workability, presented by Pratas (35).

The differential rotation of the GGBS level effect lines with increasing age, described previously for 20°C wet curing, is much less obvious under 20°C dry curing. A systematic effect of slag type is apparent in the medium, and to a lesser extent low, cementitious content mixes. Slag type 2 mixes are up to 7 MPa stronger than the corresponding slag type 1 mixes. The almost linear reduction in strength with increasing GGBS level, observed at 1 day, was maintained at the other ages under dry curing. A peak in compressive strength at the 40$ GGBS level, prevalent at 28 and 91 days under the medium curing temperatures, was only slightly apparent under 20°C dry curing.

All but one of the 40$ GGBS mixes under 20°C wet curing attained strength parity with their OPC control. In contrast, no GGBS mixes attained strength parity under 20°C dry curing.

The slower rate of hydration of GGBS mixes means that dessication is able to remove much more evaporable water from the concrete. This is reflected in the density of the concrete, which in GGBS mixes falls progressively below the OPC control mix with age (Fig A.2.3-d). As a consequence of this greater loss of water the hydration reaction is arrested at a much earlier stage in GGBS mixes, leading to a greater loss of strength. However, it should be emphasised that the specimens used in the investigation were very small compared to structural elements. Pomeroy has shown that increasing the cube size will extend hydration and increase the ultimate strength under dry curing (75).

9.3.3.4 Low curing temperatures

Figs 8.3*3*g and 8.3.3*h show the compressive strength data under 10°C and 5°C wet curing respectively.

The compressive strength-log age relationships differ from those under 20°C wet curing in having a reduced curvature at their upper ends and, for the GGBS mixes, an increased curvature at their lower ends. The 91-day compressive strength values under 10°C wet curing are less than 3 MPa lower than under 20°C wet curing, in the OPC mixes, but up to 13 MPa lower in the 70$ GGBS mixes. (The compressive strength in the high cementitious content OPC control mix is actually highest under 5°C; this being confirmed by both blocks of data.)

The GGBS effect lines rotate clockwise about the OPC control mix result with increasing age, up to about 7 days, suggesting an increase in the effect of GGBS level. Thereafter, the lines remain parallel, or rotate slightly anticlockwise. A peak in the 91-day compressive strength, at the 40$ GGBS level, is present in the slag type 2 mixes at all three cementitious contents, but is only present at the high cementitious content for slag type 1. Moreover, at the low cementitious content the 40$ GGBS type 1 mixes display disproportionally low compressive strength values at 28 and 91 days. The GGBS type 2 mixes are consistently stronger than the GGBS type 1 mixes from 3 days onwards. The maximum difference in compressive strength between the slags types under the low curing temperatures is approximately 8 MPa.

At 28 days the mean strength of the 40$ GGBS mix under 5°C wet curing, across the slag types and cementitious contents, is approximately two-thirds of that of the corresponding OPC control mix. This is in close agreement with 28-day strength reductions in 30 and 50$ GGBS mixes of 20 and 30$ respectively under 5°C, proposed by Pratas. Under 10°C wet curing strength parity with the OPC control is attained only in the low cementitious content mix, containing 40$ GGBS type 2. Non of the GGBS mixes attain strength parity with the control at 5°C.

In summary, out of the twelve GGBS mixes, the number gaining strength parity with the OPC control is as follows : eight at 40°C, six at 20°C, one at 10°C, and none under 20°C dry or 5°C wet curing.

9.3.3-5 Statistical Deductions

Further deductions about the data may be made using either statistical summary parameters, or by statistical analysis. The first part of this section considers the trends in percentage strength values, relative to the OPC control and standard curing, the second part of the section examines the findings of the factorial analysis.

Fig 8.3»3.i shows the compressive strength at 3, 7 and 28 days in the medium cementitious content mixes, under each of the different curing conditions, as a percentage of the corresponding OPC control mix strength. The trends observed at the other cementitious contents are broadly the same. The broken lines link the percentage strength values under wet curing conditions, the dashed *dessication' lines link the percentage strength values under wet and dry curing at **20°C.**

It is apparent that the percentage of the OPC control mix strength rises systematically with both curing temperature and age. The lines for the 40$ GGBS mixes, and the slag type 2 mixes lie above those of the 70$ GGBS mixes, and slag type 1 mixes respectively. At 3 days the percentage strength value in the *70%* GGBS type 2 mix is approximately *20%* at 5°C, and 65/6 at 40°C. At 28 days the corresponding percentages are just over 45%, and just under 100% respectively. The lines for the two GGBS levels converge with increasing age and curing temperature, but the separation of the lines associated with the two slag types increases. Consequently at 28 days and 40°C the lines for the 40$ GGBS type 1, and 70$ GGBS type 2 intersect.

At 3 days all the dessication lines rise, indicating a greater percentage strength with respect to the control under 20°C dry curing than under 20°C wet curing. However, the rise in the percentage strength values with age is greater under wet curing than dry curing, so that 28 days the values under dry curing are approximately 15 and 25 percentage points lower than under wet curing, for the 40$ and 70$ GGBS mixes respectively. At 3 days the percentage strength values in the 70$ GGBS type 2 mix under 20°C wet and 20°C dry curing is approximately 30 and 35$ respectively. At 28 days the corresponding values are approximately 75$ and 50$. In most cases the dessication lines do not cross, indicating that the ranking of the GGBS levels and types is consistent with that under wet curing.

Fig 8.3-3-j shows the compressive strength under 40°C wet, 20°C dry, and 10°C wet curing , as a percentage of the value under 20°C wet curing, for different GGBS levels, cementitious contents, and ages. The percentages indicated are the arithmetic mean values for the two slag types. A logscale has beeen used to reflect the true effect of the percentage values, thus a doubling and halving of strength are represented by similar increments on the logscale.

At 7 days the percentage strength under 40°C wet curing rises approximately linearly with GGBS level, illustrating the responsiveness of GGBS mixes to elevated curing temperatures. At the 70% GGBS level and low cementitious content, the compressive strength is almost 250$ that under standard curing. The corresponding percentage for the OPC mix is only 120$. At 91 days the percentage strength values are less than 100$ at all the GGBS levels and cementitious contents. At the low cementitious content the percentage strength rises from 85$ in the OPC control mix, to 95$ in the 70$ GGBS mixes. This deleterious effect of high curing temperatures on long-term strength development, particularly in OPC mixes, has been attributed by others to the formation of less dense hydration products (36).

At 7 days the percentage strength values in the low cementitious content mixes are greater than in the high cementitious content mixes; at 91 days this position is reversed.

The trends in percentage strength with GGBS level and cementitious content under 20°C dry curing are virtually a mirror image of those already described for 40°C wet curing. At 7 days the value in the low cementitious mixes lie between 75$ and 85$ at all GGBS levels. At 91 days the percentage strength falls almost linearly with GGBS level, from about 65$ in the OPC control, to just under 25$ in the 70$ GGBS mixes. This highlights the greater sensitivity of GGBS mixes to dry curing.

Under 10°C wet curing the trends in percentage strength relate only to the medium cementitious content mixes. At 1 day the percentage strength, with respect to standard curing, rises unexpectedly with GGBS level, from just over 30$ in the OPC control mix, to approximately 50$ in the 70$ GGBS mixes. This would seem to indicate a greater sensitivity in the OPC mixes to lower curing temperatures, than in the GGBS mixes. The same pattern was repeated at the other cementitious contents. In contrast, at 7 days the percentage strength values in the 70$ GGBS mixes are approximately 25 percentage points lower than those in the OPC mix. At 91 days the percentage strength values are higher than at 7 days, and fall systematically with GGBS level. In the OPC control mix the compressive strength is over 95$ of that under standard curing. The corresponding value for the 70$ GGBS mixes is approximately 75$.

Logarithmic transformation of compressive strength (see Section B.3.2) did not consistently improve the normality or homogeneity of variance of the compressive strength data. The transformation improved the homogeneity at early ages, but worsened the acceptability of the data at later ages. This appears to support the relationship between standard deviation and magnitude, for compressive strength values up to 20 MPa, presented in the "Design of Normal Concrete mixes" (52).

The factorial analysis of the strength data at each age proved problematical because of the number of significant interactions involving cementitious content, GGBS level, and curing. Splitting the analysis by cementitious content and GGBS level (Section B.3.3) produced degrees of freedom of unity for the main factors and first-order interaction terms, permittting direct comparison of their F-ratios. Discussion of the split analyses will concentrate on the effects of curing and slag type.

Fig 9.3*3.a to 9.3*3«c show the pattern of change in the F-ratios with GGBS level and age for the medium cementitious content mixes , under the medium curing temperatures, different curing humidities, and low curing temperatures. Only the ratios for the medium cementitious mixes are shown; trends observed at the other cementitious contents are similar, unless otherwise stated. A logscale was used to facilitate plotting of the F-ratios. The points for the curing and type main effects are linked by solid lines, whilst a dashed lines link their interaction F-ratios. Gaps in the line and arrows indicate that a point has not been plotted because its F-ratio

0% GGBS

40% GGBS

70% GGBS

70% GGBS

40% GGBS

0% GGBS

0% GGBS

40% GGBS

70% GGBS

falls below 0.1. The linking of the F-ratios from the separate analyses at each age is not to imply strict comparability but to highlight broad patterns of change. The significance of factors is dependent on the interactions present, however an F-ratio value of 10 is the approximate lower level of significance for the limited degrees of freedom available.

For the medium curing temperature comparison the F-ratios associated with curing are initially high, but decrease with age at all the GGBS levels. The curing main efect appears to reach a minimum at 7 days at the 0% GGBS level and 28 days at the 40/6 GGBS level. In each case the age is sensibly the point at which the compressive strength-age relationships at 40°C and 20°C intersect. The increase in curing temperature effect after the minimum reflects the depression of ultimate compressive strength when curing at elevated temperatures, and is especially pronounced at the 0/6 GGBS level.

The slag type effect at 1 day is much lower than that of curing temperature, however it rises with increasing age to surpass the curing effect at 28 and 91 days. At the *70%* GGBS level the slag type effect reached a peak at 3 days. Similar maxima were present at the other cementitious contents, though at different GGBS levels. Interactions are genearlly small in magnitude and the effects of curing at early ages, and slag type at later ages are likely to be significant.

The F-ratios from the comparison of different curing humdities are shown in Fig 9*3*3«b. In contrast to curing temperature, the effect of curing humidity increases steadily with increasing age. At the 40$ GGBS level the F-ratios rises from around 15 at 1 day to over 2500 at 91 days. The effect of slag type increases with increasing age between 1 and 7 days, but decreases at 28 days at both GGBS levels. The effect of type is less than that of curing, except at 1 and 3 days at the 70% GGBS level. Both the slag type and curing effects are sufficiently large to be significant, were it not for a large main effect of block and a potentially confounding interaction effect between block and type.

Fig 9.3»3»c indicates the F-ratios for the low curing temperature comparison. The F-ratio values for the main effects are smaller than in the previous curing comparisons; non of the values rise above 1000. The curing temperature effect appears to reach a maximum at 3 and 7 days. Similar maxima were present at the other cementitious contents. The curing temperature effect is ultimately lowest at the 0% GGBS level. The F-ratios associated with the slag type effect are generally lower than those of curing temperature. They rise in value from 1 day, reaching a peak at 7 days at the 70% GGBS level. Similar maxima were present at the high cementitious content.

In general the F-ratios associated with the curing and slag type effects are greater as the GGBS level increases. In over three-quarters of the analyses the slag type increases in effect from 1 day, the exception being the the high cementitious content mixes, in the comparison of medium curing temperatures, and different curing humidities. In over half the analyses a peak in slag type effect occured at around 7 days.

A more complete account of the analaysis of variance of the compressive strength data is given in Section B.4.2.

9-3-3•6 Maturity Functions

The combined effects of temperature and age can be summarised in terms of a maturity parameter, either by multiplying the age by the temperature, relative to a base (76), or by applying a maturity function to the age to give the equivalent age at 20°C (77). For simplicity the dry cured data is not considered in this section.

Fig 8.3*3.k shows typical plots of compressive strength against equivalent age for different cementitious blends and maturity functions. An ideal compressive strength-log equivalent age relationship would be linear and independent of curing temperature. Unfortunately, the strength-log equivalent age relationship is clearly not linear, and the range of curing temperatures produces a band or envelope of relationships. It can be observed that the slope of the strength-log age relationships is lower in the 70% GGBS mixes than the OPC mix at early ages, but this position is reversed at later ages. Futhermore, the envelope of relationships relating to the different curing temperatures is wider, for the 70% GGBS mix data, when the Nurse-Saul function is used to calculate the equivalent age, than when the Sadgrove function is used (Section C.2.1). This point is covered in more detail elsewhere (78), however as a consequence the Sadgrove function was adopted throughout.

It can be seen in Figs A.2.2.b to A.2.2.f, that whilst in the OPC mixes the points associated with 40°C and 5°C curing lie respectively at the bottom and top of the envelopes for each of the different cementitious contents, in the GGBS mixes this position is reversed. Compressive strength values under 40°C curing at equivalent ages between 7 and 14 days are up to 10 MPa lower in OPC mixes, and 5 MPa higher in GGBS mixes than those under 20°C curing. This is consistent with values suggested by Wainwright and Reeves for temperature cycled concrete (36).

After considering the graphs it was decided that the regression analysis should be split into three parts as follows:

a) Early ages (1 to 7 days), all temperatures
b) Later ages (7 to 28 days), 40 and 20°C data
c) Later ages (7 to 28 days), 20, 10 and 5°C data

The equivalent ages were calculated in hours at the early ages, and days at the later ages. They were logarithmically transformed prior to linear regression to produce an expression :

$$fc = a \log M + c,$$

similar to that proposed by Plowman (76); where M is a measure of maturity.

It would be expected that the regression analyses (shown in Tab 8.3.3) would confirm the shape of the compressive strength - log equivalent age relationship and their changes with cementitious content and blend. Indeed the lower rates of strength development at early ages in GGBS mixes, and later ages in OPC mixes are reflected by lower correlation coefficients and slopes. With increasing GGBS level both the coefficient and intercept generally decrease. The coefficient and intercept in the slag type 2 mixes are usually higher and lower respectively than in the GGBS type 1 mix, signifying a rotation of the strength-age plots about a similar 1-day compressive strength value. With each 100 kg of cementitious material the slope and intercept generally increase and decrease in value by approximately ten respectively.

At later ages the units of age were changed from hours to days, so comparison of the coefficients with those from early ages is not possible. At medium curing temperatures the standard error increases with cementitious content, having average values of approximately 3> 4.5 and 5.5 MPa, in the low, medium and high cementitious content mixes respectively. This reflects an underlying relationship between the standard deviation and magnitude of compressive strength. The values of slope and correlation coefficient in the OPC mixes were approximately half those in the GGBS mixes indicating the flattening of the compressive strength age relationships in the OPC mixes, and the sustained hydration in the GGBS mixes. At the lower curing temperatures the standard deviation decreases to levels observed in the early age data analysis. The slope and correlation coefficient are consistently higher in these analyses than at the medium curing temperatures. This difference is most apparent in the OPC mixes, where the value of the slope is more than doubled. This appears to contradict the findings others that the break in the strength-maturity relationship at high maturity values is unconnected to the cementitious blend or curing temperature (36).

The estimated equivalent age at which the the strength of a GGBS mixes equals that of the corresponding OPC control is lower when derived from the 40-20°C maturity relationship than from the 20-5 °C relationship. In the 40$ GGBS type 2 mixes at the medium cementitious content the equivalent ages are 41 and 136 days for the high and low temperature expressions. This illustrates the relative advantage of curing GGBS concrete at elevated temperatures.

The relative advantage of thermal treatment of GGBS concrete is also confirmed by the apparent activation energies of the blends, calculated by applying the compressive strength data to the the Arrhenius function (Section C.3.2.). OPC has the lowest activation energy value of 49 kJ/mol. This value increases to 58 and 55 kJ/mol in the 40^ GGBS type 1 and 2 mixes, and 67 and 58 kJ/mol in the 70% GGBS type 1 and 2 mixes. This increase in the activation energy with GGBS level is consistent with the work of others, although the values obtained were higher than those reported elsewhere (33 ,34).

9*3*4 Indirect Tensile Strength

9*3*4.1 The measurement of Indirect Tensile Strength

As mentioned in Section 5.4.1 the measurement of indirect tensile strength from the flexural test is inherently higher than that from the splitting test. This point is illustrated in Fig 8.3*5.a, which shows the indirect tensile strength values at 28 and 91 days, under 20°C wet curing, plotted against the compressive strength. The splitting strength at any compressive strength is between a half and two-thirds the flexural strength. Supplementary results under this curing were obtained to facilitate the plotting of the two curves, which are also shown superimposed on Figs 8.3*4.b and 8.3*4.c.

9.3*4.2 Relationship with Compressive Strength

Figs 8.3*4.b to 8.3*4.d show the indirect tensile strength plotted against the compressive strength for themedium curing temperatures, different curing humdities, and low curing temperatures respectively. In each graph the flexure and splitting test results have been partitioned by a diagonal line, and curves have been drawn through the OPC control mix results (solid curves originate from the extended data shown in Fig 8.3*4.a).

At medium curing temperatures there appears to be a slight tendency for higher flexural strength values in slag mixes at compressive strength values above 50 MPa. However the effect is small compared to the large scatter of the points, and is not confirmed in the tensile splitting results. This increasing scatter of the points, as the strength values increase, is present in the work of others (79).

Fig 8.3.4.0 shows the effect of curing in air upon the indirect tensile strength results. Under dry curing the tensile splitting strength and flexural strength values at any compressve strength are approximately three-quarters and a half respectively of those on the best-fit curves for wet curing. This indicates that dry curing has a greater effect on indirect tensile strength than compressive strength and that the flexural value is more affected than the tensile splitting value. This may be attributed to the higher shrinkage at the surface of the specimen, compared to the interior. Tensile stresses and cracking induced by this differential shrinkage would promote failure in specimens in tension at, or near to, the outer surfaces (12). From the test theories it would beexpected that the tensile splitting strength, because the tensile stress blocks lie within the specimen, would be less sensitive than the flexural strength to surface drying (75, 79).

Under low curing temperatures (Fig 8.3.4.d) there appears to be some evidence of higher flexural and splitting strength values, at any compressive strength, in the GGBS mixes. On average there are three times as many points associated with the GGBS mixes above the curves, drawn through the OPC control mix results, as below them. The magnitude of the increase in indirect tensile strength is approximately 0.2 and 0.4 MPa for the splitting and flexural tests respectively. Wainwright made similar findings for concrete which had been subject to fixed and temperature cycled curing, by splitting cylindrical specimens (25).

Both measures of indirect tensile strength appear to have a curvilinear relationship with compressive strength; and a power expression is often adopted (12). The coefficients obtained when regressing the indirect tensile strength upon the compressive strength are shown in Tab 8.3.4.

The power index for flexural strength under wet curing is 0.69; close to the value of 0.66 adopted by Raphael (79) • The corresponding index for the splitting tests is 0.89, which is much larger that the value of approximately 0.7 suggested by Carino and Lew, for cylindrical specimens. This difference could arise from the differing shapes of specimen used, or the method of fitting the power law (80).

Under dry curing the indirect tensile strength - compressive strength relationship becomes straighter, and there is a corresponding increase in the power index. The range on the correlation coefficient is 0.965 to 0.898 in the flexural test, and 0.982 to 0.947 in the splitting test. The lower correlation in the flexural results could be due, in part, to mishandling of the specimens (thermal shock,early overstressing, or surface drying). Although the equivalent cube strength and compressive strength were closely related (Fig A.2.2.a), it may be possible to obtain an improved correlation between the flexural strength and equivalent cube strength.

Under wet curing the relationship between indirect tensile strength and compressive strength does not appear to be greatly influenced by the the curing temperature. For compressive strength values of 20, 40 and 60 MPa the flexural strength is approximately 3.5, 5.0 and 5.5 MPa respectively, and the tensile splitting strenth is approximately 1.75, 3.0 and 4.0 MPa respectively. The latter values are in close aggreement with tensile splitting strengths of 1.7, 3.0 and 4.2 MPa, obtained for the same compressive strength values from a linear expression, proposed by Marrison for similar aggregates (81).

9.3.5 Ultrasonic Pulse Velocity

Ultrasonic pulse velocity is commonly used to get either a relative picture of concrete quality, or as a predictor of concrete strength using appropriate calibration charts or equations. The author could find very little data on the effect of cement replacement materials upon the strength-UPV calibration.

9.3.5.1 Development with Age

Fig 8.3-5.a shows the development in UPV, in cubes under 10°C and 5°C wet curing, as a multiple bar chart. The lower and upper values of 2 and 5 km/s on the scale represent the extremes of pulse velocity likely to be encountered in practice. Values of UPV less than 2 km/s are unreliable because of the possibility of indirect transmission in the underwater method. The relationship between the UPV underwater through cubes, and that measured in air through beams is indicated in Fig A.2.2.g.

In general UPV rises with cementitious content, age and curing temperature. Other regimes are not shown since the response of UPV to the development of mechanical properties falls rapidly with maturity (63). The pulse velocity supports the compressive strength ranking of the mixes, that is, in decreasing order of magnitude : OPC, 40^ GGBS type 2, *H0%* GGBS type 1, *10%* GGBS type 2 and *10%* GGBS type 1. However, the development of the two parameters with age differs. It can be observed that the gain in pulse velocity between 1 and 3 days is substantially greater than that between 28 and 91 days. For compressive strength the opposite is the case (Fig 8.3.3.c).

9.3-5.2 Relationship with Compressive Strength

By convention (38) an exponential relationship is assumed between compresive strength and UPV, of the sort :

Consistent with this, compressive strength is shown plotted on a logscale against the pulse velocity from beams in Figs 8.3*5.b to

8.3.5.d, for the medium curing temperatures, different curing humidities, and low curing temperatures respectively.

Under wet curing the points form a curve, which can be approximated by two straight lines. Elvery, measuring the velocity at early ages (63), also adopted a bi-linear relationship, although he considered that the point of discontinuity occured around a pulse velocity of 2 km/s. Elvery attributed this discontinuity to a physical interlocking of aggregate particles and hydration products. However, it should be noted that the use of a logarithmic scale for compressive strength, coupled with the curvilinearity, produces large positive residuals near to the origin, which could be misinterpreted as a sudden change in the gradient. It is possible that a single function could replace the two exponential functions, but investigation of this is outside the scope of the work.

The UPV value of 3.5 km/s, chosen by the author as the point to break the relationship into upper and lower portions, is the approximate point of formwork striking. The dashed lines represent the 90% confidence interval on observations in the upper portion, formed by regression analysis. The presence of points above the confidence interval at the ends of the portion, and below it at the centre, illustrate the curvilinearity. The widest and narrowest confidence intervals relate to 5°C and 20°C wet curing respectively, and are equivalent to about a third to a half of the observed compressive strength values.

Close examination of the distribution of the results within the confidence intervals relating to wet curing reveals that at the top of the upper portion (compressive strength greater than 30 MPa) the points for the GGBS mixes seem lie above those of the OPC mixes. The maximum increase in compressive strength at any pulse velocity for the GGBS mixes is equivalent to about 30/6. Facaoaru has reported similar findings (38). In addition, at the bottom of the upper portion (compressive strength less than about 5 Mpa) the compresive strength values in the GGBS mixes appear to be slightly lower than in the OPC mixes.

The greatest scatter in the results in the lower portion is under the low curing temperatures. Some of this can be attributed to the overlapping use of different frequency transducers, affecting UPV values between 2.5 and 3.3 km/s (Section 7.5).

A number of factors are known to affect the relationship between compressive strength and UPV (BS 1881 : Part 203), including the curing and test conditions. Fig 8.3*5.e shows the compressive strength-UPV relationship, for each of the curing regimes, obtained by regressing the results in the upper portion. It can be observed that the lines associated with the different curing regimes converge at a UPV value of 5 km/s and a compressive strength value of 80 MPa. However, the line relating to dry curing has a much lower slope than those relating to wet curing. Consequently at a UPV value of 3*5 km/s the compresive strength under 20°C dry curing is approximately 6 MPa, whilst that under 20°C wet curing is approximately 3 MPa; a percentage difference of 66^. The maximum difference between the relationships in terms of magnitude is equivalent to about 10 MPa. This effect of dessication has been reported previously by Tomsett (73).

In addition to the effect of curing humidity, in Fig 8.3.5.e, there also appears to be a small effect of curing temperature. The lines relating to wet curing indicate an increase in compressive strength at any value of UPV with increasing curing temperature. No such influence of curing temperature was reported by Elvery, and it is possible that some of it arises from the residual temperature of the beams at testing; the UPV is known to decrease slightly as the specimen temperature increases (BS 1881 : Part 203).

Tab 8.3.5 shows the coefficients obtained from the regression of strength with the pulse velocity. The correlation coefficient for the upper portions are quite high, the minimum being 0.96. The correlation coefficients for the lower portion are generally less, despite the reduced number of points, the minimum value being 0.75. The closeness of the coefficients for the GGBS and OPC control mixes indicates little overall effect of blend upon the relationship. Under wet curing the coeffcient (a) is generally lower and index (b) is higher in the GGBS mixes than the OPC mixes.

Linear relationships between indirect tensile strength and UPV are shown for completeness. Only a limited range of UPV and indirect tensile strength values are available, however the relationship between flexural strength and UPV for wet curing is in reasonable agreement with an expression,

$$fcf = 7 V - 30,$$

derived by the author from data presented by Nwoyke, for an irregular gravel (82).

9*3*6 Dynamic Elastic Modulus

The dynamic elastic modulus may be thought to be a measure of material stiffness. The value of dynamic elastic modulus is approximately equal to the initial tangent modulus in a static stress-strain cycle and, as such, is higher than the secant modulus obtained by static testing. The dynamic elastic modulus and ultrasonic pulse velocity are closely related parameters : both non-destructive; linked by a fundamental equation; and displaying similar trends with compressive strength. However, unlike UPV, the dynamic elastic modulus is a meaningful engineering parameter. This difference is reflected in the discussion.

9.3.6.1 Development with Age

Figs 8.3*6.a to 8.3.6.C show the development of dynamic elastic modulus at medium curing temperatures, different curing humidities, and low curing temperatures respectively. Some results are missing at early ages beacause the specimens were to weak to test (see Section 7.5 for criteria) and this is signified by crosses at the top of the columns. Several broad trends can be identified :

a) At early ages the dynamic modulus rises with increasing cementitious content and curing temperature, but falls with increasing GGBS level.

b) At later ages the dynamic modulus is less affected by cementitious content and GGBS level; and appears to be greatest under 20°C wet curing.

c) Like compressive strength, the dynamic modulus decreases slightly between 28 and 91 days in some of the dry cured specimens.

d) The dynamic modulus values are generally higher in the slag type 2 mixes, than the corresponding slag type 1 mixes.

Although dynamic modulus generally ranks the mixes at early age in the same order as compressive strength, it is clear, from a comparison of Fig 8.3.6.b and Fig 8.3-3-b* that the gain in dynamic modulus at early ages is greater than that of compressive strength. At later ages this position is reversed. At 91 days the dynamic modulus in the medium cementitious content mixes is virtually constant at 46 GPa, whilst the compressive strength varies between 40 MPa and 54 MPa, with cementitious blend.

9. 3*6.2 Relationship with Compressive Strength

The different responsiveness of compressive strength and dynamic modulus suggests an exponential or power relationship between these parameters; indeed, in CP 110 : 1972, a cube root expression was adopted (12). Although a linear function did not give a good fit to the data (Tab 8.3* 6.a), the author considered that an exponential function, similar to that used for UPV, could be adequate. Consistent with this Figs 8.3.6.d to 8.3*6.f show the compressive strength, plotted on a logscale, against the dynamic modulus, for the medium curing temperatures, different curing humidities, and low curing temperatures. As with the pulse velocity, the broken lines represent the 90/5 confidence intervals on observations produced by regression. Slight curvilinearity of the relationship is indicated by the presence of points above the upper confidence limit at the extreme ends of the relationship. The nature of the curvature suggests that additional logarithmic transformation of the dynamic modulus is unjustified. The widest and narrowest confidence intervals were obtained for the 20°C dry and 20°C wet data, representing a dynamic modulus range of approximately 9 and 5 GPa respectively.

There are no immediately apparent effects of GGBS level upon the relationship between compressive strength and dynamic modulus. However, examination of the distribution of the results within the confidence intervals indicates that at dynamic modulus values greater than about 40 GPa (or compressive strength of 30 MPa) the compresive strength is slightly higher in the GGBS mixes than in the OPC mixes. The maximum effect of GGBS can be considered to be a 30$ increase in compressive strength, or a 4 GPa decrease in dynamic modulus. In addition, it can be observed that in the low curing temperature data there is a slight tendency towards lower compressive strength values in the GGBS mixes, compared with the OPC mixes, at dynamic modulus values less than about 25 GPa. The maximum effect of GGBS is approximately equivalent to a 30$ reduction in compressive strength, or a 4 GPa increase in dynamic modulus. These findings conflict with a comparison of OPC and slag mixes under standard curing carried out be Wainwright. That study indicated higher elastic modulus values in slag mixes than OPC mixes at high compressive strength values, and lower moduli at low compressive strength values.

The regression relationships between compressive strength and dynamic modulus are shownin Fig 8.3.6.g, for the different curing conditions. The lines for 20°C dry and 40°C wet curing lie above the other lines, intersecting with them at compressive strength values of approximately 1 and 30 MPa respectively. Below the latter point the compressive strength at any dynamic modulus increases with increasing curing temperature. The compressive strength values at an elastic modulus value of 20 GPa are approximately 3*8, 4.2 and 4.5 MPa under 5°C wet, 20°C dry and 40°C wet curing respectively; the corresponding values at a dynamic modulus of 50 GPa are 63, 100 and 65 MPa.

The coefficients associated with the regression analysis of compressive strength and dynamic modulus are presented in Tab 8.3.6.a. The improved fit of the exponential function compared with the linear function is reflected in a significant increase in the correlation coefficient from 0.88 to 0.98. Under 20°C dry, 10°C wet and 5°C wet curing the coefficient (a) and index (b) associated with the OPC mixes are higher and lower in value than those derived for all the mixes. This is consistent with the effect of cementitious blend described previously.

9.3*6.3 Relationship with Stiffness Constant

The fundamental relationship linking dynamic modulus and UPV also includes concrete density and Poisson's ratio terms (Section C.2.3). It would be expected thefore that allowance for these terms would improve the relationship between dynamic modulus and pulse velocity. Indeed, Nwokye (82), reports such an improvement when using the product of the square of the pulse velocity and density. The later value, called the stiffness constant, was calculated by the author for each of the mixes (see Tab A.2.2.f). The relationship between dynamic modulus and stiffness constant for the different curing humidities is shown in Fig 8.3.6.h. The other curing conditions are shown in Figs A.2.2.h and A.2.2.i.

Under 20°C wet curing the relationship appears to consist of a linear upper portion (stiffness constant values greater than approximately 20 GPa), and a lower curvilinear section which deviates towards higher dynamic modulus and lower stiffness constant values. The scatter of the results in the upper portion, which encompass different cementitious contents and blends, is very low and there are no discernible effects of GGBS level. The lack of scatter is also signified by the low standard error values, of approximately 1 GPa, yielded by the regression analysis (Tab 8.3»6.b). Under 20°C dry curing the curvilinear portion appears to be absent, and all the data was included in the regression.

The regression relationships for the linear upper portion, are shown in Fig 8.3*6.i for all the curing conditions. It can be observed that the lines converge at stiffness constant and dynamic modulus values of approximately 55 and 50 GPa respectively. Below this point the line for 20°C dry curing lies above that for wet curing, due to its lower slope, and the lines associated with wet curing ascend with decreasing curing temperature; both of these signify an increase in dynamic modulus value at any stiffness constant. At a stiffness constant value of 20 GPa the dynamic modulus values under 20°C dry, 10°C wet and 40°C wet curing are approximately 16, 12 and 9 GPa respectively. The closeness of the lines for wet curing suggest that a single relationship could be fitted to the data. Regression analysis produced the expression:

Eoq « 1-02 Eu - 9.5,

with a high correlation coefficient of 0.992, and a low standard error of 1.3 GPa.

In order to accommodate the lower curvature in the dynamic modulus-stiffness constant relationship, Nwokoye fitted a power expression to his data (82). Linear regression of the dynamic modulus and stiffness constant for all the wet cured data combined, after logarithmic transformation gave rise to the power expression in Tab 8.3.6.b. The power index obtained is, at 1.3*1» slightly higher than the value of 1.2 proposed by Nwokoye, unfortunately there are problems with the units quoted in his work.

Fig 8.3*6.i shows the power relationship for wet curing, and the linear relationship for dry curing. Located on these relationships are the associated dynamic Poisson’s ratio values, calculated by applying the power and linear expressions to the fundamental theory (see Section C.2.3). The Poisson’s ratio values rise from approximately 0.4 in immature concrete, with a dynamic modulus and stiffness constant of less than 10 GPa, to 0.2 in mature concrete, with dynamic modulus and stiffness constant values of more than 60 GPa. This is consistent with Poisson’s ratio values of 0.3 at 1 day, and 0.2 at 28 days, presented by Simmons (83).

The decrements in Poisson's ratio with changes in the dynamic elastic modulus are greater at early ages than later ages, particulary under dry curing. The average decrease in Poisson's ratio under wet curing is 0.04 for every 10 GPa rise in the stiffness constant.

9.3.7 Water Absorption

The water absorption provides a measure of both the extent of hydration and the potential of the concrete to resist the ingress of harmful agents.

9.3.7.1 The factors affecting Water Absorption

When the specimens are placed in contact with the reservoir of water, the water absorbed rises rapidly, but with time the rate begins to drop (Fig A.2.3*e). A square root relationship appears to exist between the water absorbed and the time of contact; other workers have also suggested such a relationship (84). A time of contact of 60 minutes was found to be the optimum time for differentiating between concretes of different quality; beyond this time some cores became saturated.

The water absorption results are summarised in Fig 8.3-7.a. Water absorption is indicated on a logscale which has been adjusted to reflect the change in water absorption between wet and dry curing. Under dry curing the absorption values range from approximately 1.4 to 0.3 ml/m^2s, whilst under wet curing the corresponding range is only 0.5 to 0.2 ml/m^2s. The water absorption decreases with increasing cementitious content across all the curing regimes, this decrease being most apparent between the low and medium cementitious contents. The water absorption appears to be related to the water-cement ratio, however the increased proportion of aggregates in the concrete at lower cementitious contents may also be important, due to the preferential absorption observed at the cement paste-aggregate interface, Under 20°C dry curing the water absorption is consistently greater at higher GGBS levels, and in the slag type 1 mixes. The absorption values in the 70/6 GGBS mixes are approximately twice those in the OPC control, and the slag type 1 values are approximately 20% higher than those of the corresponding slag type 2 mixes.

In wet cured specimens the trends in water absorption are slight, and have to be judged against a measure of the inherent variability of the test. Such a measure is provided by the two blocks of data, which have been plotted for the OPC control mix. The range in the results reaches a maximum of about 20% of the absorption values; although in most cases it is much smaller.

In over half the GGBS mixes the mean water absorption value falls outside the range of the corresponding OPC control mix results. In slag type 2 mixes the water absorption generally decreases or remains constant with GGBS level. In slag type 1 mixes a similar pattern is maintained at the 40^ GGBS level. However, at the 70% GGBS level some high water absorption values were obtained, these values often being confirmed by both blocks of data (Tab A.2.3«b). As the curing temperature decreases the general level of water absorption rises. In the low cementitious content mixes the absorption rises from 0.39 ml/m2s at 40°C, to 0.45 ml/m2s at 5°C.

It would appear from the above that the mix design and curing affect the water absorption in the following descending order of importance: curing humidity, cementitious content, GGBS level, GGBS type and curing temperature.

9.3.7.2 Statistical Deductions

As with the compressive strength data the analysis of variance of the water absorption data was split into a comparison of medium curing temperatures, different curing humidities, and low curing temperatures. In the comparison of medium curing temperatures and different curing humidities there were significant three-factor interactions, and it was necessary to split the analysis by cementitious content (Section B.3.3).

The results of the analysis of variance are summarised in Tab 9.3.7. At the medium curing temperatures a significant effect of curing and a significant interaction effect between GGBS level and type were identified in the low cementitious content data. The comparison of different curing humidities yielded a significant interaction effect between GGBS level and curing humidity, at all three cementitious contents. This interaction, in addition to illustrating the sensitivity of GGBS mixes to curing humidity, prevents high main effects of GGBS level and curing from being proved significant. Despite the higher water absorption values in the GGBS type 1 mixes, described earlier, the slag type effect was only significant at the medium cementitious content.

The initial analysis of the low curing temperature data does not indicate any significant interactions, so splitting the analysis was unnecessary. Cementitious content and GGBS level are highly significant; the probability of the cementitious content effect occuring by chance was less than 0.1$. A least significant difference study was carried out on this data (Section B.2.4) to see ifit was grouped in any way. This study indicates that the results from all three cementitious contents are significantly different, and the water absorption in the OPC control mix is significantly higher than in the GGBS mixes.

9.3.7.3 Relationship with Compressive Strength

The specimen for the water absoprtion test was taken from a beam, broken in flexure, and tested in compression as equivalent cubes. Fig 8.3«7.b shows the relationship between the water absorption and the equivalent cube strength obtained from the same beam. Initial plotting of the results (Fig A.2.3*f) suggested a power relationship, so a logscale has been adopted here. The relationship appears to be an inverse power law, with an index of -0.74. The strong relationship is to be expected considering the number of common factors affecting

Tab 9.3.7 : Summary of the Analysis of Variance of the Water Absorption data.

Factor	40W/20W			20D/20W			10W/5W
	Cm1	Cm2	Cm3	Cm1	Cm2	Cm3	All
Cm	--	---	--	--	---	--	▲
Rp	I	0	I	I	I	I	■
Ty	0	0	0	0	□	0	0
Cu	■	0	0	I	I	I	0
Bk	0	0	0	0	0	0	□
Rp x Ty	▲	0	0	0	0	0	0
Rp x Cu	0	0	0	▲	▲	▲	0
Cu x Ty	0	0	0	0	0	0	0

	Probability Level (%)	Significance Attributed
0	> 2.5	None
□	^ 2.5	JU61
A	sc: 1.0	Moderate
■	^ 0.5	Very
▲	< 0.1	Extremely

I indicates where main effects are high but not proven because of significant interaction terms both parameters. The OPC control mix results lie close to the regression line, whilst the points associated with the GGBS mixes lie above and below them at high and low equivalent cube strength values respectively. This seems to indicate that in well cured concrete the water absorption of slag mixes is lower than that of OPC mixes of equal strength, whilst in poorly cured concrete the opposite is the case. This is in general agreement with previous research in to the durability of slag cement concretes (Section 2.6.6.3)*

Although a relationship appears to exist between water absorption and compressive strength the regression coefficients vary with the mix design and curing (see Tab 8.3.7). The power index rises from 0.44, under 5°C wet curing, to 0.82, under 20°C dry curing. This indicates the limitations of judging potential durability from even an in situ strength.

9.3*7.4 The measurement of Water Absorption

The new method of water absorption was designed to overcome some disadvantages of the British Standard immersion method. Fig 8.3.7.C shows the relationship between the results from the two methods for a limited number of specimens, which encompass good to poor quality concrete, defined by BS 1881 absorption values of less than *2%* and greater than 4^ respectively (65). A strong linear relationship, with a correlation coefficient of 0.94, exists between the two sets of water absorption values. In spite of this relationship, work with different sizes of core (not presented) indicates that unlike the British Standard water absorption the new parameter is relatively independent of the diameter and length of the specimen.

9.4 Secondary Study

As stated in Chapter 3, this study is an extension of the Main programme work, outside of its rigid factorial experimental design. The aims of the Secondary study were to explore the response of workability and compressive strength to changes in the water-cement ratio, as the cementitious content and blend alters. In addition data was gathered on the relationships between the static and dynamic modulus, and the UPV at early ages and setting. Only the medium (300 kg/m^) and high (400 kg/m^) cementitious content mixes were investigated : each at low, medium, and high water-cement ratios (see Tab 3*5). The medium ratio was the same as that used in the Main Programme. No replications were carried out in this work, so increased variability of these individual results, compared with the mean values from the Main Programme, is to be expected.

9.4.1 Workability

Figs 8.4.a and 8.4.b show the workability, as assessed by the slump and two-point parameters g and h, plotted against the GGBS level (on the left) and the water-cement ratio (on the right) for the medium and high cementitious content mixes respectively. The scales of the g and h axes have been inverted to facilitate comparison with the trends in slump.

Immediately apparent form Fig 8.4.a is the similarity in the trends in the slump and g values, and the contrasting trends in the h value. At the low, medium and high w/c ratios the workability, as assessed by slump and g, in the 40$ GGBS type 2 mixes is increased with respect to the OPC control and the corresponding slag type 1 mixes. However, between the 40 and 70$ GGBS levels the workability of the slag type 1 and 2 mixes increase and decrease respectively, signifying an interaction between GGBS level and type. At the 70$ GGBS level the workability of the slag type 2 mixes is less than or equal to that of the corresponding OPC control and slag type 1 mixes.

The values of slump and g show a range of 15 to 230 mm, and 0.3 to 6.0 Nm respectively with w/c ratio and cementious blend. In contrast, the corresponding range in h is only 1.3 to 3.7 Nms(Tab A.3.A). The only consistent trend in h is a peak in the workability of the slag type 2 mixes at the 40$ GGBS level, observed previously in the other parameters.

Considering the effect of w/c ratio we observe that the for slag type 1 the slump values of the OPC controlmixand 40$ GGBSmix are very similar at all w/c ratios, whilst those of the 70$ GGBS mix are consistently higher. This is particularly the case at the medium w/c ratio, where the slump is over 100 mm greater in value. A comparable pattern exists in the slag type 2 mix although, in this case, the higher workability is obtained in the 40$ GGBS mix. The rise in slump between the low and medium w/c ratios (0.5 to 0.55) for the 70$ GGBS type 1 and 40$ GGBS type 2 mixes isapproximately 140 mm. This compares with an increase in slump of less than 80 mm in the other mixes. This difference in the sensitivity of workability to w/c ratio could have important quality control implications. The above trends are generally confirmed by the two-point parameter g, although a lower than expected g value was obtained for the low w/c ratio, 70$ GGBS type 1 mix.

The change in h with w/c ratio appears to be completely different from that of the other workability parameters. Tattersall contends(85) that g and h should decrease with increasing w/c ratio, and indeed the change in h for the 70$ GGBS type 1 and 40$ GGBS type 2 mixes is consistent with this. However in the other mixes the h value at the low w/c ratio was less than would be expected. It is possible that these low h values arise from the observed formation of a stable annulus of concrete adjacent to the impeller orbit, and a consequent decrease in the volume of concrete being sheared.

At the high cementitious content (Fig 8.4.b) both slump and g generally indicate a rise and fall in workability with an increasing proportion of slag type 1 and slag type 2 respectively. In the latter case the slump decreases from 200 mm to 70 mm, and the g value increases from 0.6 to over 5.4 Nm, as the GGBS level increases from 0 to 70$. The trends in h were consistent with, if less pronounced, than those of the other workability parameters. The greatest change in h with GGBS level was a rise of about 4 Nms in the 70$ GGBS type 2 mix compared with the OPC control. The low values of g and h values at the low w/c ratio, may be attributed to the annulus formation described earlier.

With the exception of the low w/c ratio control mix, the slump, g, and h values in the OPC and GGBS type 1 mixes are very similar. As the w/c ratio increases from O.36 to 0.46, the slump in the 70$ GGBS type 1 mix increases from 5 to 205 mm , and g decreases from 5.5 to 0.6 Nm. The corresponding change in h is from approximately 3.5 to 1.8 Nms.

The change in workability with w/c ratio for the slag type 2 mixes appears to be less systematic than in the other mixes. The slump values in the OPC control and 40$ GGBS mixes are very similar, whilst those in the 70$ GGBS mix are significantly lower at the medium and high w/c ratios. In the 40$ GGBS mixes the rise in slump of 150 mm between the low and high w/c ratios (0.36 to 0.46) was accompanied by corresponding decreases in g and h of approximately 5 Nm and 2 Nms respectively.

Low and high values of the two-point parameters were obtained in the 40$ GGBS mix, at the low w/c ratio, and in the 70$ GGBS, at the high w/c ratio, respectively. The latter mix was associated a relatively low correlation coefficient of 0.943 between impeller torque and speed (see Section C.1.2)

It can be observed from the above that an increase in the w/c ratio of 0.1 produced a corresponding increase in the value of slump of more than 160 mm, in most mixes. In comparison, an increase in the GGBS proportion from 0 to 70$ produced increases of slump of less than 120 mm, in most mixes (see Section 9.4.3).

9.4.2 Hydration

Figs 8.4.c and 8.4.d show the development in UPV over the first 12 hours for the medium and high cementitious content mixes, at the medium w/c ratio. A line has been drawn thorugh the points relating to the OPC control mix to give an indication of the shape of the profile. There are gaps in the data, due to malfunctioning of the equipment, and steps in the profiles at approximately 2 hours, due to the removal of the external amplifier from the system (Fig 5.3.b). The numerical values used to form the profiles are given in Tab A.3.b.

It can observed that the pulse velocity increases rapidly up to about 4 hours, after which the rate of increase falls. The values of UPV obtained 4 hours after mixing are about 1.7 km/s and 2.5 km/s in the medium and high cementitious content mixes respectively; the corresponding values at 12 hours are approximately 3.5 and 4 km/s.

Overall the UPV values at 6 hours rank the ten mixes in the following descending order of magnitude : 4S0, 4P4, 4S4, 3P4, 3S0, 4P7, 4S7, 3P7, 3S4, 3S7. This compares with a 1-day compresive strength ranking of the mixes of 4S0, 3S0, 4S4, 4P4, 3P4, 3S4, 4P7, 4S7, 3P7, 3S7. Except for the medium cementitious content OPC control mix (3S0) and the 40^ GGBS type 1 mix (3S4), the ranking of the mixes is strikingly similar. The consistent ranking of the two slag types is interesting but, because of the lack of randomisation, requires further investigation.

It was hoped by the author that some connection could be established between the UPV and the time of initial set , as defined by penetration resistance measurements on mortar to BS 5075. Fig 8.4.c shows the point of setting marked on a limited number of UPV profiles. These results indicate a trend between increased setting time and GGBS level, which is accompanied by delays in the development of UPV. At the medium cementitious content the setting time increases from under 3 hours in the OPC control mix, to about 4 hours in the *70%* GGBS type 1 mix. The initial set seems to occur when the velocity is around 1.4 km/s, the value falling with increasing setting tme. This is consistent with previous research which determined that the end of workability, or initial set, was defined by the time at which the pulse velocity increased from 1 to 1.5 km/s (64).

This work indicates that UPV measurements can be made from early ages and that these measurements may be used to rank mixes with different cementitious contents and blends, or as a setting time criteria.

9.4.3* Strength

Fig 8.4.f shows the compressive strength at 1, 7 and 28 days plotted against the GGBS level (on the left) and w/c ratio (on the right), in the medium cementitious content mixes. The compresive strength scale has been adjusted to suit the changes occuring at each age. The relationship between compressive strength and GGBS level at 1 day consists of pairs of lines for the two slag types, descending in strength with increasing w/c ratio, and converging at the 70% GGBS level. At 7 and 28 days the relationships become bilinear, and their separation, according to w/c ratio and slag type, increases, particularly at the 70% GGBS level.

The relationship between compressive strength and w/c ratio is approximately linear. At 1 day the change in compressive strength with w/c ratio in the 70^ GGBS mixes is very low, suggesting that the sensitivity of the crushing machine at low compressive strength may be a limiting factor. The OPC control mix shows the greatest change with w/c ratio at all ages; the compressive strength value at the high w/c ratio being 44% and 62^ of that at at the low w/c ratio, at 1 and 28 days respectively. The separation of the lines for the different GGBS levels at 1 and 7 days appears to be greater than the change in strength with w/c ratio . At 7 days the compressive strength values in the 70% GGBS mixes are typically a third of the corresponding OPC control mixes. This compares with strength values in the high w/c ratio mixes which are approximately two-thirds of those at the low w/c ratio.

Fig 8.4.g shows the trends in compressive strength with w/c ratio and GGBS level in the high cementitious content mixes. At 1 day the trends in compressive strength with GGBS level are similar to those described previously for the medium cementitious content mixes, although the compressive strength values are more than doubled. At 7 days the linearity in the compressive strength-GGBS level relationship breaks down and, as in the Main Progamme, the 40$ GGBS mixes display a disproportionally high strength. At 28 days the separation of the relationships according to w/c ratio and slag type leads to the slag type 2 mixes being stronger than the type 1 mixes at both the 40 and 70/6 GGBS levels. The maximum difference in the strength of the two slags is 12 MPa.

The greatest change in compressive strength with w/c ratio is witnessed in the 70% GGBS type 1 mixes. The compressive strength at the high w/c ratio is 66$ of that at the low w/c ratio. The sustained hydration in the GGBS mixes is reflected in the reduced separation of the different GGBS levels at 28 days, compared with 7 days. Consequently the effect of w/c ratio is more important than that of GGBS level at 28 days. Compressive strength values at the high w/c ratio are approximately 80$ of those at the low w/c ratio, whilst the strength in the 70$ GGBS mixes are approximately 85$ of those of the OPC control.

From the above it can be observed that the effect of a an increase in w/c ratio of 0.1 is less than a 40$ reduction in the 7-day compressive strength. Whereas the effect of increasing the GGBS level is approximately a 50$ reduction in the 7-day strength. This greater effect of the GGBS level compared to w/c ratio is contrary to that witnessed in the workability data.

The trends in compressive strength described so far are not of much practical relevance since a constant workability and not w/c ratio, is often adopted. This deficiency can be overcome bycomparing the compressive strength values on an equal slump basis.

Fig 8.3*4.h shows the relationship between the 28-day compressive strength and slump for the two cementitious contents, and three GGBS levels. Looking at 40$ GGBS mixes with a 80 and 160 mm slump it can be observed that slag type 2 produces strength values greater than or equal to OPC, whilst the strength values associated with slag type 1 are up to 5 MPa lower.

At the 70% GGBS level, and medium cementitious content, the lines for OPC and slag type 2 intersect at a slump value of 120 mm. At slump values less than 120 mm the compressive strength associated with OPC is greater than that of slag type 2. The strength produced by slag type 1 is up to 10 MPa lower than that of slag type 2. In contrast, at the high cementitious content the lines for the two slag types coincide, reflecting the reduced workability of slag type 2, mentioned earlier. At slump values of 80 and 160 mm respectively the compressive strength values produced by high cementitious content, 70% GGBS mixes are approximately 10 and 13 MPa lower than for OPC.

9.^.4 Elasticity.

Two measures of elasticity were made: the dynamic modulus, in which a beam is subject to a very rapid cycle of low stress, and the static modulus, in which a cylinder is subject to a prolonged cycle of stress.

Fig 8.4.i shows the gain in static modulus at 7 and 28 days. Although the 7-day moduli of the high cementitious content mixes rank the blends in a similar order to compressive strength, this is not the case in the medium cementitious content mixes, where there are some unexpectedly low results for the slag type 2 mixes. In contrast, at 28 days the static moduli of the slag type 2 mixes are greater than, or equal to, those of the other mixes.

Fig 8.4.j shows the static modulus plotted against the compressive strength. The relationship appears to be curvilinear, although a linear expresson may be adequate over a limited range of moduli. The relationship between static modulus and compressive strength is often described by a power expression (12). Regression analysis on the untransformed and logarithmicaly transformed compressive strength and static modulus data produced the linear and power relationships indicated. The power expression has a index of 0.29, which is close to the cube root value adopted in CP110 : 1972. The linear expression is similar to equation 17 in Section seven of

BS8110 : Part 2, that is, EC2g = 2 0 + 0 . 2 fQU 2g> f°r estimating the static modulus from the characteristic strength, for normal-weight aggregates.

It can be observed that whilst the OPC results lie either on or above the power relationship; in the GGBS mixes there are twice as many points below the curve, as above it. This suggests lower values of static modulus at any compressive strength in the GGBS mixes. However the effect is small, and the moduli of the GGBS mixes are less than 5 GPa lower than those predicted by the power relationship.

Fig 8.4.k shows the static and dynamic elastic moduli at 7 and 28days, plotted against each other, together with the linear relationship and confidence interval proposed in BS 8110 (equation 19, Section seven).

The dynamic modulus is inherently higher than the static modulus (Section 5.^.2), and indeed the dynamic values in Fig 8.4.k are approximately 10 GPa greater than the corresponding static values. Although the points lie predominantly within the confidence interval, the static modulus values are generally lower, at any dynamic modulus, than would be predicted by the BS 8110 relationship. The limited results available indicate a slightly lower static modulus at any dynamic modulus in the OPC mixes; three of the four points associated with these mixes fall below the lower confidence interval.

9.5 Summary

Three concrete parameters are of over-riding importance during construction : workability (usually slump), strength (usually 28-day compressive strength), and the formwork striking time.

In order to provide practical guidance for engineers, and tie together the various parts of the investigation, the author utilised relationships between compressive strength and slump, and compressive strength and age as follows.

The mean cube strength for striking formwork can be calculated for a required in situ cube strength by applying a factor of 1.88, as shown in Ciria Report 73 (86). Futhermore, the time to reach the required mean cube strength may be predicted from the relationships between compressive strength and age. The equivalent ages to reach in situ cube strength values of 2 and 5 MPa are shown in Tab A.2.2.g. The author related these striking times to the 28-day compressive strength, as proposed by Sadgrove (77), and expanded Fig 8.4.h, relating slump and 28-day compressive strength, to form Fig 8.5. The adopted in situ strength values of 2 and 5 MPa are those recommended in CIRIA 73 and BS 8110 to avoid frost damage to unsaturated and saturated concrete respectively; intermediate values are also shown.

Fig 8.5 is intended as a mix design and formwork striking guide for engineers, allowing all three of the parameters listed above to be predicted for different cementitious contents and blends.

70% GGBS

**09; GGBS

0% GGBS

(sjnoi| JO) sAep 'a6\/ jusieAinbg

(uJUI) duun is

10.1 Introduction

This chapter draws together the findings of the Main Programme of research and the Secondary Study under the headings adopted in Section 2.6, that is: workability, hydration and potential reactivity , strength ,elastic properties and long-term performance. For clarity each of the major conclusions is listed separately and labelled.

The significant interactions between factors, identified in the workability, compressive strength and water absorption data, vindicates the choice of a factorial design for the experimental work.

A constant water content was used throughout the Main Programme, and adoption of a constant workability, instead, would affect the findings.

10.2 Workability (Section 8.3*1)

a) The workability assessment methods generally indicate concordant trends in workability.

b) Increased replacement of OPC by GGBS has a significant effect on workability. At the low cementitious content the increase in workability associated with the incorporation of 70% GGBS is approximately equivalent to a seven litre addition of water to the OPC control mix. At the high cementitious content the workability appears to remain the same or decrease as the proportion of GGBS increases.

c) The differing effects of GGBS upon workability at low and high cementitious contents may be connected with a transition of the effective fines ratio, through an optimum value for workability.

d) The two GGBS types used in the investigation had divergent effects on the workability in the medium and high cementitious content mixes. The decrease in workability associated with the incorporation of GGBS type 2 is probably connected with its a narrow particle size distribution, requiring increased mix water for void filling and surface wetting.

e) The trends in workability observed in the Main Programme were generally supported by the results at the 100^6 GGBS level and other water-cement ratios. However, at low concrete workabilities the two-point test parameters seem to be affected by the formation of a stable annulus of concrete about the impeller orbit.

f) The workability of concrete containing *10%* GGBS type 1, or 405S GGBS type 2, was much more sensitive to a change in the water-cement ratio than those mixes containing OPC or the other cementitious blends. This could have implications for workability control.

g) Quadratic models for each of the GGBS types, involving cementitious content and GGBS level, provide a reasonable fit to the workability data.

h) The transition in the effects of GGBS level and type with cementitious content is supported by significant interactions between cementitious content, GGBS level and GGBS type in the analyses of variance of the slump and compacting factor data.

i) Least significant difference follow-up studies on significant main effects of GGBS level and block indicate that, whilst the GGBS levels are not grouped in any way, one block of workability results are significantly lower than the rest. This was thought to be due to a rise in the dust content of the coarse aggregate.

j) The relationship between slump and g, for different cementitious contents, consists of a series of power expressions; producing higher slump values with increasing cementitious content, particularly at low g values. Significant correlations (>99.8/6 probability) were obtained between the British Standard and two-point test parameters.

The low cementitious content mixes, particularly those containing GGBS, were adjudged to have bled excessively, whilst the high cementitious content mixes containing GGBS type 2 were adjudged to be over-cohesive. A region of ideal cohesion marks is located about g and h values of approximately 2.5 and 3.5 respectively.

The change in impeller torque when concrete is subjected to a period of shearing in the two-point test correlates significantly (>99.856 probability) with the subjective assessment of fresh concrete bleeding, and an objective measure of hardened concrete segregation. This seems to support the use of the two-point test as an indicator of mix stability.

Hydration and Potential Reactivity (Sections 8.3*2 and 8.4)

GGBS type 2 was found to be finer than GGBS type 1, with a higher chemical modulus and lime-silica ratio. These differences, together with possible changes in mineralogy, would be expected to lead to a higher reactivity in GGBS type 2 than GGBS type 1; confirmed by physical tests on cement paste, mortar, and concrete.

Vacuum flask calorimetry is a simple method of generating heat evolution data for concrete. This data appears to give an indication of the temperature differential in modest sections, or may be used to estimate the first-order corrected adiabatic temperature rise.

The vacuum flask data indicates a significant reduction in the peak differential temperature with GGBS level, and an increase in the time to the peak temperature, particularly at the 200 kg/m^ cementitious content. The temperature rise coefficients of the 0,40 and 70% GGBS mixes were approximately 4, 3 and 2 °C per 100 kg of cementitious material.

UPV measurements at early ages can be used to generate profiles which appear to characterise the hydration of concrete mixes with different cementitious blends and contents. These profiles indicate a greater pulse velocity development at higher cementitious contents, at low GGBS levels, and in the GGBS type 2 mixes.

The end of workability , as defined by penetration resistance measurements on mortar, seems to occur when a pulse velocity of about 1.4 km/s is reached.

The activation energy, calculated by applying Arrhenius law to the compressive strength data, has a value of : 50 kJ/mol for pure OPC, 58 and 55 kJ/mol for 40% blends of GGBS type 1 and type 2, and 67 and 58 kJ/mol for 70$ blends of GGBS type 1 and type 2. The higher activation energies in the blended cements suggests a greater response of the hydration rate to elevated curing temperatures; confirmed in the compresssive strength data.

Strength (Sections 8.3*3, 8.3*4 and 8.4)

Compressive strength generally increases with age and cementitious content.

At early ages the compressive strength decreases almost linearly with increasing GGBS level. At later ages, the 40$ GGBS mixes may display a disproportionally high strength; this becomes more pronounced as the curing temperature increases.

The percentage strength values in the GGBS mixes, relative to the OPC control, increase with curing temperature; rising in the 70$ GGBS type 2 mixes from less than 20$ at 3 days under 5°C curing, to over 60$ at 40°C, at the same age.

The compressive strength values at 3 days onwards in the GGBS type 2 mixes are consistently higher, under wet curing conditions, than those of the corresponding slag type 1 mixes. The maximum difference in strength between the slags is approximately 8 MPa.

e) An interaction between age, GGBS level and GGBS type is signified by a differential anticlockwise rotation of the GGBS effect lines about the OPC control mix result, in the pseudo three-dimensional graphs. This rotation means that out of the twelve mix designs incorporating GGBS, strength comparability with the OPC control is attained in eight at 40°C , six at 20°C, one at 10°C, and none under 20°C dry or 5°C wet curing.

f) At early ages, under wet curing conditions, the strength development increases with increasing curing temperature. At later ages compressive strength rises with increasing curing temperature up to 20°C in all mixes, except the OPC control, but then falls slightly at 40°C. This indicates the deleterious effect of elevated curing temperatures on the ultimate strength.

g) The percentage strength values, with respect to standard curing, indicate a greater sensitivity of the 1-day compressive strength of OPC mixes to lower curing temperatures, compared to GGBS mixes. In contrast, at 91 days the percentage strength falls almost linearly with GGBS level, from over 95% in the OPC control, under 10°C wet curing, to approximately 75% in the 70^ GGBS mixes.

h) Curing in air severely retards the development of compressive strength in laboratory specimens from about 3 days onwards. Consequently, compressive strength values at 91 days are between two-thirds and a quarter of the corresponding values for standard curing; this proportion decreasing as the GGBS level increases.

i) When the 28-day compressive strength values of the medium and high cementitious content mixes are compared on an equal slump basis, the values associated with 40$ GGBS type 2 are at least equal to those of OPC, and exceed those of slag type 1 by about 5 MPa. In contrast, at the 70$ GGBS level the compressive strength values of the GGBS mixes are lower than those of the OPC mixes at slump values less than 120 mm. Futhermore, at 70$ GGBS level, and the high cementitious content the relationship between compressive strength and slump coincides for the two slags,

j) Analyses of variance of the compressive strength data yielded significant interaction effects involving cementitious content, GGBS level, curing and GGBS type. These interactions prevent definite conclusions from being drawn about the significance of the main effects,

k) Relative changes in the F-ratios associated with the different effects indicate that, in general : the effects of GGBS type and curing increase with GGBS level; the slag type effect rises from 1 day (the most notable exception being in the high cementitious content mixes) and reaches a peak at around 7 days; and the effect of curing humidity increases with age, whilst that of temperature is sensibly minimised where the compressive strength-age relationships, for the compared regimes, intersect.

l) The cementitious blend affects the shape and temperature dependency of the compressive strength-equivalent age relationships. Lower rates of strength development, at later ages in OPC mixes and early ages in GGBS mixes, are indicated by a decrease in the slope of the relationship in each case; confirmed by regression analysis,

m) Curing at 40°C produces strength values at equivalent ages between 7 and 14 days, up to 10 MPa lower in the OPC mixes and 5 MPa higher in the GGBS mixes, than curing at 20°C. This indicates the relative advantage of heat treating GGBS mixes,

n) Tensile splitting tests give strength values two-thirds to half of those from flexural tests, for the same compressive strength.

The relationship between indirect tensile and compressive strength can be expressed as a power relationship. Under wet curing the relationship for the flexural strength data is similar to that obtained by other workers. However, the power index for the tensile splitting data is higher than has been reported by other workers, using cylindrical specimens.

Curing in air results in a reduction in the indirect tensile strength at any compressive strength. This greater effect of dessication upon indirect tensile strength, compared to compressive strength, is thought to be connected with surface shrinkage cracking. Consistent with the underlying theory of the tests the flexural strength is more affected than the splitting strength.

The indirect tensile strength at any compressive strength appears to be higher in GGBS mixes than OPC mixes, under low curing temperatures. The effect is only slight, producing splitting and flexural strength values 0.2 and 0.4 MPa greater respectively, at any compressive strength.

Elastic Properties (Sections 8.3.5, 8.3-6 and 8.4)

The elastic properties, ultrasonic pulse velocity and dynamic elastic modulus, support the compressive strength ranking of the cementitious blends at early ages. That is, in order of decreasing magnitude: OPC, 40% GGBS type 2, 40^ GGBS type 1, 70% GGBS type 2, and 70% GGBS type 1.

The elastic properties appear more responsive than compressive strength at early ages to changes in mechanical properties brought about by mix design and curing, but less responsive at later ages.

The relationships between compressive strength and the elastic properties may be approximated by exponential functions. Plots of the compressive strength, on a logscale, against pulse velocity and dynamic elastic modulus are curvilinear or bilinear, for wet curing conditions.

d) The greatest change in the relationships between compressive strength and the elastic properties was introduced by a change in the curing humidity. Curing in air gives rise to an increased compressive strength at any value of pulse velocity or dynamic modulus, compared with curing underwater. Under wet curing conditions the compressive strength at any value of pulse velocity or dynamic modulus appears to increase with increasing curing temperature.

e) At compressive strength values greater than about 30 MPa there is a tendancy for the pulse velocity or dynamic modulus to be lower in GGBS mixes than in OPC mixes. At compressive strength values less than about 5 MPa, the reverse is true.

f) The dynamic elastic modulus and the stiffness constant are linked by a fundamental equation, and as expected a very strong relationship was found to exist between them. The relationship seems to be independent of the mix design, but is influenced by the curing conditions. It consists of an upper portion, which is approximately linear, and a lower, curvilinear portion, which can be modelled using a power expression.

g) The linear portions of the relationship between dynamic elastic modulus and the stiffness constant form a series of lines converging at a dynamic modulus of approximately 50 GPa. Below this point curing in air produces a higher elastic modulus, at any value of stiffness constant, than curing underwater. Under wet curing conditions the elastic modulus at any value of stiffness constant decreases with increasing curing temperature.

h) Dynamic Poisson’s ratio can be located on a plot of dynamic modulus and stiffness constant. The ratio rises from approximately 0.4 to 0.2 as the concrete matures.

Curing in air increases the linearity of the relationships between the compressive strength and the elastic properties, and that between the dynamic elastic modulus and the stiffness constant.

The static moduli generally rank the medium water-cement ratio in the same order as the dynamic modulus, although the the 40% GGBS type 2 mixes are promoted above the OPC control mix at 28 days.

The relationship between the static and dynamic elastic moduli appears to be linear. The limited results available indicate that Equation 19 in BS 8110 may overestimate the static modulus at any dynamic modulus, particularly in OPC mixes.

The relationship between the static elastic modulus and compressive strength can be approximated by a linear expression, similar to equation 17 in BS 8110 , or a power expression with an index of 0.29. There are some indications of a lower static modulus at any compressive strength in the GGBS mixes, compared with the OPC mixes; the reduction in the static modulus being less than 5 GPa.

Long-term Performance (Section 8.3-7)

A simple water absorption test has been developed in which only the end of the specimen is in contact with water. This test has potential advantages over the alternative British Standard test, which uses the full immersion of specimens. As expected, a strong linear relationship exists between the water absorption under end-contact and that under full immersion.

The water absorption values at sixty minutes decrease consistently with increasing cementitious content, and when wet curing, relative to dry curing. The range in water absorption with cementitious blend was 1.4 to 0.3 ml/m^2s under dry curing, compared to a range of 0.5 to 0.2 ml/m^2s under wet curing.

c) Under dry curing the water absorption rises with GGBS level, the value more than doubling for 70>6 GGBS mixes compared to the corresponding OPC control mix.

d) Water absorbed and compressive strength can be related by an inverse power law whose coefficents are dependent on the mix design and curing. There was some indication of a slightly lower water absorption in well cured GGBS mixes compared to OPC control mixes of equivalent strength.

e) Analysis of variance of the water absorption data for 10°C and 5°C curing indicates significant main effects of cementitious content and GGBS level; the water absorbed decreases as the cementitious content and GGBS level increase. The other analyses indicate a significant interaction between cementitious content, GGBS level, and either curing humidity or GGBS type.

10.7 Practical Recommendations

The interrelationship between the parameters measured in this investigation, and their bearing upon the engineering performance of concrete, was explained in Section 2.3. The significant difference in workability and strength development of mixes made with the two GGBS typesindicates that consideration must be given both the trial mixes and construction to the source of the slag used. This is particularly the case where there are high demands on the concrete, such as in slip-forming.

When estimating the in situ compressive strength of concrete from pulse velocity measurements, allowance must be made for the curing humidity, curing temperature and cementitious blend.

Dry curing of laboratory specimens detrimentally affected all mixes, leading to a severe reduction in strength, especially indirect tensile strength, and an increase in the water absorption. The properties of GGBS mixes are particulary susceptible to dessication and attention must be paid to the curing on site. The minimum periods of curing and protection in Table 6.5 of BS 8110 do not allow for the level of GGBS in the cementitious blend, and a further tier of curing times is required for LHPBFC. The author, on a basis of equal compressive strength at the cessation of curing, tentatively recommends a period in days of 140/(t + 10) for average ambient conditions and 200/ (t + 10) for poor ambient conditions; where t is the average surface temperature of the concrete.

The reduced early rate of strength development and lower heat evolution in GGBS mixes, compared to OPC mixes, could result in extended formwork striking times in thin sections, at low ambient temperatures. Guidance should be given to engineers, perhaps relating the concrete workability to 28-day strength and the equivalent age for striking formwork.

FURTHER WORK

Significant effects of slag type upon workability and compressive strength have been identified by this work. However, isolation of these effects to physical, chemical or mineralogical properties was not possible. An investigation of slags with similar chemistry but varying particle size distributions, such as that being carried out at Leeds University by F.T.Olorunsogo, may determine the relative importance of the granulate and grinding.

The experimental design used in this work was distorted at the *0%* GGBS level by the provision of a slag type effect. A better method of analysing the results would be a response surface approach (87), which allows the effect of continuous variable, such as GGBS level, to be taken into consideration when testing the significance of a qualitative variable such as GGBS type. A natural extension of this approach would be the fitting of a polynomial model to the compressive strength data.

The work indicates a significant interaction effect of cementitious content and type upon the workability of concrete. The importance of the fine fraction (less the 600 microns) of the fine aggregate has been recognised in the BRE guide "Design of normal concrete mixes" (52). It may be possible to extend this methodology to include a consideration of the cementitious content and grading.

Work by other researchers has indicated that the internal temperature cycle generated within structural elements can significantly influence the relationship between compressive strength and other parameters, such as maturity. An investigation into the effect of low temperature cycles on the development of in situ strength, from cores and temperature profiled cubes,has been carried out by the author (88)•

A diagram combining slump, 28-day compressive strength and striking times was proposed in Section 9.5. Additional data to check its reliability needs to be obtained.

Encouraging results were obtained for the use of torque in the two-point test to assess the stability of mixes to segregation and bleeding. Further work on this topic using short columns has been carried out by the author in the laboratory, however site trials involving the casting of columns or piles would be more relevant.

Other techniques which were promising but which require further research and development are the the measurement of UPV at early ages and water absorption under end-contact. In particular correlations between the water absorption and long-term performance, such as carbonation, could provide a guide to acceptable absorption levels.

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A. 1 Peripheral Work

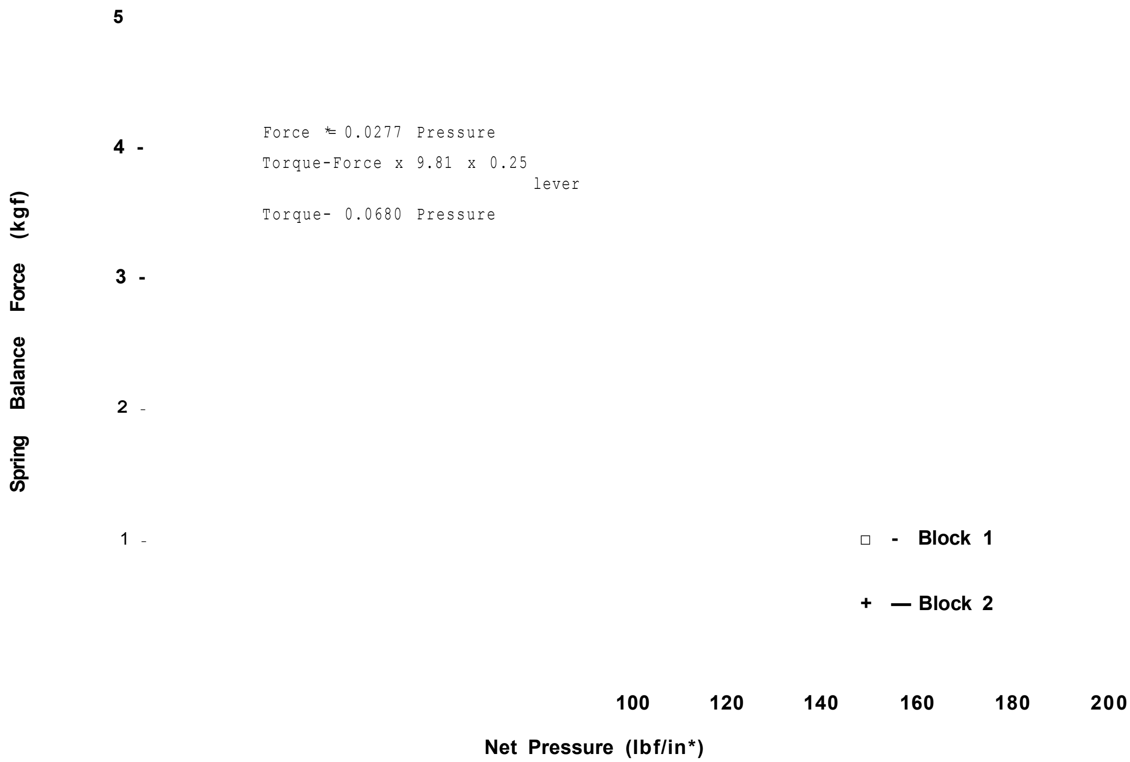

Fig A.1.a : Typical two-point test calibration, showing two blocks of results and adopted relationship.

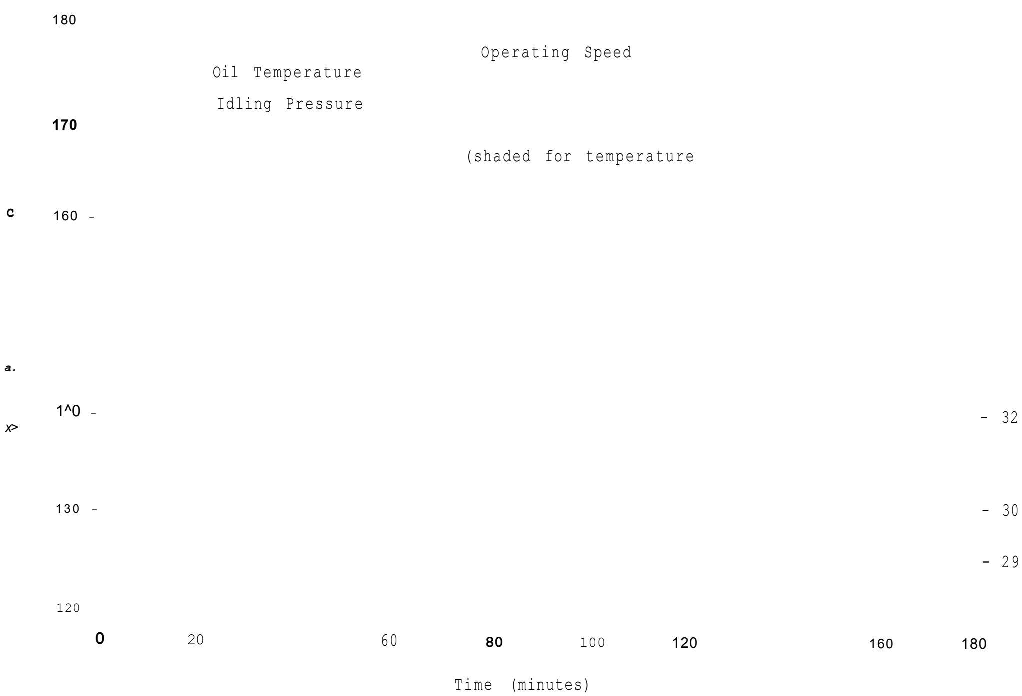

Fig A.1.b : Change in oil temperature and idling pressure (measured at 1.1Hz) with a sequence of operating speeds.

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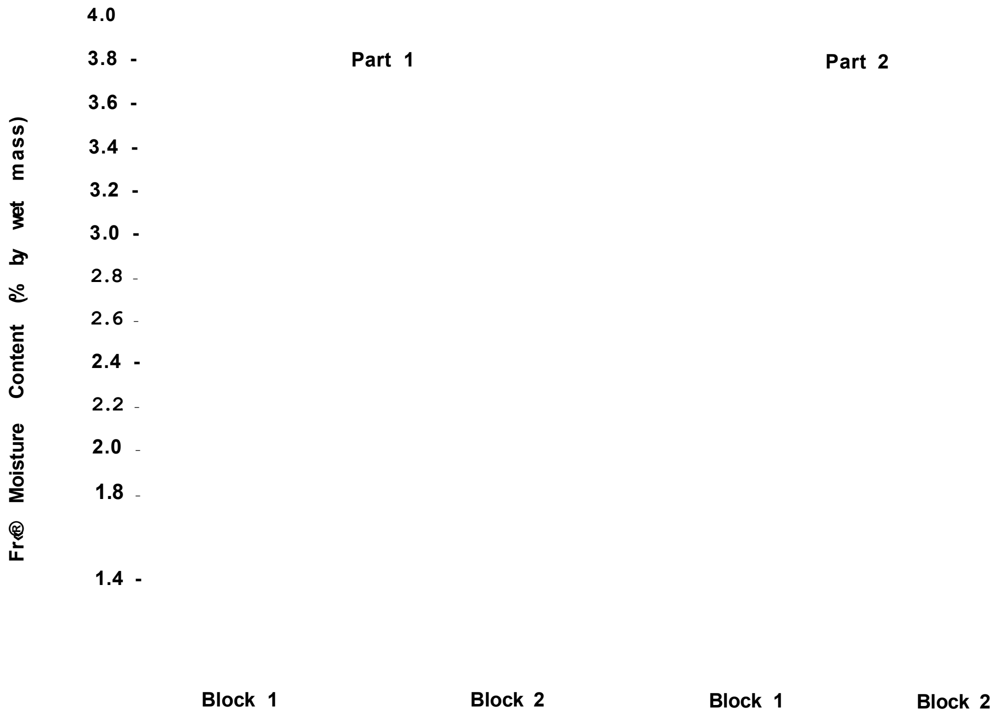

Fig A.1.d : Free moisture content of the fine aggregate.

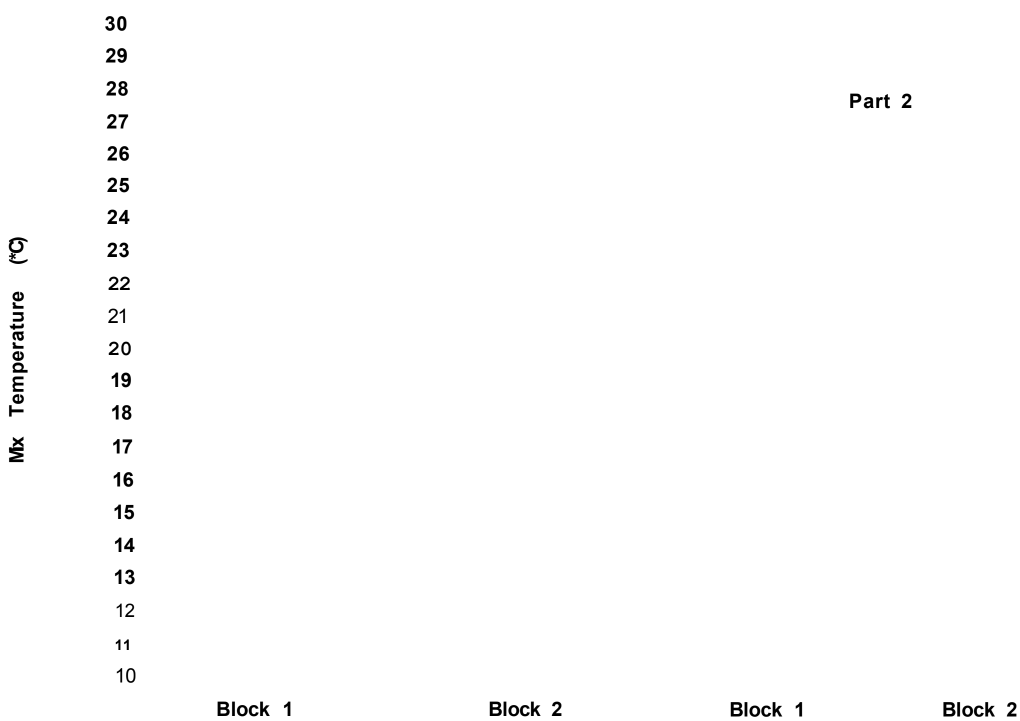

Fig A.1.e : Fresh concrete temperature.

Tab A.1.a : Particle Size Distribution of the Cementitious Materials using three methods of determination.

CUMULATIVE % SMALLER

Particlte Size (dm)	Cilas Granulometre OPC	Slag Type 1	Slag Type 2	Microtrac OPC	Slag Type 1	Slag Type 2	Sedigraph OPC	Slag Type 1	Slag Type 2
128	100.0	98.0	100.0	100.0	100.0	100.0	___	___	___
a 96	100. 0	97.9	100.0	93.1	93.0	100.0	99.2	97 .8	100. 0
64	90.0	91.8	100. 0	88.0	85 .5	100 .0	95.8	91.6	100.0
b 48	88.5	86.9	100.0	82.3	80.7	100.0	86.9	82.2	100.0
32	70.5	74.1	94.3	71.8	71.5	95.2	78.3	76.5	96.8
24	61. 0	64.7	84.9	64.2	63.8	83.2	64.3	66.5	89 .8
16	48.3	54.3	66.4	53.7	58 .1	71.4	47 .8	55.8	76.2
12	42.0	46.1	51.9	42.7	48. 5	57.5	35 .6	45.6	59.5
8	33.0	38.0	38.0	33.0	38.6	40.2	28.3	38.2	45.5
6	28.2	31.5	30.0	27.6	32.9	31.6	18.7	28.8	31.5
4	20.9	25.4	22.7	17.3	20.2	19.1	13.0	19.7	20.0
c 3	16. 1	20.2	17.7	6.6	8.0	7.1	7.1	12.3	12.5
2	11.0	14.9	12.9	—	—	—	4.3	5.8	7 .8
1.5	8.3	10.2	8.8	—	—	—	1.3	2.3	4.0
1	6.8	8.3	7.2	—	—	—	0.9	0.8	2.0

Not available
a b c Actual sizes for the Microtrac and Sedigraph were 90, 45 and 2. 8 (am respectively.

Tab A. 1.b : Concrete mix proportions allowing for the true relative densities and moisture condition of the constituents.

Batch Quantities kg per cubic metre

Mix Design No.	Code	WATER (Free)	CEMENT OPC	GGBS	AGGREGATES Fine	Coarse	W/C	A/C	%Fines
1	2S0	165	200		840	1165	0.82	9.92	41. 84
2	2S4	165	120	80	835	1165	0.82	9.90	41.82
3	2S7	165	60	140	835	1160	0.83	9.93	41.83
10	2P4	165	120	80	835	1165	0.32	9.90	41.82
11	2P7	165	60	140	835	1160	0.83	9.93	41 .33
4	3S0	165	300	___	755	1165	0.55	6.35	39.36
5	3S4	165	180	120	755	1160	0.55	6.36	39 .36
6	3S7	165	90	210	750	1155	0.55	6.36	39.36
12	3P4	165	180	120	755	1160	0.55	6.33	39 .36
13	3P7	165	90	210	750	1155	0.55	6.34	39.36
7	4S0	165	405	___	675	1160	0.41	4.55	36.68
8	4S4	165	240	160	670	1155	0.41	4.57	36.67
9	4S7	165	120	280	670	1155	0. 41	4.55	36 .68
14	4P4	165	240	160	670	1155	0 .41	4.56	36.67
15	4P7	165	120	280	670	1155	0.41	4.56	36 .66

* W./C=Free Water/Total Cementitious Content
A/C= Aggregate/Total Cementitous Content
! Oven-dried and saturated surface-dry Relative Densities

Main Programme

Workability

Tab	A.2.1.a	summary of the data
Tabs	A.2.1.b-c	test results
Tab	A.2.1.d	mix stability
Tab	A.2.1.e	100% GGBS mixes

Tab A.2.1.a : Summary of the Workability data, showing mean and standard deviation of the four blocks of results.

Mix Design No.	Code	Slump (mm)	sd*	Compacting Factor	sd	*E* (Nm)	sd	h (Nms)	sd
1	2S0	17	6	0.902	0.009	5.72	1.19	5.10	0.31
2	2S4	33	11	0.915	0.009	2.80	1.13	6.82	0.95
3	2S7	35	13	0.918	0.008	0.91	0.63	6.95	0.56
10	2P4	25	8	0.916	0.013	3.98	1.66	5.32	0.80
11	2P7	41	18	0.920	0.019	2.09	1.66	6.29	1.13
4	3S0	81	24	0.956	0.007	2.57	0.58	3.46	0.61
5	3S4	96	23	0.956	0.016	1.91	0.17	3.52	0.64
6	3S7	147	22	0.971	0.004	1.42	0.14	3.03	0.45
12	3P4	83	25	0.951	0.013	2.83	0.75	3.48	0.44
13	3P7	62	12	0.937	0.009	3.84	1.45	3.80	0.85
7	4S0	85	13	0.958	0.012	2.59	0.61	2.93	0.48
8	4S4	94	24	0.962	0.009	2.88	0.67	2.87	0.19
9	4S7	114	26	0.967	0.007	2.61	0.43	3.35	0.44
14	4P4	46	16	0.892	0.033	5.02	0.92	3.36	0.47
15	4P7	37	8	0.846	0.031	6.74	0.59	4.67	0.31

* Standard deviation

Tab A.2.1.b : British Standard Workability test results.

Mix Design No.	Code	Block	Slump A (mm)	Slump B (mm)	Mean	CF	plastic density (kg/m 3)
1	2S0	1	20	15	18	0.903	2402
		2	5	20	13	0.905	2371
		3	15	10	13	0.889	2397
		4	30	20	25	0.910	2386
2	2S4	1	40	45	43	0.924	2391
		2	25	30	28	0.903	2400
		3	30	10	20	0.918	2395
		4	45	35	40	0.915	2399
3	2S7	1	35	40	38	0.918	2373
		2	45	35	40	0.918	2380
		3	20	10	15	0.908	2386
		4	55	35	45	0.928	2393
10	2P4	1	20	25	23	0.918	2415
		2	20	30	25	0.900	2415
		3	35	35	35	0.931	2393
		4	20	10	15	0.915	2380
11	2P7	1	30	40	35	0.903	2404
		2	75	50	63	0.945	2413
		3	20	20	20	0.908	2389
		4	50	40	45	0.922	2402
4	3S0	1	80	90	80	0.954	2417
		2	70	60	65	0.962	2402
		3	60	70	65	0.947	2409
		4	100	130	115	0.962	2409
5	3S4	1	85	90	88	0.957	2417
		2	110	125	118	0.966	2426
		3	65	70	68	0.933	2408
		4	115	105	110	0.966	2413
6	3S7	1	160	160	160	0.976	2411
		2	110	125	118	0.967	2406
		3	170	165	168	0.969	2404
		4	155	130	143	0.971	2411
12	3P4	1	65	70	68	0.940	2415
		2	140	100	120	0.968	2408
		3	80	60	70	0.942	2415
		4	80	70	75	0.953	2406
13	3P7	1	45	45	45	0.929	2420
		2	75	70	73	0.945	2406
		3	60	60	60	0.929	2400
		4	75	60	68	0.944	2406
7	4S0	1	105	90	98	0.975	2433
		2	65	70	68	0. 956	2437
		3	90	90	90	0.949	2433
		4	90	80	85	0.950	2442
8	4S4	1	85	80	83	0.956	2433
		2	65	65	65	0.954	2429
		3	120	115	118	0.966	2422
		4	125	90	108	0.973	2422
9	4S7	1	120	105	113	0.965	2420
		2	125	155	140	0.974	2399
		3	80	75	78	0.958	2400
		4	140	110	125	0.972	2417
14	4P4	1	50	55	53	0.895	2426
		2	50	45	48	0.891	2417
		3	20	25	23	0.850	2417
		4	60	60	60	0.930	2428
15	4P7	1	30	35	33	0.851	2415
		2	45	50	48	0.886	2408
		3	30	30	30	0.832	2417
		4	35	35	35	0.813	2418

Tab A.2.1.C : Two-point Workability test results.

Mix Design No.	Mix Design Code	Block	g (Nm)	h (Nme)	r	upper g (Nm)	lower g (Nm)	upper h (Nms)	lower h (Nms)
1	2S0	1	6.26	5.51	0.970	6.90	5.61	6.50	4.53
		2	6.45	4.79	0.985	6.83	6.06	5.38	4.20
		3	6.21	4.95	0.996	6.42	6.00	5.27	4.62
		4	3.94	5.15	0.991	4.28	3.60	5.67	4.65
2	2S4	1	2.54	7.78	0.980	3.28	1.81	8.90	6.65
		2	4.37	7.47	0.996	4.70	4.04	7.97	6.97
		3	2.62	5.87	0.993	2.96	2.29	6.37	5.36
		4	! 1.68	6.15	0.996	1.98	1.38	6.57	5.72
3	257	1	0.82	7.27	0.965	1.76	-0.12	8.69	5.85
		2	0.48	6.77	0.969	1.30	-0.35	8.02	5.53
		3	1.82	7.51	0.991	2.30	1.34	8.23	6.78
		4	0.50	6.25	0.984	1.05	-0.04	7.07	5.44
10	2P4	1	4.86	4.42	0.993	5.12	4.61	4.80	4.03
		2	5.32	5.97	0.997	5.54	5.09	6.32	5.63
		3	1.60	6.02	0.988	2.04	1.16	6.68	5.35
		4	4.14	4.87	0.991	4.45	3.83	5.34	4.40
11	2P7	1	4.56	7.13	0.995	4.89	4.23	7.64	6.63
		2	! 1.48	5.03	0.979	1.96	1.00	5.85	4.20
		3	1.19	7.36	0.980	1.90	0.48	8.43	6.30
		4	1.12	5.65	0.969	1.81	0.43	6.67	4.62
4	3S0	1	2.83	3.01	0.984	3.09	2.56	3.40	2.62
		2	2.96	3.35	0.982	3.27	2.64	3.81	2.88
		3	2.76	4.35	0.996	2.95	2.57	4.63	4.07
		4	1.71	3.11	0.989	1.93	1.48	3.44	2.78
5	3S4	1	1.98	3.28	0.958	2.45	1.51	3.98	2.57
		2	1.66	3.30	0.988	1.91	1.41	3.67	2.93
		3	2.06	4.46	0.994	2.29	1.83	4.81	4.11
		4	1.93	3.03	0.988	2.16	1.70	3.38	2.69
6	3S7	1	1.40	2.52	0.983	1.62	1.17	2.86	2.18
		2	1.60	2.99	0.990	1.80	1.40	3.28	2.69
		3	1.25	3.61	0.996	1.41	1.08	3.86	3.37
		4	1.42	2.99	0.990	1.63	1.21	3.30	2.68
12	3P4	1	3.87	3.41	0.981	4.19	3.55	3.89	2.92
		2	2.11	3.29	0.988	2.36	1.87	3.66	2.91
		3	2.55	4.11	0.986	2.88	2.23	4.60	3.62
		4	2.79	3.11	0.983	3.06	2.51	3.53	2.69
13	3P7	1	5.43	2.79	0.980	5.70	5.17	3.19	2.38
		2	2.65	3.61	0.977	3.03	2.28	4.17	3.05
		3	4.70	4.84	0.981	5.15	4.24	5.52	4.15
		4	2.57	3.95	0.994	2.77	2.36	4.26	3.64
7	4S0	1	2.42	2.55	0.984	2.65	2.20	2.88	2.22
		2	3.48	2.75	0.983	3.73	3.24	3.12	2.38
		3	2.35	3.63	0.990	2.61	2.09	4.01	3.25
		4	2.11	2.80	0.979	2.39	1.83	3.22	2.38
8	4S4	1	3.08	3.15	0.970	3.46	2.70	3.71	2.59
		2	3.74	2.77	0.980	4.01	3.47	3.17	2.37
		3	2.36	2.81	0.995	2.49	2.22	3.01	2.61
		4	2.33	2.75	0.983	2.58	2.09	3.11	2.38
9	4S7	1	2.58	3.07	0.991	2.78	2.37	3.38	2.77
		2	2.59	3.58	0.994	2.78	2.40	3.86	3.30
		3	3.16	3.84	0.976	3.57	2.75	4.46	3.23
		4	2.12	2.90	0.982	2.39	1.86	3.29	2.50
14	4P4	1	5.19	2.74	0.991	5.37	5.02	3.00	2.47
		2	5.33	3.88	0.991	5.57	5.09	4.24	3.51
		3	5.85	3.42	0.980	6.18	5.52	3.92	2.93
		4	3.70	3.41	0.989	3.94	3.46	3.78	3.05
15	4P7	1	7.53	5.09	0.995	7.77	7.28	5.46	4.72
		2	6.65	4.60	0.991	6.94	6.36	5.03	4.16
		3	6.09	4.35	0.988	6.41	5.78	4.83	3.87
		4	6.67	4.65	0.988	7.01	6.33	5.17	4.12

one set of impeller torques and speeds
removed to give 6ix degrees of freedom

Tab A.2.1.d : Subjective and Objective Assessments of Mix Stability.

Mix Design No.	Code	Block	Subjective Cohesion Mark	Subjective Bleeding Mark	Objective Torque Change (Nm)	Objective Mean Transit Time Range (ps)
1	2S0	3	3.5	3.5	2.78	3.05
		4	4.0	6.0	2.93	2.45
2	2S4	3	1.5	8.0	3.26	5.30
		4	* 3.0	3.5	3.38	5.05
3	2S7	3	4.0	7.0	4.62	4.30
		4	* 3.0	6.5	4.05	7.20
10	2P4	3	4.0	3.5	3.60	5.60
		4	3.0	6.0	2.81	4.70
11	2P7	3	3.0	7.0	4.71	7.45
		4	3.0	6.0	3.69	4.65
4	3S0	3	5.0	0.0	2.15	2.85
		4	6.0	1.0	1.36	2.10
5	3S4	3	5.5	1.0	2.30	3.40
		4	7.0	2.5	1.54	3.10
6	3S7	3	2.0	2.5	1.42	3.90
		4	3.0	3.0	1.21	4.10
12	3P4	3	5.5	2.0	2.33	2.95
		4	5.5	2.0	2.02	3.05
13	3P7	3	6.0	3.0	2.99	3.40
		4	6.0	1.5	1.96	3.35
7	4S0	3	5.5	1.0	1.78	2.10
		4	6.0	0.0	1.33	1.75
8	4S4	3	6.0	0.5	0.97	2.60
		4	6.0	1.0	1.45	2.90
9	4S7	3	6.0	2.0	2.09	1.25
		4	6.0	2.0	1.48	2.30
14	4P4	3	7.5	0.0	1.03	1.70
		4	7.0	1.0	1.84	1.90
15	4P7	3	9.0	1.5	1.75	1.55
		4	* 10.0	0.5	1.60	2.30

* Temporary Assessor

Tab A.2.1.e : Workability results for the 100$ GGBS mixes.

Mix Design Code	Slump (mm)		Compacting Factor		g (Nm)	h (Nms)
2S10	170	6	0.951		0.73	3.14
2P10	150	s	0.937	!	0.36	5.98
3S10	208	C	0.970		0.47	2.22
3P10	118	U	0.943		2.08	4. 15
4S10	175		0.981		1.52	2.79
4P10	18		0.753		7.50	4.06

6 shear
c collapse
u unstable
! one set of impeller torques and speeds removed

A.2.2 Strength and Elasticity

Figs A.2.2.a	equivalent cube strength
Figs A.2.2.b-f	strength against equivalent age
Fig A.2.2.g	pulse velocity in air and underwater
Figs A.2.2.h-i	dynamic modulus and stiffness constant
Tabs A.2.2.a-f	summary of the data
Tab A.2.2.g	formwork striking times
Tabs A.2.2.h-j	results for 40°C wet curing
Tabs A.2.2.k-m	results for 20°C wet curing
Tabs A.2.2.n-p	results for 20°C dry curing
Tabs A.2.2.q-s	results for 10°C wet curing
Tabs A.2.2.t-v	results for 5°C wet curing

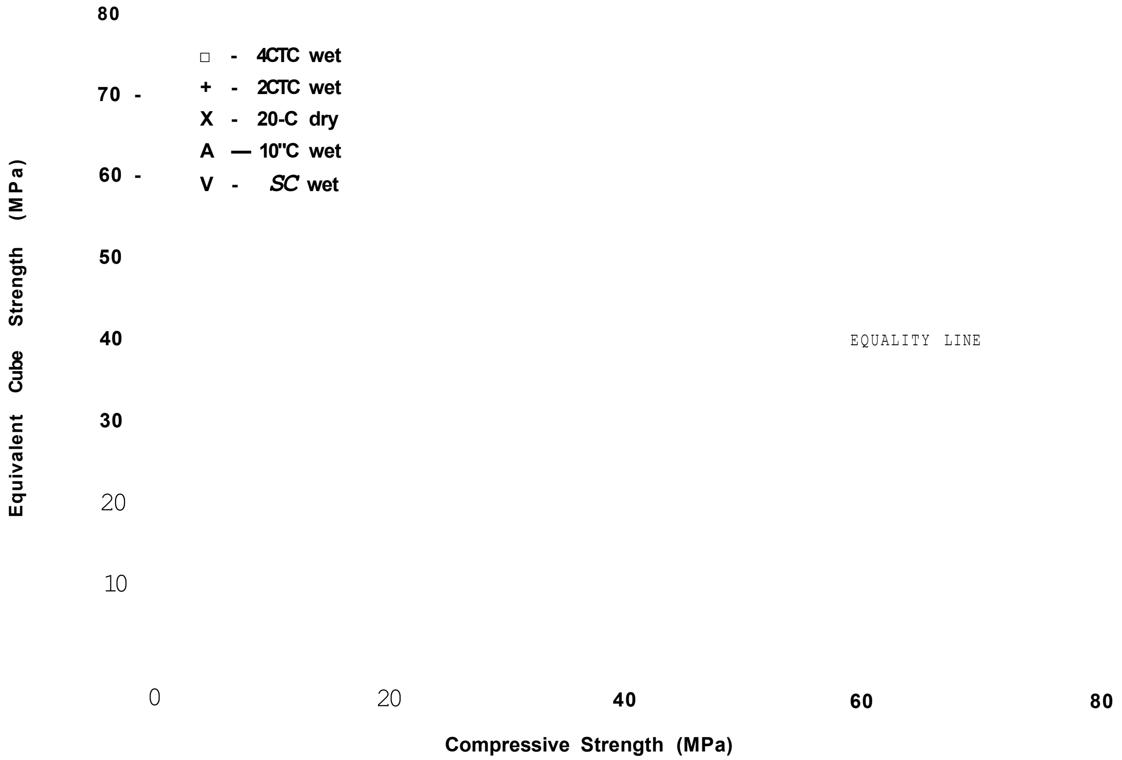

Fig A.2.2.a : Equivalent cube strength against compressive strength for different curing conditions.

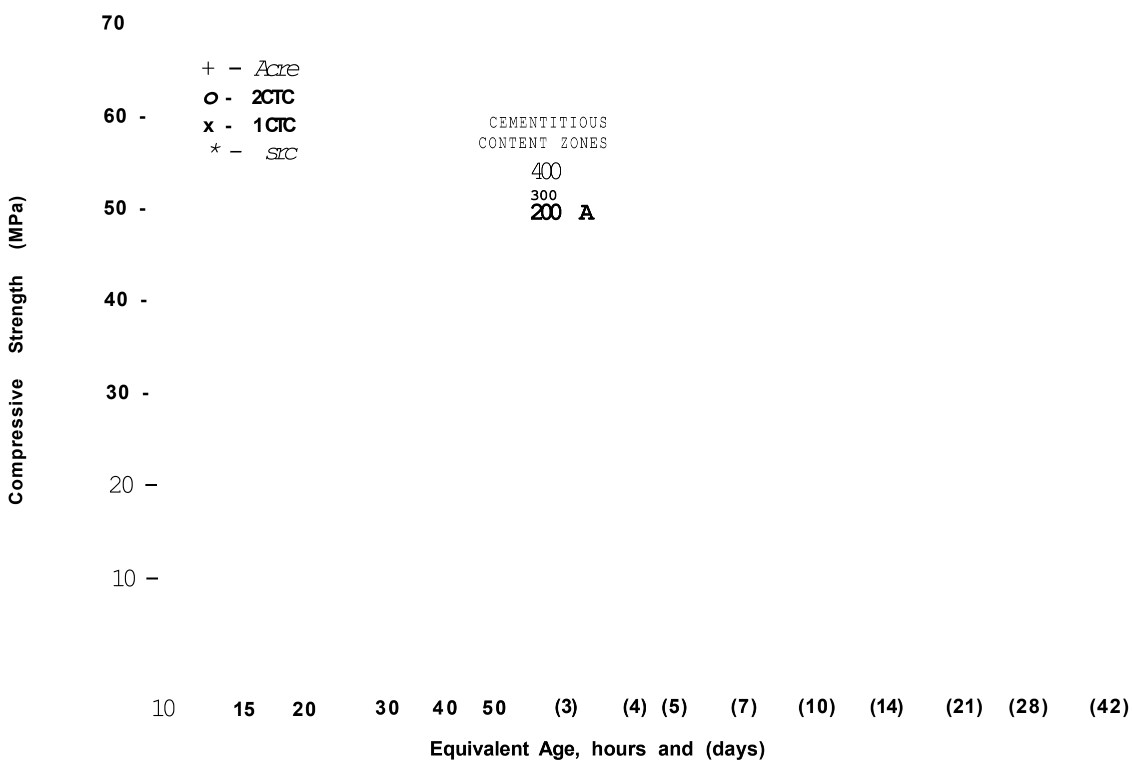

Fig A.2.2.b : Compressive strength against equivalent age (Sadgrove formula on a logscale) for the OPC control mixes.

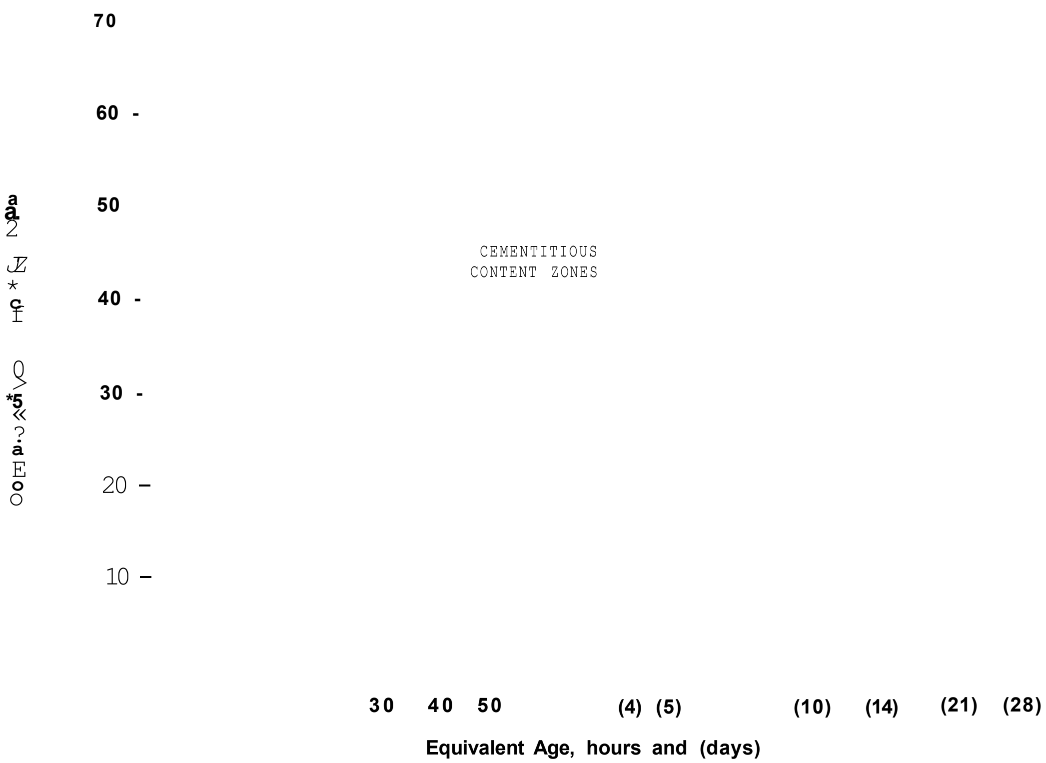

Fig A.2.2.C : Compressive strength against equivalent age (Sadgrove formula on a logscale) for the 40$ GGBS Type 1 mixes.

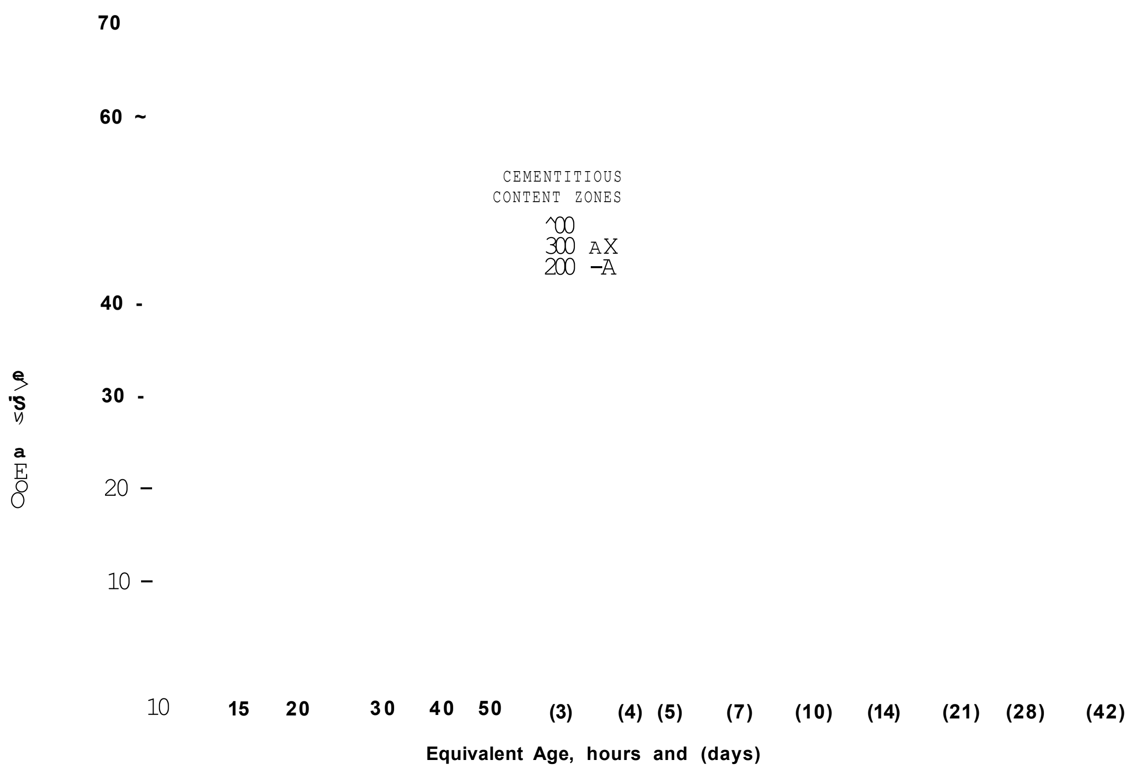

Fig A.2.2.d : Compressive strength against equivalent age (Sadgrove formula on a logscale) for the 40$ GGBS Type 2 mixes.

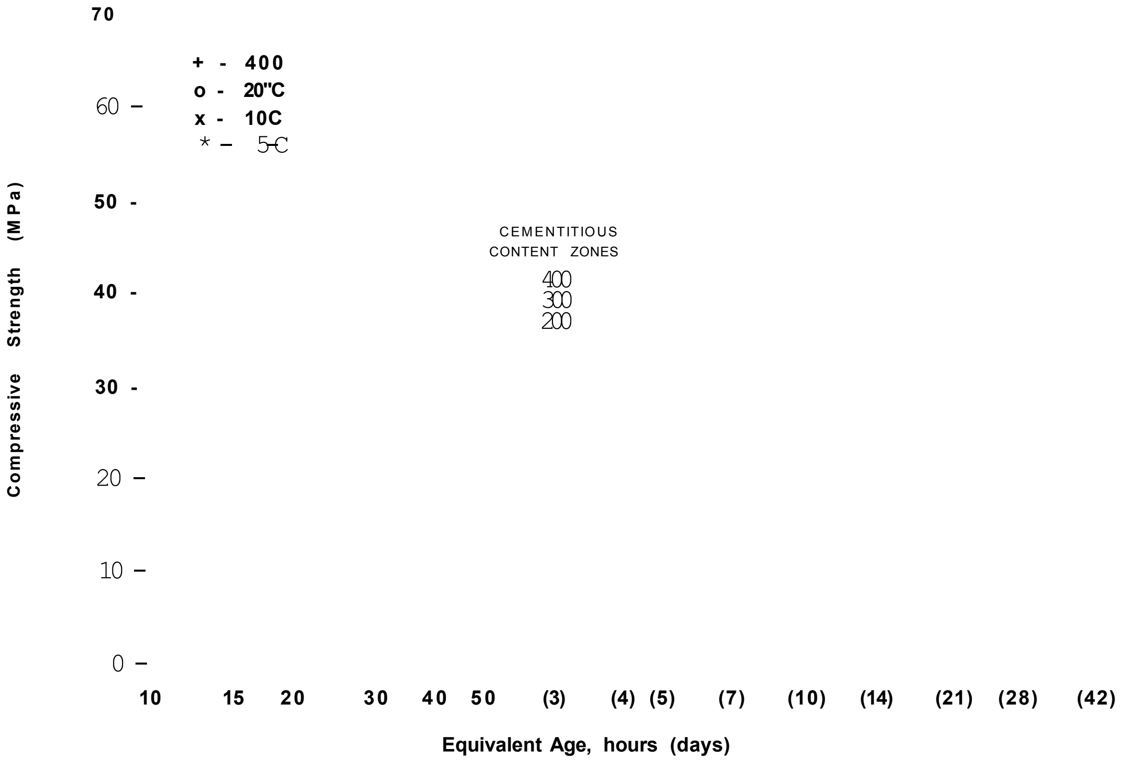

Fig A.2.2.e : Compressive strength against equivalent age (Sadgrove formula on a logscale) for the 70% GGBS Type 1 mixes.

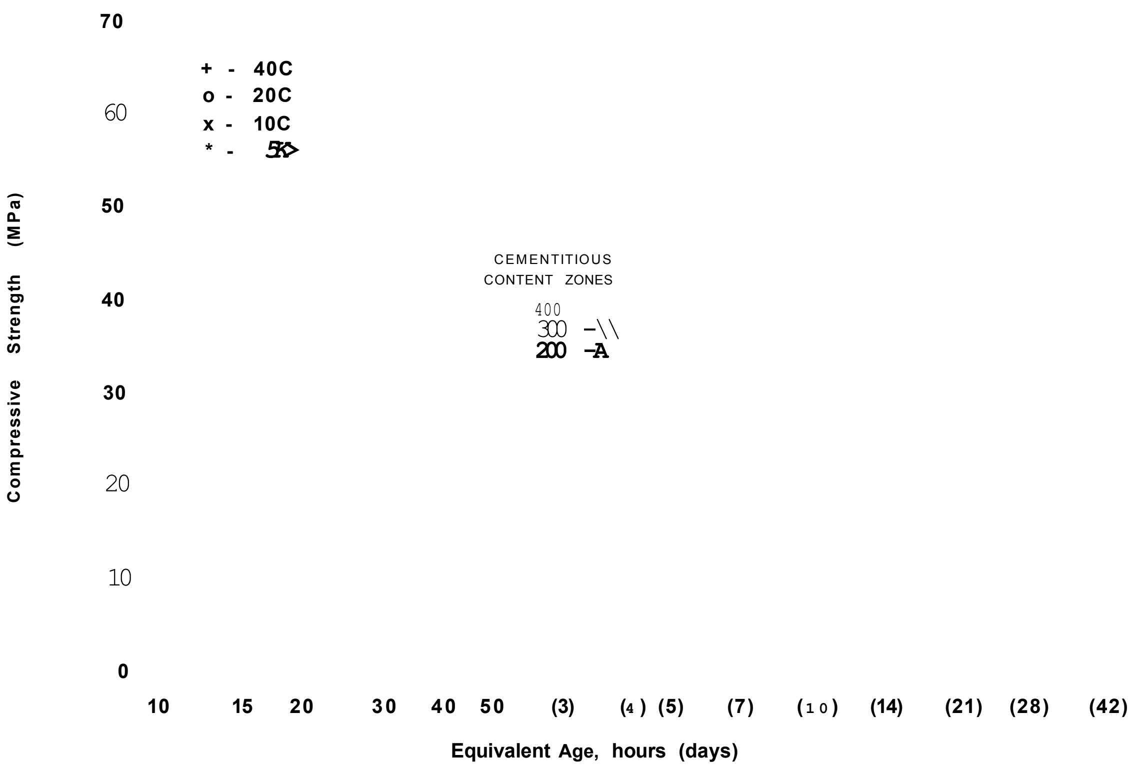

Fig A.2.2.f : Compressive strength against equivalent age (Sadgrove formula on a logscale) for the 70% GGBS Type 2 mixes.

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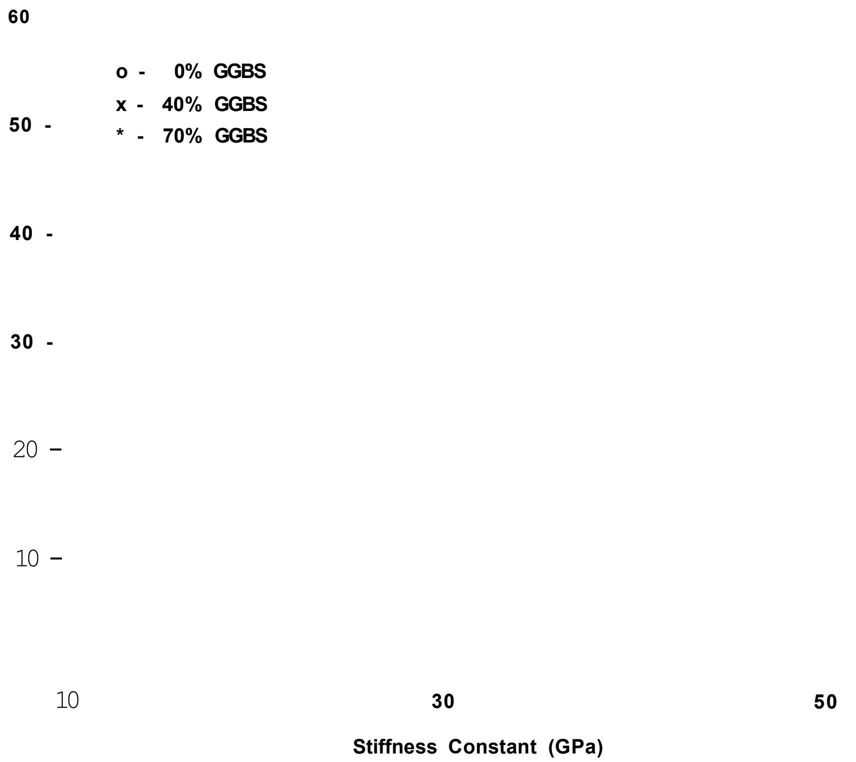


(i) 40°C wet curing

(ii) 20°C wet curing

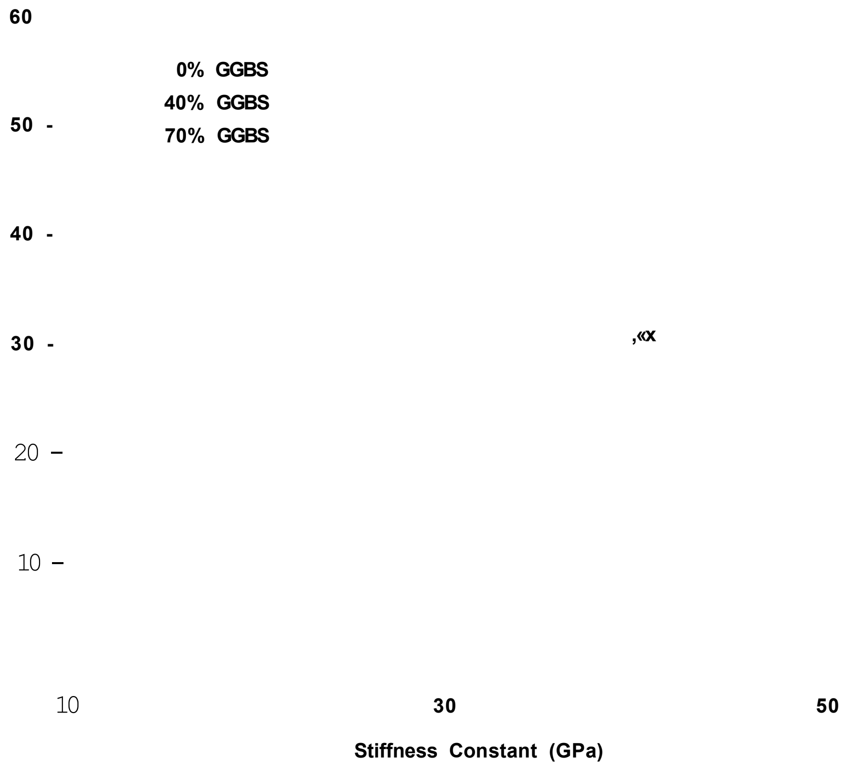
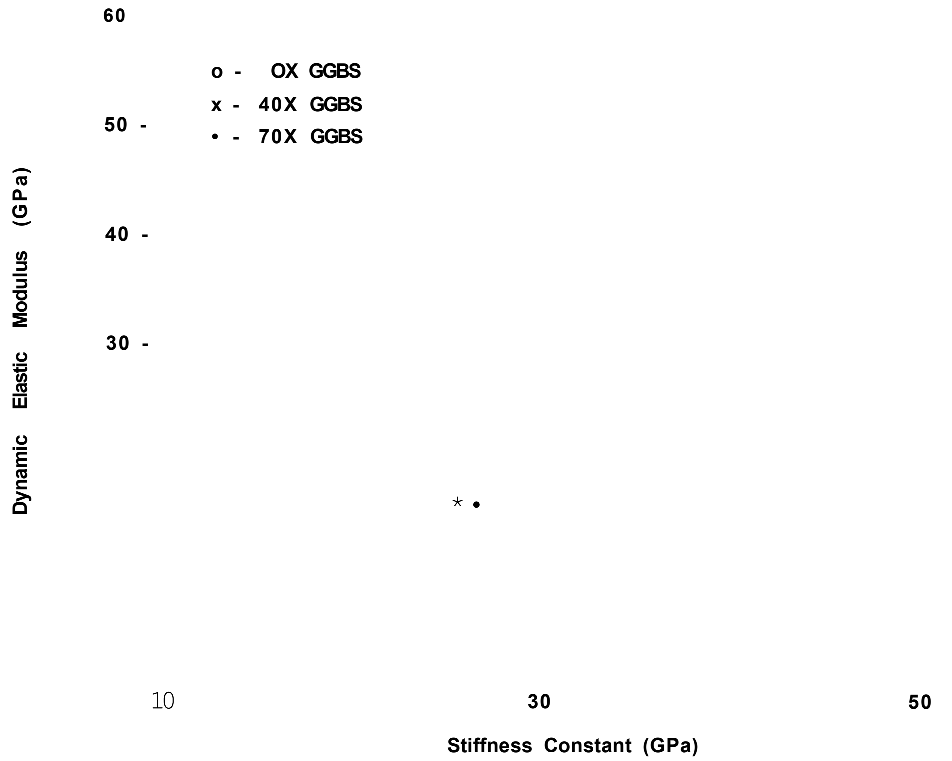


Fig A.2.2.h : Dynamic elastic modulus against the stiffness constant at medium curing temperatures.



(i) 10°C wet curing

(ii) 5°C wet curing

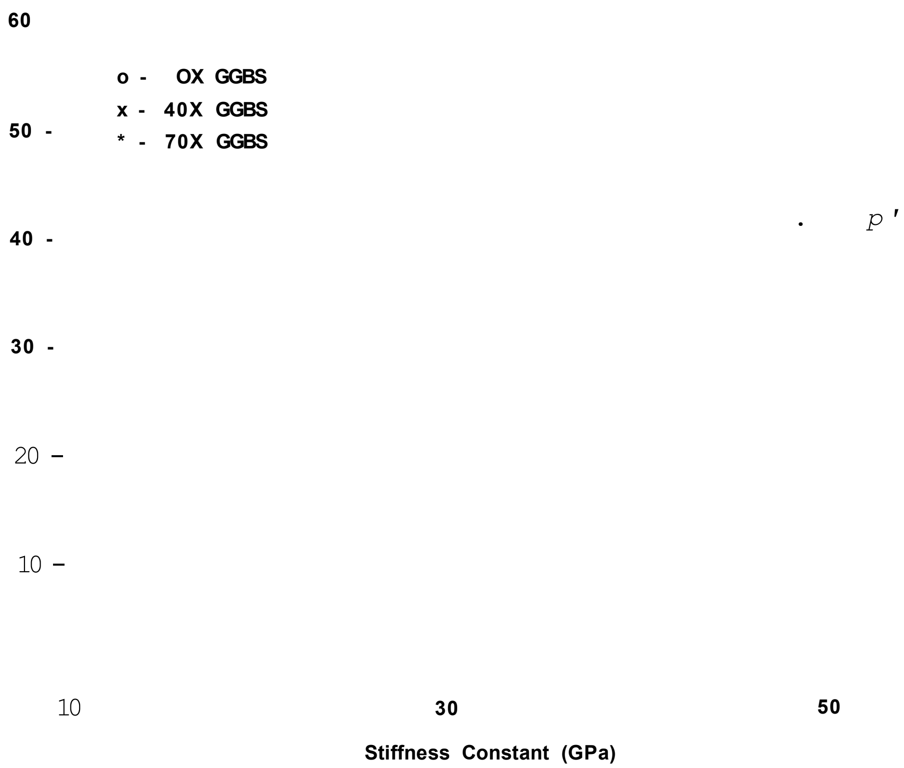


Fig A.2.2.i : Dynamic elastic modulus against the stiffness constant at low curing temperatures.

Tab A.2.2.a : Summary of the Compressive Strength data, showing the mean of the two blocks of results.

[illegible]

Tab A.2.2.b : Summary of the Pulse Velocity data for the beams

Tab A.2.2.C : Summary of the Pulse Velocity data for the cubes

Tab A.2.2.d : Summary of the Dynamic Elastic Modulus data, showing the

[illegible]

O 1O C4 D' H O G G G G ro CM <3' CM o

M ' O X O O f - 03 M CM CM CO O rf HT rr G

CM CM M CM M rr G CM G CM

f f 1 O O O D N CD H G— G G N O) r-

rr CO CD CO t- IP H CO CO N C M H H I C H

M M O M O CM CM rH CM rH CO CO CM CM CM

CO CO CD CO CO CD co rr CM 03 CM H O) ^ 03

O CD CO 03 rr t- 1O C- CO 03 r- CM rr CM CM

M O O O O M M O M O CM CM M CM M

rr 03 CM CO C- rr f~ G G G O CD O CM 1O G O G rr rr G CM G G G G rH O CM G

ocoHoo) rr OO 03 03 T-I rH f- to G G GGGGG CM O CM G G

CM CM CM CO CM G rr rT G rr CD CD LO CD CD rT G CM G G G G rT G rr

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CO rr CO rr rr LO LO LO LO LO LO CD CD IO G G G rT rr G G G G r r

MOHor CD CM 03 CD H t-i CD rH CO rr O G G G LO G G G CM CM G f- G G CH

CM O CM O CD o c-- co oo rr G G— G G G G G rH rH G G C- O O G

IrH rH CM rH CO CO CM CO CM rr CO CO CO CO rH O O O O G CM CM G CM

C D r H O O C D CO G CM CM CM G C '-r T C M * G N C M H G rH G G O G— G r T G G G

O rr 03 rr to rH to OO 03 CO G G CM CM G CM O G rT rH G O CM G G

CM CM rH CM CM rr rr co rr rr LO LO IO CO LO CM CM rH CM CM rT rr G rr G

G O G O CM CO N G rr DO G O rH LO CD O CM G G G C. f- G G rr

H C C H r T C M CM LO C^ rr CO G CO IO CO rr GGGGG G CM G CM D-

G G G G G LO rr rr LO LO G G G G G G G C M G G G G r T G r T G G G G G

CO G i-H rH G G— G 03 H CM LO r-t r T G O rH CM G rr G rH G t- G

CD LO rr f- t— G CM rT CM O CO LO OO C- GO G G G rH G G G rr OO

1-H TH TH CM G CM G G G G G G G rH O O rH O G CM CM G CM

o rr t—rr r- o r r r - r r r - o rr c-- rr c~ o rr r- rr c- orrr-rrt^ o rr t~ rr c-

CM CM CM04 CM CO CO CO PH PH G CO CO OH PH CO CD CD Or Ph GGGGG CO CO CO PH PH

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rT LO CD W G f- G G rr to rH CM G O rH rT G G CM G G- G G r T G

Tab A.2.2.f : Summary of the calculated values of Stiffness Constant

Tab A.2.2.g : Times to reach In Situ Cube Strength values of 2 and 5 MPa.

Time to reach an in situ Compressive Strength of 2 Mpa *

Mix Design Code	Age at 10°C (days)		Equivalent Age at 20°C (days)		Age at 5°C (days)		Equivalent Age at 20°C (days)	
	Blk 1	Blk 2	Blk 1	Blk 2	Blk 1	Blk 2	Blk 1	Blk 2
2S0	1.8	2.1	0.94	1.10	2.6	2.9	0.88	0.99
2S4	5.5	5.8	2.87	3.03	8.0	8.2	2.72	2.79
2S7	11.4	13.5	5.95	7.04	17.3	16.4	5.89	5.58
2P4	4.4	4.7	2.30	2.45	6.1	6.9	2.08	2.35
2P7	8.1	10.0	4.23	5.22	12.4	13.5	4.22	4.59
3S0	1.0	1.0	0.52	0.53	1.4	1.4	0.47	0.47
3S4	1.4	1.7	0.73	0.89	2.4	2.5	0.80	0.83
3S7	5.1	5.7	2.66	2.97	7.6	8.2	2.59	2.79
3P4	1.3	1.4	0.68	0.73	2.3	2.5	0.77	0.83
3P7	3.6	4.0	1.88	2.09	4.9	5.5	1.65	1.85
4S0	0.7	0.8	0.39	0.40	1.0	1.0	0.34	0.35
4S4	0.9	0.9	0.46	0.46	1.5	1.5	0.49	0.52
4S7	2.5	3.2	1.28	1.67	3.9	4.2	1.31	1.41
4P4	0.9	1.0	0.47	0.54	1.2	1.3	0.42	0.43
4P7	1.6	1.7	0.81	0.86	3.0	3.3	1.02	1.11

Time to reach an in situ Compressive Strength of 5 Mpa

Mix Design Code	Age at 10°C (days)		Equivalent Age at 20°C (days)		Age at 5°C (days)		Equivalent Age at 20°C (days)	
	Blk 1	Blk 2	Blk 1	Blk 2	Blk 1	Blk 2	Blk 1	Blk 2
2S0	5.5	8.7	2.87	4.54	9.2	11.3	3.13	3.85
2S4	24.2	25.0	12.62	13.04	37.0	42.0	12.59	14.29
2S7	31.0	32.0	16.17	16.69	55.0	60.0	18.72	20.42
2P4	16.3	18.0	8.50	9.39	28.0	28.0	9.53	9.53
2P7	23.8	26.0	12.41	13.56	36.5	39.5	12.42	13.44
3S0	1.8	1.8	0.93	0.93	2.6	2.8	0.88	0.94
3S4	4.6	3.9	2.37	2.03	6.2	6.9	2.11	2.35
3S7	12.6	13.2	6.57	6.89	19.2	20.7	6.53	7.04
3P4	3.7	3.9	1.93	2.03	5.7	6.5	1.94	2.21
3P7	10.1	8.2	5.27	4.28	12.2	15.0	4.15	5.10
4S0	1.0	1.1	0.54	0.57	1.5	1.5	0.49	0.49
4S4	1.9	2.0	0.99	1.02	3.1	3.4	1.05	1.16
4S7	6.7	6.9	3.49	3.60	8.8	9.8	2.99	3.33
4P4	1.7	1.7	0.89	0.89	2.3	2.5	0.78	0.85
4P7	4.1	4.4	2.11	2.30	7.2	7.5	2.45	2.55

* requiring cube strengths of 3.8 and 9.4 MPa respectively

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Tab A.2.2.1 : 7 and 28-day results for oonorete under 40°C wet curing

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	20	[illegible]	4,[illegible]	[illegible]	[illegible]	4.[illegible]	34 .3	37 .2
[illegible]	19 .0	.72	4,[illegible]	4	[illegible]	4.[illegible]	35 [illegible]	38 .7
[illegible]	20 .0	.66	4.[illegible]	4 [illegible]	4 [illegible]	4.[illegible]	34 .3	39 .3
[illegible]	19 .9	.52	4.[illegible]	4 [illegible]	4 [illegible]	4.[illegible]	35 .1	40 .3
[illegible]	16 [illegible]	.43	4.[illegible]	4 [illegible]	4 [illegible]	4.[illegible]	31 .5	39 .2
[illegible]	17 .1	.39	4.[illegible]	4,	4,[illegible]	4.[illegible]	31 .4	39 .8
10	21 [illegible]	.67	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	35 .2	40 .1
[illegible]	21 .3	.75	4 [illegible]	4.[illegible]	4.[illegible]	4 [illegible]	34 .9	40 .1
11	23 .0	.81	4 [illegible]	4.[illegible]	4.[illegible]	4.[illegible]	36 [illegible]	42 .0
[illegible]	22 .4	.65	4,[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	34 .3	40 .5
[illegible]	42 .3	3 .16	4.[illegible]	4.[illegible]	4.[illegible]	[illegible]	41 [illegible]	43 [illegible]
[illegible]	39,.4	2,.77	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	41 .9	44 .0
[illegible]	40,.1	3..05	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	41,.3	44.[illegible]
[illegible]	41..1	[illegible] .40	4.[illegible]	4.[illegible]	4.[illegible]	[illegible]	42.[illegible]	46 ,5
[illegible]	34..1	2.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	41.,5	44.[illegible]
[illegible]	33.,7	2.,32	4,[illegible]	[illegible]	[illegible]	4 [illegible]	41. 9	45.,7
[illegible]	[illegible] ,7	3. 45	[illegible]	4 [illegible]	[illegible]	[illegible]	42. 1	45. 3
[illegible]	44. 4	2.96	4.[illegible]	4 [illegible]	4 [illegible]	4.[illegible]	41. [illegible]	45. [illegible]
[illegible]	40. [illegible]	[illegible] 56	4.[illegible]	4 [illegible]	4 [illegible]	4.[illegible]	41. [illegible]	45. 0
[illegible]	40. 0	2. 48	4.[illegible]	4.[illegible]	4,[illegible]	4.[illegible]	40. [illegible]	44.
[illegible]	53. [illegible]	3. 20	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	45.	47.[illegible]
[illegible]	54. [illegible]	4. 09	4.[illegible]	4.[illegible]	4.[illegible]	4,[illegible]	45. [illegible]	46.[illegible]
[illegible]	55. [illegible]	[illegible] 62	4.[illegible]	4.[illegible]	4.[illegible]	4,[illegible]	44. [illegible]	47 .[illegible]
[illegible]	56. [illegible]	3. 40	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	44. [illegible]	47 .[illegible]
[illegible]	49. 0	4. 03	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	43.	47. 1
[illegible]	47. 3	3. 65	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	43 [illegible]	46. 3
[illegible]	59.	3. 93	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	43.[illegible]	[illegible]
[illegible]	56. [illegible]	3. 52	4.[illegible]	4 [illegible]	4.[illegible]	4.[illegible]	45.[illegible]	47.[illegible]
[illegible]	54. [illegible]	3. 57	4.[illegible]	4.[illegible]	4.[illegible]	4.	43.[illegible]	47 .[illegible]
[illegible]	[illegible]	4. 03	4.[illegible]	4.[illegible]	4.[illegible]	4.[illegible]	43.[illegible]	46 .0

Tab A.2.2.j : 91-day results for concrete under 40°C wet curing.

Mix Design No.	Code	Density (kg/m3)	Strength (MPa) Compressive	Equivalent Cube	Flexural	Pulse Velocity (km/s) Cube	Beam	Dynamic Modulus (GPa)
1	2S0	2381	20. 0	20.9	3.24	4.61	4.409	38.8
		2394	20.6	20.6	3.13	4.43	4.482	39 .9
2	2S4	2395	22.5	24.0	3 .33	4.72	4.597	42.0
b		2395	22.4	24.2	3.87	4.74	4.627	42.9
3	2S7	2386	18.6	18.8	3.26	4.79	4.532	40.7
		2391	18.9	19.2	3. 10	4.71	4.533	41.7
10	2P4	2393	23.5	23.1	3 .46	4.67	4.513	41.5
		2395	23.6	24. 8	3.34	4.79	4.559	41.5
11	2P7	2380	25.0	26.5	3.27	4.80	4.621	43.9
		2396	24.9	25.0	3 .16	4.74	4.561	42 .2
4	3S0	2411	43.3	42.3	4.97	4.82	4.717	44.6
		2406	43.4	41.2	5.48	4.77	4.690	45.2
5	3S4	2401	43.2	44.2	4.75	4.77	4.705	45.7
		2413	43.5	45.7	4. 39	4.89	4.766	47 .5
6	3S7	2401	38.8	39.7	4.64	4.83	4.692	46 .0
		2420	37.5	36.6	4.76	4.89	4.744	46.8
12	3P4	2420	50.5	49.9	5.33	4.97	4.769	47 .0
		2409	48.6	48.5	5.55	4.84	4.756	46. 1
13	3P7	2392	46.1	43.5	5.11	4.70	4.670	46 .4
		2400	44. 1	42.8	5.64	4.87	4.715	45.9
7	4S0	2442	57. 1	57.5	6.05	4.86	4.805	48.9
		2425	57 .6	58.4	5.93	4.94	4.848	48.5
8	4S4	2422	60.5	60.7	6.86	4.87	4.820	48.5
b		2419	65.4	58.7	6.34	5.00	4.836	49. 1
9	4S7	2407	54.4	51.9	6.71	4.77	4.747	47.5
		2415	51.1	52.9	6.31	4.89	4.748	47 .3
14	4P4	2425	64.4	62.8	5.98	4.92	4.786	47.6
		2418	63. 1	61.2	6.71	4.95	4.820	48.8
15	4P7	2418	57 .9	55.9	6.21	4.94	4.800	48.3
		2411	58.9	54.8	6.70	4.93	4.748	47 .4

b Tested at 94-98 days.

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Tab A.2.2.1 : 7 and 28-day results for concrete under 20 C wet curing

Tab A.2.2.m : 91-day results for concrete under 20°C wet curing.

Mix Design No.	Code	Density (kg/m3)	Strength (MPa) Compressive	Equivalent Cube	Flexural	Pulse Velocity (km/6) Cube	Beam	Dynamic Modulus (GPa)
1	2S0	2390	24.5	25.3	3.79	4.68	4.492	40.6
		2388	24.3	25.4	3.77	4.72	4.524	40.6
2	2S4	2398	24.4	26.2	3.97	4.72	4.524	41.4
b		2387	25.8	27.5	4..05	4.84	4.533	41.6
3	2S7	2393	21.1	20.3	3.50	4.82	4.499	40.5
		2394	21.4	22.1	3.32	4.73	4.484	40.5
10	2P4	2398	29.3	30.9	4.15	4.73	4.584	43.1
		2395	29.6	29.6	4.50	4.78	4.598	43.0
11	2P7	2393	27.5	29.8	4.59	4.79	4.591	43.2
		2379	26.0	29.6	3.69	4.68	4.580	42.1
4	3S0	2416	50.8	48.9	5.38	4.88	4.763	46.3
		2419	52.3	51.9	4.92	4.84	4.739	46.1
5	3S4	2414	45.9	51.2	5.29	4.77	4.726	45.8
		2414	44.4	48.2	5.15	4.83	4.732	45.4
6	3S7	2411	40.4	43.8	5.44	4.81	4.660	44.8
		2414	39.2	38.8	4.79	4.88	4.711	45.9
12	3P4	2427	54.3	55.2	5.13	4.93	4.782	47.3
		2420	54.0	54.3	5.94	4.87	4.780	47.3
13	3P7	2410	48.0	48.6	5.22	4.79	4.730	45.8
		2411	46.5	49.0	5.53	4.87	4.705	46.1
7	4S0	2434	65.3	63.5	6.40	4.97	4.883	49.0
		2441	64.0	64.4	5.38	5.00	4.870	50.1
8	4S4	2439	69.6	70.1	7.45	4.94	4.872	49.2
b		2430	71.5	67.0	6.72	5.00	4.847	49.4
9	4S7	2421	58.6	59.8	5.96	4.88	4.739	47.2
		2419	56.1	58.2	7.24	4.96	4.732	47.8
14	4P4	2431	69.7	68.7	5.91	4.88	4.819	48.8
		2435	72.7	69.7	6.76	4.96	4.843	49.2
15	4P7	2427	59.7	61.0	4.71	4.88	4.759	47.7
		2418	60.9	61.9	6.63	4.90	4.751	47.8

b Tested at 94-98 day6.

Tab A.2.2.o : 7 and 28-day results for concrete under 20°C dry curing

[illegible]

Tab A.2.2.p : 91-day results for concrete under 20°C dry curing.

Mix Design No.	Code	Density (kg/m3)	Strength (MPa) Compressive	Equivalent Cube	Flexural	Pulse Velocity (km/s) Cube	Beam	Dynamic Modulus (GPa)
1	2S0	2298	16.1	13.7	1.32	4.15	3.805	29.0
		2298	16.3	14.2	1.60	4.08	3.882	29.9
2	2S4	2291	10.0	8.8	1.10	3.93	3.567	25.2
b		2295	10.1	10.1	1.50	4.07	3.655	26.6
3	2S7	2256	5.6	6.4	0.59	3.51	3.207	18.2
		2298	5.6	5.9	0.60	3.51	3.197	17.8
10	2P4	2287	9.9	10.8	1.19	3.84	3.608	26.2
		2290	10.4	10.6	1.56	4.06	3.686	26.2
11	2P7	2306	7.7	7.7	0.94	3.59	3.475	22.7
		2285	7.0	6.4	0.60	3.65	3.237	20.2
4	3S0	2365	28.9	30.0	2.69	4.44	4.350	39.9
		2365	27.1	27.9	2.43	4.36	4.360	39.7
5	3S4	2372	22.3	22.7	1.70	4.28	4.204	36.6
		2342	22.2	19.8	2.51	4.34	4.178	35.8
6	3S7	2343	10.3	12.6	1.41	4.01	3.834	29.2
		2335	11.0	13.1	1.33	3.87	3.807	28.6
12	3P4	2373	28.7	22.3	2.21	4.39	4.224	37.4
		2346	21.4	23.4	2.44	4.27	4.212	36.5
13	3P7	2328	17.8	17.3	2.12	4.01	3.993	30.4
		2329	18.4	16.4	1.37	4.03	3.937	29.2
7	4S0	2392	42.6	40.6	3.04	4.64	4.584	43.1
		2395	40.4	39.9	3.40	4.61	4.575	43.6
8	4S4	2372	39.1	35.3	3.62	4.53	4.484	41.9
b		2374	34.8	33.0	2.65	4.53	4.455	41.0
9	4S7	2345	27.6	25.4	2.28	4.36	4.217	35.5
		2352	25.1	23.3	1.99	4.26	4.254	35.9
14	4P4	2361	35.6	36.2	2.81	4.49	4.468	41.0
		2364	37.3	32.2	2.57	4.56	4.456	40.7
15	4P7	2340	25.7	22.4	2.45	4.33	4.171	35.3
		2333	21.0	23.5	1.88	4.09	4.097	32.9

b Tested at 94-98 days.

Tab A.2.2.r : 7 and 28-day results for concrete under 10°C wet curing

No.	Mix Code	
[illegible]	2S0	[illegible]
[illegible]	2S4	[illegible]
[illegible]	2S7	[illegible]
10	2P4	[illegible]
11	2P7	[illegible]
[illegible]	3S0	[illegible]
[illegible]	3S4	[illegible]
[illegible]	3S7	[illegible]
12	3P4	[illegible]
13	3P7	[illegible]
	4S0	[illegible]
[illegible]	4S4	[illegible]
[illegible]	4S7	[illegible]
14	4P4	[illegible]
15	4P7	[illegible]

Tab A.2.2.S : 91-day results for concrete under 10°C wet curing.

Mix Design No.	Mix Design Code	Density (kg/m3)	Strength (MPa) Compressive	Strength (MPa) Equivalent Cube	Strength (MPa) Flexural	Pulse Velocity (km/6) Cube	Pulse Velocity (km/6) Beam	Dynamic Modulus (GPa)
1	2S0	2391	23.8	23.2	3.65	4.56	4.442	39.5
		2398	22.3	22.4	3.55	4.68	4.525	41.2
2	2S4	2390	19.2	20.9	3. 17	4.65	4.448	39.2
		2399	18.4	20.4	3 .46	4.71	4.483	39.2
3	2S7	2382	17.4	19.1	3. 12	4.44	4.289	35.6
		2393	17.5	17.2	2.85	4.50	4.363	36.6
10	2P4	2408	23.7	23.9	3 .45	4.70	4.519	41.2
		2394	24. 1	24.3	3.70	4.72	4 .499	40.4
11	2P7	2399	20.9	21.4	3.38	4.56	4.395	38.5
		2396	22.0	21.6	3.37	4.64	4.422	39.4
4	3S0	2425	49.0	48.7	5. 15	4.82	4.736	45.6
		2432	49.7	47.5	5.62	4.91	4.791	47 .3
5	3S4	2415	38.1	40. 1	5.11	4.72	4.615	43.4
		2423	39 .6	41.5	5.43	4.72	4.650	44.6
6	3S7	2415	30.9	33.5	4.65	4.70	4. 466	39.4
		2415	33.2	32.1	4.52	4.69	4.550	41.2
12	3P4	2419	44.5	44.6	5.26	4.74	4.632	44. 4
		2419	46. 1	45.4	5.20	4.77	4.692	45.6
13	3P7	2423	35.2	37.5	5.08	4.65	4.621	43.8
		2413	33.9	35.9	4.40	4.71	4.617	43. 1
7	4S0	2447	62.4	63 .4	5.23	4.95	4.815	49.2
		2443	63.5	61.8	5.94	4. 94	4.878	50.3
8	4S4	2439	56.7	55.9	5.68	4.80	4.711	46.0
		2434	55.9	54.8	5.45	4.87	4.751	47. 1
9	4S7	2418	43.8	48.8	5. 18	4.69	4. 617	44. 0
		2431	45.2	44.7	5.41	4.76	4. 644	45. 1
14	4P4	2427	62.6	58.0	5.85	4.86	4.718	45.8
		2441	60.6	60.6	5.89	4.90	4.773	47 .6
15	4P7	2427	46.4	48.5	5.35	4.72	4. 600	43.6
		2426	47.3	50. 1	4.70	4.83	4.696	45.2

Tab A.2.2.U : 7 and 28-day results for concrete under 5°C wet curing

28-day

10

12

13

14

Tab A.2.2.V : 91-day results for concrete under 5°C wet curing.

Mix Design No.	Code	Density (kg/m3)	Strength (MPa) Compressive	Equivalent Cube	Flexural	Pul6e Velocity (km/s) Cube	Beam	Dynamic Modulus (GPa)
1	2S0	2397	20.9	21.7	2.34	4.53	4.482	38 .9
		2400	18.4	22.1	3.14	4.59	4.496	40.7
2	2S4	2406	15.2	16.2	2.51	4.47	4.377	35.0
		2414	14.2	17.8	2.69	4.53	4.425	37.9
3	2S7	2419	14.3	16.7	1.73	4. 46	4.383	36.9
		2405	12.6	13.9	1.57	4.51	4.302	35.2
10	2P4	2415	17.3	19.5	3.44	4.51	4.462	38.6
		2403	17.4	19.3	3. 16	4.64	4. 404	38 .4
11	2P7	2426	15.7	19.0	2.37	4.46	4.376	38 .7
		2413	17.3	19.8	3.44	4.55	4.451	39 .1
4	3S0	2439	44.5	46.5	4.91	4.80	4.742	46.8
		2430	47.3	45.0	5. 18	4.90	4.751	46.5
5	3S4	2426	34.0	37.3	5.72	4.67	4.579	42.8
		2427	33.7	35. 1	4.50	4.73	4.635	42.2
6	3S7	2424	26.0	29.3	4.06	4.60	4.447	39.2
		2432	25.6	29.3	3.67	4.69	4.537	40.7
12	3P4	2419	37 .5	39. 1	4.88	4.73	4.653	43.6
		2435	37 .6	40.4	4.68	4.80	, 4.689	44.0
13	3P7	2410	32.6	34.5	4.63	4.64	4.494	41 .4
		2420	27.7	32.6	3.42	4.65	4.563	42.9
7	4S0	2464	67 .8	64.8	6.09	4.93	4.848	49.4
		2448	63.5	60.8	4.40	4.90	4.882	50.0
8	4S4	2446	50.3	49.9	5.34	4.75	4.666	44 .4
		2441	49.5	50.3	5.75	4.85	4.676	45.7
9	4S7	2421	38.9	43.9	5. 16	4.66	4.554	41.5
		2432	38.4	40. 1	5.33	4.71	4.569	41.3
14	4P4	2425	59.6	60.6	6.77	4.75	4.733	47 .0
		2442	55.7	55.7	5.88	4.79	4.744	46.3
15	4P7	2421	42.0	43.6	4.96	4.72	4.552	42.5
		2427	41.3	44.0	4.82	4.74	4.655	43.6

Hydration and Durability

Tab A.2.3.a · A summary of the Vacuum Flask Calorimetry Profiles.

Mix Design		Flask	Temperature (6C)		Time to Peak	Temperature (°C)			
No.	Code	No.	Casting	Peak	(hrs)	Rise	Diff.	Gain	Mean
1	2S0	1	20..2	27 ,9	13..7	7 ,7	7 ,9	18.9	25 .2
		2	20..1	29.,3	13..3	9.,2	9..3	18 .2	26. 4
2	2S4	1	18 ,1	23.,8	13,.0	5..7	3..8	10.6	22. 2
		2	18..3	24.,0	14..3	5,,7	4.,0	9.8	22. 5
3	2S7	1	16..5	20.,9	26,.7	4,,4	0.,9	4. 1	19. 9
		2	16..1	21.,7	31..0	5.,6	1..7	5.7	20. 2
10	2P4	1	18..6	23.,9	13..3	5.,3	3.,9	10. 5	22. 4
		2	18,.6	24. 7	14..3	6.,1	4.,7	10.9	23. 2
11	2P7	1	16..9	22.,3	28..7	5.,4	2.,3	7.6	20.,9
		2	16 ,8	22. 0	25..7	5.,2	2.,0	6 .4	20. 6
4	3S0	1	18 ,6	32.,5	14..0	13..9	12..5	25. 1	28. 1
		2	18.,5	31. 5	13.,7	13..0	11.,5	28.7	27. 3
5	3S4	1	17.,8	26. 7	14..0	8.,9	6..7	17.8	24.,1
		2	17.,8	28.,0	15.,7	10.,2	8..0	18.3	25. 1
6	3S7	1	17..0	22..9	14..7	5..9	2..9	9.7	21.,5
		2	16..8	23.,1	20..0	6..3	3..1	9.1	21..6
12	3P4	1	17..3	26.,7	14,.3	9,.4	6..7	18.7	24..0
		2	17..2	27..2	15,.7	10,.0	7..2	17.0	24..3
13	3P7	1	19..1	23..9	17..3	4,.8	3..9	11.7	22..7
		2	19,.0	24,,4	20,.0	5..4	4,.4	10.6	22..9
7	4S0	1	16,.9	35.,0	13,.3	18 .1	15,.0	38.2	29,.3
		2	16,.9	34..3	13,.0	17,.4	14,.3	---	26,.6
8	4S4	1	18 .8	30..9	13 .7	12,.1	10..9	30.2	27,.4
		2	18..6	29..5	13,.0	10,.9	9,.5	19.3	26 .1
9	4S7	1	17,.5	24..3	14 .3	6,.8	4,.3	13. 1	22 .5
		2	17,.3	24..5	17 .0	7,.2	4 .5	11.9	22 .8
14	4P4	1	16 .3	27..9	14 .3	11,.6	7 .9	21.8	24 .4
		2	16,.2	29,.4	15,.3	13,.2	9 .4	21.9	25 .5
15	4P7	1	17,.2	24,.3	18 .0	7 .1	4 .3	13.6	22 .6
		2	17 .1	25..5	22 .3	8,.4	5 .5	13.7	23 .0

Re6ulte not available
Rise = Peak - Casting temperature
Diff.= Peak - Ambient temperature
Gain = gain after allowance for the insulating characteristics of the flasks and the Casting and Ambient temperatures
Mean = Arithmetic mean of temperatures over first 24 hours

Tab A.2.3«b : Summary of the Water Absorption data, showing the British Standard test results.

Mix Design No.	Code	Block	Water Absorption (ml/m2s) Curing Code 40W	20W	20D	10W	5W	BS1881 (%)	End-Contact (ml/m2s)
1	2S0	1	0.40	0.43	0.73	0.48	TT. 4'6	3.1	0.3&
		2	0.39	0.40	0.74	0.40	0.46	2.8	0 .40
2	2S4	1	0.30	0.39	1.26	0.38	0.52	3.0	0.51
		2	0.34	0.43	1.11	0.44	0.43	2.9	0.47
3	2S7	1	0.58	0.51	1.44	0.48	0.38	3.2	0.52
		2	0.47	0.52	---	0.45	0. 48	2.3	0.32
10	2P4	1	0.35	0.43	1.00	0.44	0.48	2.3	0.28
		2	0.41	0.42	0.95	---	---	1.7	0.25
11	2P7	1	0.35	0.45	1.18	0.41	0.43	2.3	0.35
		2	0.35	0.41	1.12	0.43	0.40	1.5	0. 19
4	3S0	1	0.28	0.30	0.43	0.33	0.33	1.8	0.21
		2	0.32	0.28	0.37	0.29	0.33	2.9	0.29
5	3S4	1	0.30	0 v28	0.57	0.30	0.38	1.6	0.25
		2	0.25	0.26	0.70	---	0.30	1.7	0.27
6	3S7	1	0.29	0.39	1.11	0.37	0.33	3.5	0.67
		2	0.25	0.35	1.02	0.35	0.29	2.0	0.29
12	3P4	1	0.22	0.23	0.52	0.33	0.28	2.1	0.31
		2	0.24	0.33	0.52	0.23	0.28	4.5	0.74
13	3P7	1	0.27	0.28	0.88	0.27	0.30	1.9	0.25
		2	0.25	0.26	0.78	0.28	0.30	2.1	0.26
7	4S0	1	0.31	0.28	0.35	0.31	0.31	4.1	0 .78
		2	0.25	0.26	0.32	0.30	0.28		
8	4S4	1	0.20	0. 16	0.31	0.28	0.31		
		2	0. 19	0.21	0.41	0.25	0.29		
9	4S7	1	0.26	0. 19	0.65	0.26	0.25		
		2	0.25	0.27	0.67	0.21	0.25		
14	4P4	1	0. 18	0.21	0. 35	0.25	0.25		
		2	0. 19	0.21	0.29	0.23	0.27		
15	4P7	1	0.23	0.27	0.62	0.26	0.27		
		2	0.26	0.25	0.50	0.23	0.23		

Results not available.

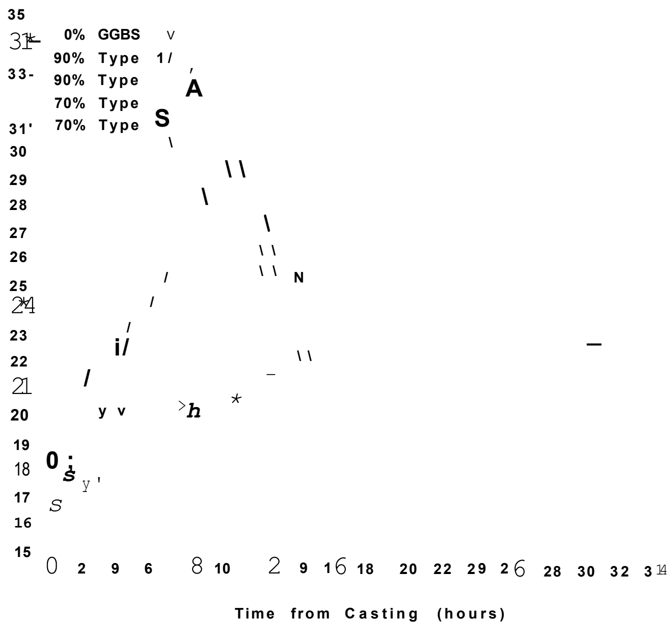


Fig A.2.3.a : Vacuum flask calorimetry profiles for the low (200 kg/m3) cementitious content mixes.

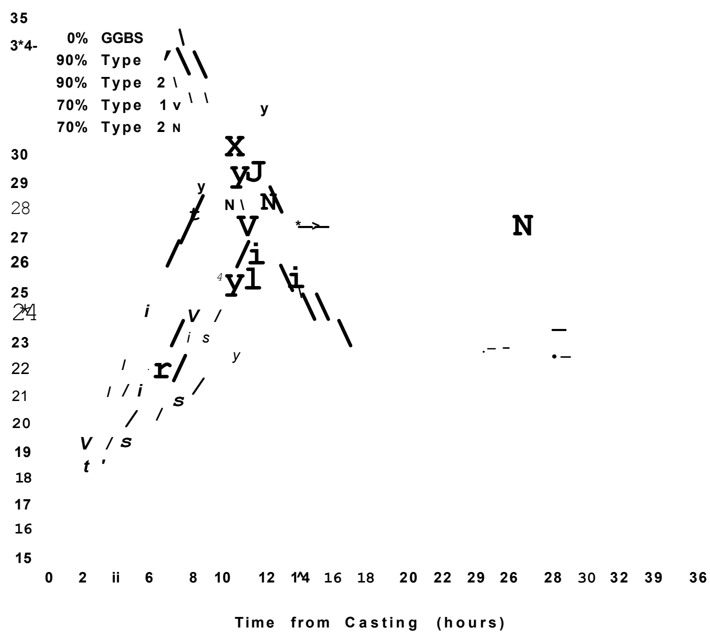


Fig A.2.3.b * Vacuum flask calorimetry profiles for the medium (300 kg/m^) cementitious content mixes.

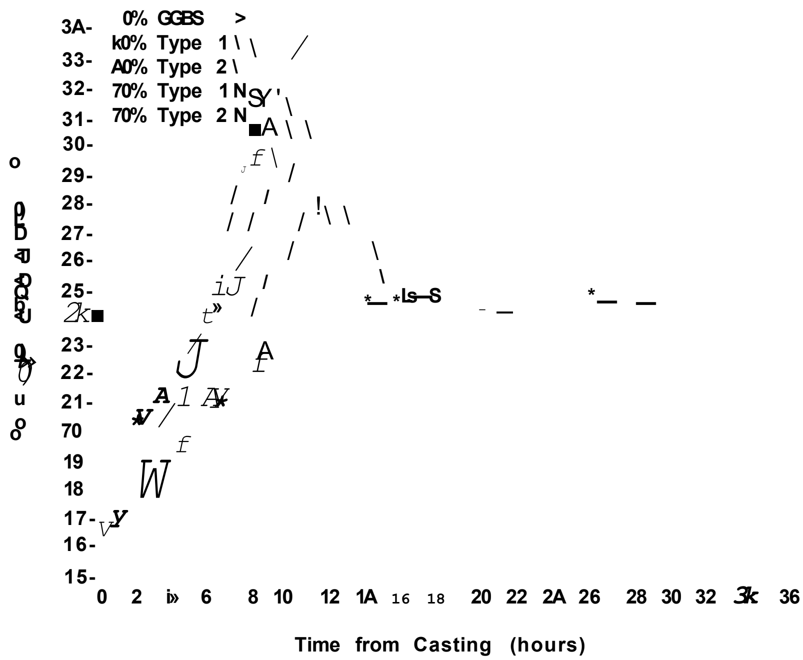


Fig A.2.3.C : Vacuum flask calorimetry profiles for the high (400 kg/m^) cementitious content mixes.

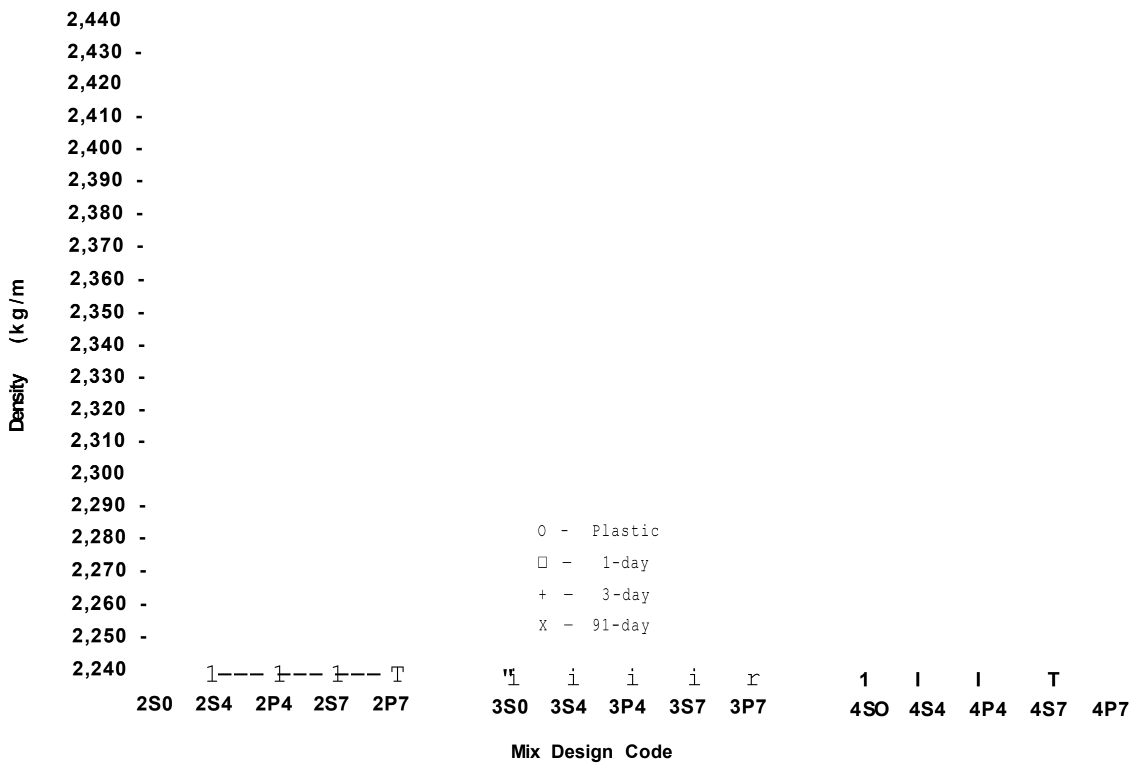


Fig A.2.3.d : Pattern of change of density with age and mix design under 20°C dry curing.

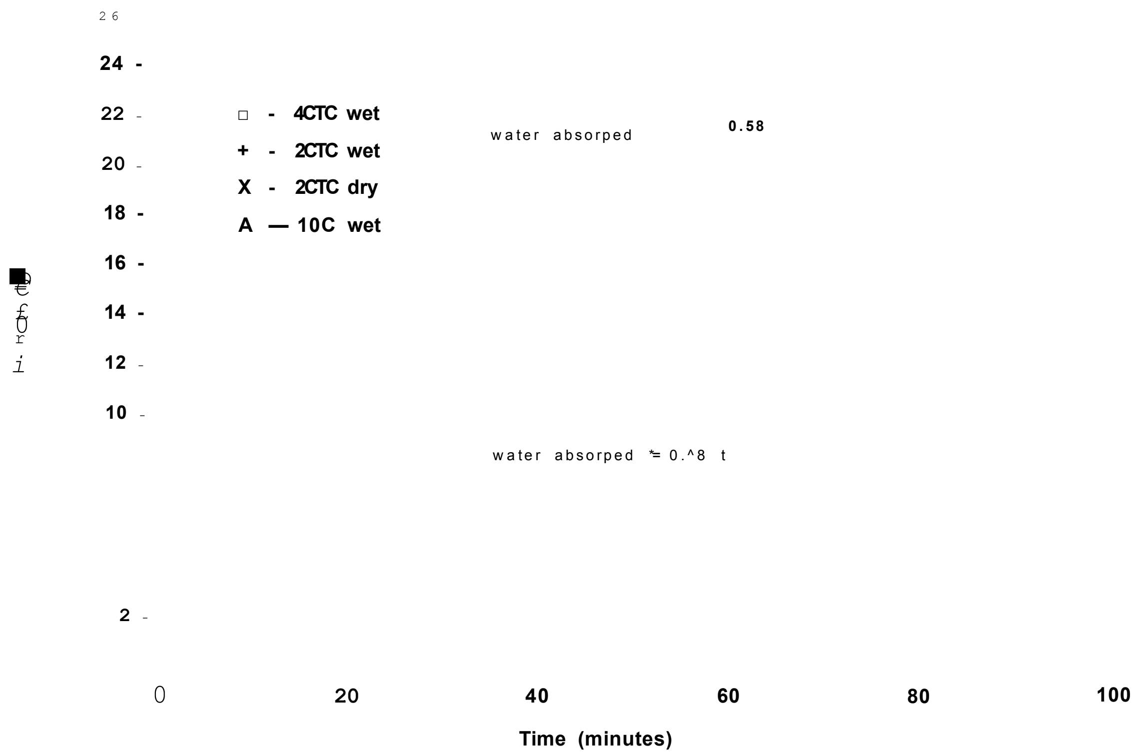


Fig A.2.3.e : Typical profiles of water absorped against tine showing regression relationships.

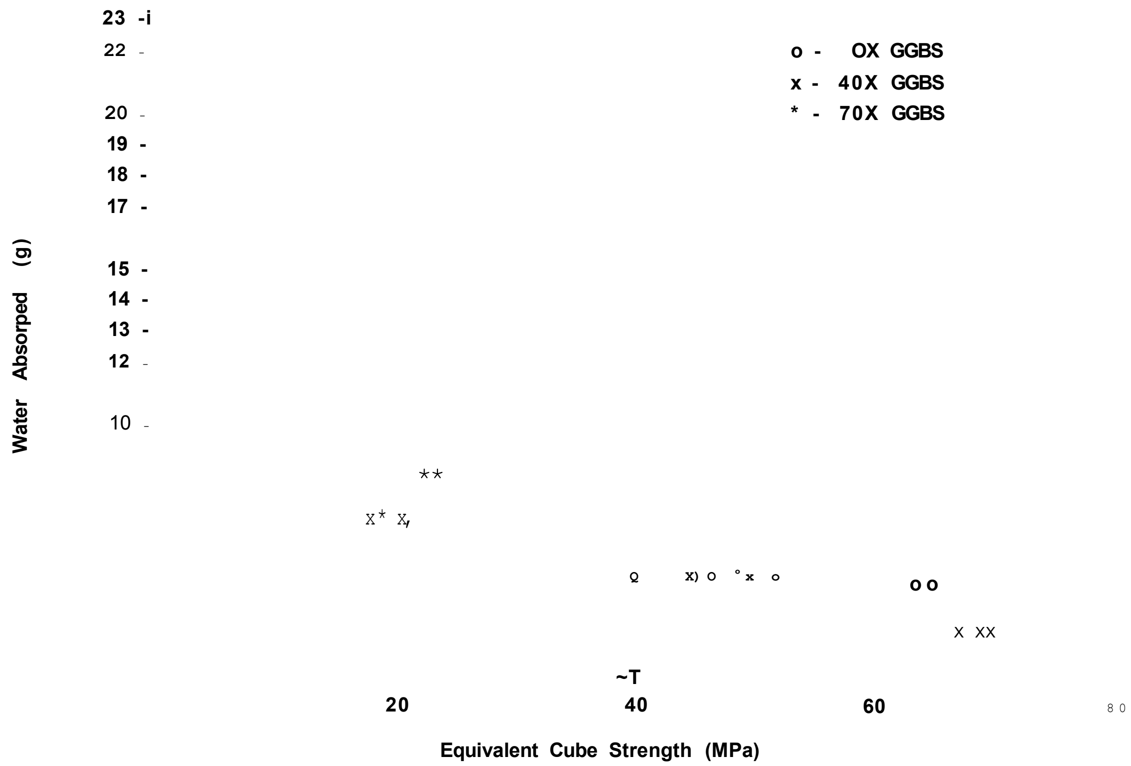


Fig A.2.3.f ′ Water absorped against equivalent cube strength for different GGBS levels.

A.3 Secondary Study

Tab A.3.a : Workability data.

Mix	W/C	Slump (mm)	E (Mm)	h (Nine)	r	10% Confidence Intervale £ (Nm)			h (Nm6)		
	L	20	5.53	2.09	0.958	6.02	_	5.05	2.76	-	1.43
3S0	M	70	2.64	2.60	0.985	3.01	-	2.28	3.10	-	2.11
	H	175	0.49	2. 12	0.991	0.73	-	0.26	2.44	-	1.81
	L	20	5.98	2.56	0.972	6.47	-	5.50	3.22	-	1.91
3S4	M	80	2.36	2.69	0.989	2.68	-	2.04	3.13	-	2.25
	H	17 0	0.66	1.75	0.976	0.97	-	0.35	2. 17	-	1.34
	L	50	3.07	3.69	0.992	3.45	-	2.68	4.21	-	3. 18
3S7	M	190	1.51	2.86	0.994	1.77	-	1.25	3.21	-	2.52
	H	185	0.54	1.55	0.989	0.72	-	0.36	1.80	-	1.31
	L	35	4.52	2.59	0.988	4.83	-	4.20	3.02	-	2. 17
3P4	M	190	0.91	1.84	0.995	1.06	-	0.77	2.04	-	1.65
	H	230	0.34	1.30	0.988	0.51	-	0. 18	1.52	-	1.09
	L	15	5.66	2.29	0.962	6. 17	-	5.15	2.98	-	1.60
3P7	M	65	3.95	3.70	0.992	4.31	-	3.58	4. 19	-	3.21
	H	185	1.39	2.41	0.992	1.64	-	1. 14	2.75	-	2.08
	L	0	2.35	1.96	0.888	3. 16	-	1.55	3.04	-	0.87
4S0	M	70	3. 12	2.73	0.981	3.54	-	2.69	3.30	-	2. 16
	H	200	0.76	1.36	0.999	0.81	-	0.70	1.43	-	1.28
	L	10	4.97	3.64	0.977	5.60	-	4.35	4.49	-	2.78
4S4	M	75	2.76	2.77	0.984	3. 15	-	2.37	3.30	-	2.25
	H	180	0.95	1.69	0.992	1.12	-	0.77	1.92	-	1.46
	L	5	5.46	3.51	0.984	5.96	-	4.97	4. 18	-	2.83
4S7	M	105	2.63	3.05	0.992	2.94	-	2.32	3.47	-	2.63
	H	205	0.62	1.78	0.991	0.81	-	0.43	2.04	-	1.52
	L	0	3.54	3.92	0.976	4.23	-	2.85	4.86	-	2.99
4P4	M	45	6.55	3.81	0.993	6.89	-	6.20	4.28	-	3.34
	H	195	1. 39	1.86	0.981	1.68	-	1. 10	2.25	-	1.47
	L	0	3.41	4.25	0.977	4. 15	-	2.67	5.23	-	3.26
4P7	M	5	3. 10	3.48	0.987	3.54	-	2.66	4.07	-	2.88
	H	70	5.40	5.48	0.943	6.92	-	3.88	7.54	-	3.42

Cement Content (kg/m3)	W/C ratios L	M	H
300	0.50	0.55	0.60
400	0.36	0.41	0.46

Tab A.3.b : Pulse Velocity at Very Early Ages.

Mix Code									
3S0		3S4		3S7		3P4		3P7	
Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)
1.75	0.64	1.75	0.31	1.75	0.29	2.05	0.61	2.00	0.49
2.00	0.77	2.00	0.35	2.00	0.32	2.17	0.67	2.13	0.55
2.25	0.93	2.25	0.38	2.25	0.35	2.42	0.76	2.25	0.59
2.75	1.39	2.75	0.45	2.83	0.39	2.92	1.23	2.75	0.87
3.25	1.79	3.00	0.49	2.83	0.53	3.17	1.41	3.00	1.01
3.75	2.17	3.25	1.08	3.25	0.73	3.42	1.59	3.25	1.16
4.00	2.34	3.75	1.47	3.75	1.06	3.92	2.11	3.75	1.53
4.25	2.42	4.00	1.58	4.00	1.18	4.17	2.30	4.00	1.69
5.75	2.91	4.25	1.72	4.25	1.36	4.42	2.46	4.25	1.83
6.00	2.91	6.00	2.43	6.00	2.22	6.00	3.11	6.00	2.62
8.00	3.24	8.00	2.81	8.00	2.69	8.00	3.44	8.00	3.15
10.00	---	10.00	2.97	10.00	2.89	10.00	3.59	10.00	3.37
12.00	---	12.00	3.17	12.00	2.95	12.00	3.71	12.00	3.44
14.00	---	14.00	3.28	14.00	3.02	14.00	3.82	14.00	3.54
24.00	4.21	24.00	3.62	24.00	3.21	24.00	3.99	24.00	3.72

4S0		4S4		4S7		4P4		4P7	
Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)	Time (hrs)	UPV (km/s)
1.75	0.57	1.75	----	1.75	0.49	1.95	0.68	____	---
2.00	0.76	2.08	0.53	2.00	---	2.00	0.731	2.00	0.56
2.25	0.99	2.25	1.23	2.25	0.53	2.50	1.29	2.25	0.73
2.83	1.64	2.75	1.75	2.5	1.27	2.75	1.53	2.75	1.12
3.00	1.80	3.00	1.97	3.00	---	3.00	1.81	3.00	1.30
3.25	---	3.25	---	3.25	1.59	3.42	2.19	3.25	1.47
3.75	---	3.75	2.49	3.75	---	3.92	2.62	3.75	1.90
4.00	2.69	4.00	2.56	4.00	1.82	4.17	2.73	4.00	2.03
4.25	---	4.25	2.66	4.25	---	4.42	2.83	4.25	2.16
6.00	3.44	6.00	3.05	6.00	2.59	6.00	3.38	6.00	2.92
8.00	3.86	8.00	3.35	8.00	3.29	8.00	3.68	8.00	3.26
10.00	4.05	10.00	3.58	10.00	---	10.00	3.91	10.00	3.48
12.00	4.24	12.00	3.77	12.00	3.50	12.00	4.07	12.00	3.65
14.00	4.35	14.00	3.85	14.00	3.65	14.00	4.22	14.00	3.77
24.00	4.60	24.00	4.09	24.00	3.83	24.00	4.42	24.00	4.04

Results not available.

Tab A.3.c : Strength and Elasticity data.

Compressive strength (Mpa)

Mix Code	1-day			7-day W/C Ratio			28-day		
	L	M	H	L	M	H	L	M	H
3S0	8.9	6.3	3.9	34.7	27.9	19.5	45.5	38.5	28. 1
3S4	4.5	3.1	2.2	21.6	17.5	12.9	39.3	33.9	28.4
3S7	1.1	1.1	0.9	11.6	9.5	7.8	30.0	25.1	20.0
3P4	4.3	2.8	2.2	22. 1	16.1	12.9	42.2	33.7	28.9
3P7	1.7	1.3	1.3	17.9	15.2	12.7	38.2	34.4	31.4
4S0	19.9	15.1	9.9	51.7	44.5	34.5	60.7	53.9	47.2
4S4	11.6	8.5	5.6	40.5	35.2	32.9	56.5	51.0	43.6
4S7	2.9	2.1	1.5	24.0	18.9	13.4	49.7	41.9	32.7
4P4	11.0	9.1	5.5	39.6	36.2	25.7	59.2	57 .2	48.5
4P7	3.6	3.2	2.1	30.7	28.0	20.9	55.6	52.6	44.5

Mix Code	Compressive strength (Mpa)		Dynamic Modulus (GPa)		Static Modulus (GPa)	
	7-day	28-day	7-day	28-day	7-day	28-day
3S0	27.9	38.5	42.2	45.4	30.5	32.7
3S4	17.5	33.9	35.6	42.0	27.5	30.4
3S7	9.5	25. 1	31.6	38 .6	23.7	27 .8
3P4	16.1	33.7	35.1	43.8	22. 1	37 .1
3P7	15.2	34.4	34.9	42.6	21.1	34.2
4S0	44.5	53.9	45.5	47 .7	33. 1	36.2
4S4	35.2	51.0	41.0	45 .1	27 .6	31.4
4S7	18.9	41.9	37.2	42. 1	24.4	32. 1
4P4	36.2	57 .2	42.7	46.3	31.3	36 .1
4P7	28.0	52.6	37.3	45.4	25.9	33.7

Cement Content (kg/m3)	W/C ratios L	M	H
300	0.50	0.55	0.60
400	0.36	0.41	0.46

B. 1 Measures of location and spread

B.1.1 Arithmetic Mean

The sum of all observations divided by their number

$$m = \frac{x}{n}$$

B. 1.2 Median

The value about which an equal number of observations lie. It is an appropriate measure where large outlying values are expected.

B. 1.3 Mean Absolute Deviation (50)

The absolute arithmetic mean deviation of the observations from the mean.

$$MAD = \frac{ABS\ (x-m)}{n^{*}}$$

B. 1.4 Variance and Standard Deviation

The variance is the mean square deviation from the mean, whilst the standard deviation is the square root of this value.

$$sd2 = \frac{\text{£}(x-m)2}{n^{\text{«}}}$$

The standard deviation of the arithmetic mean of a set of individuals, called the standard error, is the standard deviation devided by the root of the number of individuals in the sample.

B.1.5 Confidence interval (50)

An interval within which an observation from the population should lie with a known probability. The interval is calculated using information about the population from samples and a predictive model called the probability distribution. For small samples the Student's t distribution is used, whilst for larger samples the Normal

* where predictions about the population are being made the divisor should be reduced to n-1.

distribution is appropriate. In the former case the interval is

m +/″ tc^,df x sd»

where the percentage probability level within the interval is usually 100-2c and sd may be replaced by se for sample means. The degrees of freedom (df) can be considered to be the number of values available for comparison, and is equal to the number of observations reduced by the number of estimates made.

If a value lies outside a confidence interval then it can be said to be significantly different from the population on which the interval was based. Alternatively, it is possibe to compare a test statistic with critical values from the appropriate probability distribution. This statistic is calculated as the difference between the suspect value and the population mean,divided by an estimate of the population variance.

B.2 Analysis of Variance

B.2.1 Principle

By assuming that the effect of factors and random error upon a response variable are linearly additive, the variance attributable to any one source can be separated from the overall variance and may be compared with an estimate of the residual variation.

Brownlee describes the case for the three factors G,T and S as follows (89).

Source of Variance	Degrees of Freedom	Components of Variance
G	g-1	vo+ Svgt + Tv + TSg
T	t-1	vo+ Gvts + Svgt + SGt
S	s—1	vo+ Tvsg + Gvst + GTS
G x T	(g-1)(t-1)	vo+ Svgt
T x S	(t—1)(s—1)	vo+ Gvst
S x G	(s—1)(g—1)	vo+ Tvsg
Residual	(g—1)(t—1)(s—1)	vo
Total	gts-1	

The variance or mean sum of squares (ms) for each factor is calculated by dividing the sum of squares (ss) for each factor by the corresponding degrees of freedom (df). Starting with the highest order interactions, that is those terms at the bottom of the list, each sum of squares is divided by an estimate of the residual variation and this F-ratio compared with critical values from statistical tables. An F-ratio close to one indicates a non-significant component of variance which should be removed from the list. A new estimate of the residual variance can be obtained by pooling the sum of squares and degrees of freedom of the redundant term and the old residual.

B.2.2 Transformation of the response variable

Transformation, as opposed to simple recoding of the data, may be needed in order to obtain a normal probability distribution or homogeneity of variance. The compacting factor and compressive strength data was subject to angular and logarithmic transformations respectively, as suggested by Orr (90). The slump data was logarithmically transformed, consistent with the increased tolerance limits with higher slump values allowed in BS 5328. The recoded and transformed values used in at the analysis were:

1. (log-|Q slump) x 100
2. CF x 1000
3. Arcsin°(CF)0-5
4. (log(strength x 100)) x 100
5. water absorped x 10

The normality and homogeneity of the transformed and untransformed data was judged using Bartlett's test, whilst Cochran's test was used to identify outlying variance values (91).

	Probability of Acceptability		Correlation between
Parameter	Bartlett-Box	Cochran	cell mean and sd
slump	0.340	1.000	positive
log slump	0.838	0.674	slight negative
CF	0.035	0.016	negative
Angular CF	0.419	0.153	slight negative
S	0.032	0.362	positive
h	0.432	0.153	positive
compressive strength			
3-day		0.125	positive
91-day		0.010	slight positive
(log) 3-day		0.511	none
(log) 91-day		0.002	negative

Underlining indicates that the data is unacceptable according to the test. High block variances failing the Cochran test were investigated, but no justification was found for removal of results.

B.2.3 Interactions

In general to prove the significance of the component B, the variance A+B+C must be tested against A+C. If an interaction is significant then associated main effects may be tested against it. However, in this situation main effects are little value and ideally the analysis should be split up by the levels of one of the main effects in the interaction term.

The analysis of variance associated with this work involved a maximum of five factors; cementitious content (Cm), GGBS replacement level (Rp), GGBS type (Ty), Curing (Cu) and Block (Bk). In addition to these factors a within -cell variance term is available from the analysis of the slump and compressive strength data because two determinations were made at each treatment combination. A number of interactions were identified and it was necessary to split the analysis of variance as shown below.

Analysis		Factors	Interactions	Split by
Workability	1)	Cm,Rp,Ty,Bk	CmxRpxTy	—
	2)	Rp,Ty,Bk	Rp x Ty	Cm
Strength	1)	Cm,Rp,Ty,Cu,Bk	CmxRpxTyxCu	age
	2)	Rp,Ty,Cu,Bk	Rp x Ty	age,Cm
	3)	Ty,Cu,Bk	Ty x Cu	age,Cm,Rp
Absorption	1)	Cm,Rp,Ty,Cu,Bk	CmxRpxCu, CmxRpxTy	—
	2)	Rp,Ty,Cu,Bk	RpxTyxCu	Cm

The workability data gave rise to significant Cm x Rp x Ty interaction so the analysis was split by the cementitious content. Analysis of the strength data was carried out separately at each age for three pairs of curing regimes: 40 and 20°C wet, 20°C wet and dry, and 10 and 5°C wet.

The analysis was split by cement content when significant interactions involving Cm,Rp,Ty and Cu were identified (see B.4.2 for typical examples). However, the reduced analyses produced significant Rp x Ty interactions and the analysis was further divided by replacement level. Although this removed from the analysis an important factor, it also removed from the design a distortion at the 0$ GGBS level due to the provision of a slag type effect and the use of duplicate test data. In addition, this splitting of the analyses unified the degrees of freedom of all the factors facilitating direct comparison of the F-ratios. As a consequence of these division 135 three factor analyses were carried out which are summarised as tables of F-ratios in Section B.4.2.

The water absorption data produced significant interactions involving Cm and Rp for the 40 and 20°C wet, and 20°C wet and dry analyses, so these analyses were split by cement content.

Some F-ratios for the main effects were calculated using the last residual estimate at the point when the significant interaction was identified; as such they are for comparative purposes only.

B.2.4 Least significant difference (50)

If only main effects are significant it is possible to group the data associated with the levels of each main effect, ignoring any other factors, in order to indentify the contribution of each level to the significance. A confidence interval on the difference in the mean values at each level can be calculated as:

Where s is an estimate of the population sd, calculated as the root of the residual mean square; df denotes the degrees of freedom associated with the residual; and n is the number of individuals at each level.If the difference in the mean values of groups at any two factor levels is outside these limits then the groups are significantly different. Grouping within the factors levels is usually indicated by underlining.

Least significant difference studies were carried out on the slump, g, h and water absorption data, and are summarised below,

a) Slump (mm)

Significant effect- GGBS level for Cm1 (200 kg/m^)

Summing across blocks,

	Mean
Rp1 (0$ GGBS)	17.25
Rp2 (40$ GGBS)	28.63
Rp3 (70$ GGBS)	37.63

s = /233.0 =15.26

t2.5$,21 = 2*o8°

LSD = 15.26 x T2 x 2.080 = 15.9

Rp3 > Rp2 > Rp1

b) g (Nm)

Significant effect- GGBS level for Cm1 (200 kg/m^)

Summing across blocks,

	Mean
Rp1 (0$ GGBS)	5.72
Rp2 (40$ GGBS)	3.39
Rp3 (70$ GGBS)	1.50

s = 1.692 = 1.300

t2.5$,21 = 2-o8°

LSD = 1.300 x [2 x 2.080 = 1.35

Rp3 > Rp2 > Rp 1

c) h (Nm)

Significant effect- Block for Cm2 (300 kg/m3)

Summing across blocks,

	Mean
Bk1	3.00
Bk2	3.32
Bk3	4.29
Bk4	3.22

s = /b.155 = 0.394

t2.5%,21 = 2-o8°

LSD = 0.394 x [2 x 2.080 = 0.47

Bk3 > Bk2 > Bk4 > Bk 1

d) Water Absorped (g)

Significant effect- Cement Content and GGBS Replacement level

Summing across GGBS levels,

	Mean
Cm1 (200 kg/m3)	7.06
Cm2 (300 kg/m3)	4.93
Cm3 (400 kg/m3)	4.26

s = \fo. 175 = 0.419

fc2. 5/o,63 = 1,998

LSD = 0.419 x f~2 x 1.998 = 0.26

v 21

Cm1 > Cm2 > Cm3

Summing across Cement contents,

	Mean
Rp1 (0$ GGBS)	5.65
Rp2 (40$ GGBS)	**5.22**
Rp3 (70$ GGBS)	5.25

LSD = 0.26 (as previously)

Rp1 > Rp2 > Rp 3

B. 3 Regression analysis

B.3.1 Correlation

Correlation is the degree to which changes in one variable are accompanied by systematic changes in another variable. For linear relationships a measure of correlation is given by the coefficient r.

$$r = \frac{I(x-mx)\ (y-my)}{Vr[I(x-mx)2\ I(y-my)2]}$$

B.3.2 Regression

The regression line is formed by minimising the sum of squares of the deviation of the observed values from the proposed line. Solution of this produces the coefficients a and c in y = ax +c.

$$a = \frac{J(x-mx)_{(y-my)}}{I(x-mx)2} \qquad c = my-amx$$

The standard error of the observed y values about the line is formed in a similar fashion to that of a sample mean, although the divisor is reduced due to the estimation of the two coefficients.

$$se = \frac{J(y-\ (c + ax)\ )}{n-2}$$

B.3.3 Transformation

In cases where the relation between the variables is not linear it may be possible by transforming the variables to obtain an approximately linear relation suitable for linear regression.Common transformations are the logarithm, square root and reciprocal. For example :

a) Exponential function $y = aebx$

rectify $X = x$, $Y = In\ y$

$$Y = c + bX$$

where $a = ec$

b) Power function $y = axb$

rectify $X = \log x$, $Y = \log y$

$$Y = c + bX$$

where $a = 10c$

Caution has to be exercised when transforming variables since the homogeneity of the variance and the Normality of the distribution of variances will be altered. For instance, logarithmic transformation results in the variances being weighted according to their proportion of the variable, and not their magnitude.

B.3.^ Polynomial Regression

The power law shown above is a specific case of a polynomial relationship. Such an approach is not appropriate where more complex quadratic and cubic relationships are anticipated. For two independent variables W and Z in a quadratic relationship

$$Y = c + a\hat{}W + a\hat{}Z + a\hat{}WZ + a\hat{}W\hat{} + a\hat{}Z\hat{}$$

This expression may be simplified by successive elimination of non-significant terms (92). Caution has to be applied when carrying out polynomial regression to avoid adopting more terms than can be supported by the observations or justified by the required level of accuracy.

Results from the Analysis of Variance

Workability data

Tabs B.4.1.a-b   4-factor analyses

Tabs B.4.1.c-d   3-factor, split analyses

Tab B.4.1.a : 4-Factor analysis of variance of the slump data.

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Cement	107289	2	53644	c	145.68	
2	Replacement	3551	2	1776	c	4.82	
3	Type	22500	1	22500	c	61. 10	
4	Block	4363	3	1454	c	3 .95	
5	Cm x Rp	6151	4	1538	c	4. 18	
6	Cm x Ty	11176	2	5588	c	15.17	
7	Cm x Bk	1167	6	195	c	0.53	
8	Rp x Ty	16501	2	8251	c	22. 41	
9	Rp x Bk	4105	6	684	c	1.86	
10	Ty x Bk	1403	3	468	c	1.27	
11	Cm x Rp x Ty	13245	4	3311	c	8.99	>0.1
12	Cm x Rp x Bk	13431	12	1119	c	3 .04	> 1.0
13	Cm x Ty x Bk	1088	6	181	b	--	
14	Rp x Ty x Bk	1171	6	195	b	--	
15	Cm x Rp x Ty	6579	12	548	a	6. 10	
16	Within Cell	6475	72	90			

Residuals		DF	MS
a	16	72	90
b	15	12	548
c	b + 14,13	24	368

Tab B.4.1.b : 4-Factor analysis of variance of the compacting factor data.

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Cement	21686	2	10843	c	55. 19	
2	Replacement	1794	2	897	c	4. 56	
3	Type	11628	1	11628	c	59. 19	
4	Block	2170	3	723	c	3 .68	
5	Cm x Rp	10145	4	2536	c	12.91	
6	Cm x Ty	14081	2	7041	c	35.84	
7	Cm x Bk	649	6	108	c	0.55	
8	Rp x Ty	7934	2	3967	c	20.19	
9	Rp x Bk	1292	6	215	c	1. 10	
10	Ty x Bk	500	3	167	c	0.85	
11	Cm x Rp x Ty	8377	4	2094	c	10.66	> 0.1
12	Cm x Rp x Bk	3764	12	314	b	2.27	
13	Cm x Ty x Bk	636	6	106	a	--	
14	Rp x Ty x Bk	839	6	140	a	--	
15	Cm x Rp x Ty	1835	12	153			

Residuals		DF	MS
a	15	12	153
b	a + 14, 13	24	138
c	b + 12	36	196

Tab B.4.1.C : 3-Factor analysis of variance of slump, split by cementitious content.

Cement Content 200 kg/m3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	3420	2	1710	d	7.34	> 0.5
2	Type	5	1	5	c	---	
3	Block	1227	3	409	c	2.01	
4	Rp x Ty	416	2	208	b		
5	Rp x Bk	1872	6	312	b		
6	Ty x Bk	639	3	213	b		
7	Rp x Ty x Bk	734	6	122	a	1.97	
8	Within Celle	1488	24	62			

Reeiduale

	Factor Number	DF	MS
a	8	24	62
b	7	6	122
c	b + 4,6,5	18	204
d	c + 2 ,3	21	233

Cement Content 300kg/m 3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	4278	2	2139	d	2.28	
2	Type	12838	1	12838	d	13.69	
3	Block	3202	3	1067	d	1.14	
4	Rp x Ty	17114	2	8557	*	19.98	> 0.5
5	Rp x Bk	9947	6	1658	c	3.62	
6	Ty x Bk	1547	3	516	b	--	
7	Rp x Ty x Bk	2570	6	428	a	3.53	> 2.5
8	Within Celle	2913	24	121			

Reeiduale

	Factor Number	DF	MS
a	8	24	121
b	7	6	428
c	b + 6	9	457
d	c + 5	15	938

Cement Content 400 kg/m 3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	2004	2	1002	c	1.44	
2	Type	20833	1	20833	c	29.86	
3	Block	1102	3 '	367	c	0.53	
4	Rp x Ty	12217	2	6108	*	8.24	> 0.5
5	Rp x Bk	5717	6	953	b	--	
6	Ty x Bk	304	3	101	b	--	
7	Rp x Ty x Bk	4446	6	741	a	8.57	> 0.1
8	Within Celle	2075	24	86			

Reeiduale

	Factor Number	DF	MS
a	8	24	86
b	7	6	741
c	b + 6,5	15	698

* Tested against Rp x Ty x Bk

Tab B.4.1.d : 3-Factor analysis of variance of compacting factor, split by cementitious content.

Cement Content 200 kg/m ^{3}

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	1303	2	652	b	11.99	
2 Type	4	1	4	b	0.08	
3 Block	275	3	92	b	1.69	
4 Rp x Ty	2	2	1	a	--	
5 Rp x Bk	1596	6	266	b	4.89	>2.5
6 Ty x Bk	200	3	67	a	--	
7 Rp x Ty x Bk	396	6	66			

Residuals

	Factor Number	DF	MS
a	7	6	66
b	a + 6,4	11	54

Cement Content 300kg/m3

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	44	2	22	b	0.46	
2 Type	1001	1	1001	b	21.25	
3 Block	1116	3	372	b	7.90	> 0.5
4 Rp x Ty	1356	2	678	b	14.39	> 0.1
5 Rp x Bk	281	6	47	a	--	
6 Ty x Bk	175	3	58	a	--	
7 Rp x Ty x Bk	250	6	42			

Residuals

	Factor Number	DF	MS
a	7	6	42
b	a + 6,5	15	47

Cement Content 400 kg/m ^{3}

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	10592	2	5296	b	13.31	
2 Type	24704	1	24704	b	62.10	
3 Block	1428	3	476	b	1.20	
4 Rp x Ty	14953	2	7477	b	18.79	>0.1
5 Rp x Bk	3179	6	530	a	--	
6 Ty x Bk	762	3	254	a	--	
7 Rp x Ty x Bk	2027	6	338			

Residuals

	Factor Number	DF	MS
a	7	6	338
b	a + 6,5	15	398

. o-rduoor analysis or variance of g, split by cementitious content.

Cement Content 200 kg/m3

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	71.48	2	35.74	d	21. 13	> 0.1
2 Type	3.71	1	3.71	c	2.33	
3 Block	10.80	3	3.60	b	2.90	
4 Rp x Ty	1.85	2	0.93	a	--	
5 Rp x Bk	10. 16	6	1.69	a	--	
6 Ty x Bk	5.07	3	1.69	a	--	
7 Rp x Ty x Bk	3.94	6	0.66			

Residuals

	Factor Number	DF	MS
a	7	6	0.66
b	a + 6,5,4	17	1.24
c	b + 3	20	1.59
d	c + 2	21	1.69

Cement Content 300 kg/m 3

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	0.29	2	0.15	b	0.34	
2 Type	7.46	1	7.46	b	17.14	
3 Block	3.56	3	1.19	b	2.73	
4 Rp x Ty	5.96	2	2.98	b	6.85	> 0.1
5 Rp x Bk	2.26	6	0.38	a	---	
6 Ty x Bk	2.04	3	0.68	a	---	
7 Rp x Ty x Bk	2.23	6	0.37			

Residuals

	Factor Number	DF	MS
a	7	6	0.37
b	a + 6 ,5	15	0. 44

Cement Content 400 kg/m3

Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1 Replacement	17 .95	2	8.97	b	30.78	
2 Type	26.19	1	26. 19	b	89.83	
3 Block	3.38	3	1. 13	b	3.87	
4 Rp x Ty	17.00	2	8.50	b	29. 17	
5 Rp x Bk	1.85	6	0.31	a	--	
6 Ty x Bk	0.20	3	0.07	a	--	
7 Rp x Ty x Bk	2.32	6	0.39			

Residuals

	Factor Number	DF	MS
a	7	6	0.39
b	a + 6 ,5	15	0.29

Tab B.4.1.f : 3-Factor analysis of variance of h, split by cementitious content.

Cement Content 200 kg/m3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	9.49	2	4.74	c	6.51	> 0.1
2	Type	3.07	1	3.07	b	5.03	
3	Block	1.89	3	0.63	a	---	
4	Rp x Ty	2.23	2	1.12	a	---	
5	Rp x Bk	4.15	6	0.69	a	---	
6	Ty x Bk	1.28	3	0.43	a	---	
7	Rp x Ty x Bk	2.67	6	0.45			

Residuals

	Factor Number	DF	MS
a	7	6	0.45
b	a + 6,5,4,3	20	0.61
c	b + 2	21	0.73

Cement Content 300 kg/m3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	0.03	2	0.01	b	0.21	
2	Type	0.36	1	0.36	b	5.39	
3	Block	5.87	3	1.96	b	29.50	> 0.1
4	Rp x Ty	0.84	2	0.42	b	6.32	1.0
5	Rp x Bk	0.67	6	0.01	a	3.08	
6	Ty x Bk	0.04	3	0.01	a	---	
7	Rp x Ty x Bk	0.29	6	0.05			

Residuals

	Factor Number	DF	MS
a	7	6	0.05
b	a + 6	9	0.04
c	b + 5	15	0.07

Cement Content 400 kg/m3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	5.28	2	2.64	b	17.04	
2	Type	2.20	1	2.20	b	14.18	
3	Block	0.68	3	0.23	b	1.45	
4	Rp x Ty	1.80	2	0.90	b	5.80	> 2.5
5	Rp x Bk	0.98	6	0.16	a	---	
6	Ty x Bk	0.16	3	0.05	a	---	
7	Rp x Ty x Bk	1.18	6	0.20			

Residuals

	Factor Number	DF	MS
a	7	6	0.20
b	a + 6,5	15	0.15

Compressive Strength data

Tabs B.4.2.a-b	Typical 5-factor analyses
Tabs B.4.2.c-d	Typical 4-factor, split analyses
Tabs B.4.2.e-g	F-ratios

Tab B.4.2.a : 5-Factor analysis of variance of the 3-day compressive strength data for 20°C wet and dry curing.

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Cement	6767. 3	2	3383. 6	b	7387 ,8	
2	Replacement	5152. 5	2	2576. 3	b	5625,.0	
3	Type	37. 5	1	37 .5	b	81,.8	
4	Curing	394. 1	1	394. 1	b	860,.5	
5	Block	12. 5	1	12. 5	b	27 ,2	
6	Cm X Rp	1052. 5	4	263. 1	b	574 .5	
7	Cm X Ty	2. 2	2	1. 1	b	2 .4	
8	Cm X Cu	145. 8	2	72. 9	b	159 .1	
9	Cm X Bk	11. 5	2	5. 7	b	12 .5	
10	Rp X Ty	30. 9	2	15. 5	b	33 .8	
11	Rp X Cu	133. 9	2	67. 0	b	146 .2	
12	Rp X Bk	4. 1	2	2. 0	b	4 .4	
13	Ty X Cu	0. 1	1	0. 1	b	0 .1	
14	Ty X Bk	0. 0	1	0. 0	b	0 .1	
15	Cu X Bk	1.,8	1	1..8	b	3 .9	
16	Cm X Rp X Ty	8.,6	4	2.,1	b	4 .7	
17	Cm X Rp X Cu	41..0	4	10..2	b	22 .3	> 0.1
18	Cm X Rp X Bk	15..8	4	3..9	b	8 .6	> 0.1
19	Cm X Ty X Cu	0,.3	2	0,.2	a	-	
20	Cm X Ty X Bk	1,.5	2	0..7	a	-	
21	Cm X Cu X Bk	0,.8	2	0,.4	a	- -	
22	Rp X Ty X Cu	0 .0	2	0 .0	a	---	
23	Rp X Ty X Bk	0 .9	2	0 .5	a	- -	
24	Rp X Cu X Bk	2 .0	2	1 .0	a	- -	
25	Ty X Cu X Bk	0 .4	1	0 .4	a	- -	
26	Cm X Rp X Ty x Cu	0 .4	4	0 .1	a	---	
27	Cm X RP X Ty x Bk	2 .3	4	0 .6	a	---	
28	Cm X Rp X Cu x Bk	2 .9	4	0 .7	a	---	
29	Cm X Ty X Cu x Bk	0 .4	2	0 .2	a	---	
30	Rp X Ty X Cu x Bk	0 .9	2	0 .5	a	- -	
31	Cm X Rp X Ty x Cu x Bk	0 .7	4	0 .2	a	- -	
32	Within Cell	34 .6	72	0 .5			

Residual	Factor Number	DF	MS
a	32	72	0.5
b	a + 31 to 19	105	0.5

Tab B.*l.2.b : 5-Factor analysis of variance of the 91-day compressive strength data under 20°C wet and dry curing.

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Cement	23887	2	11944	a	5701.8	
2	Replacement	2296	2	1148	a	548.0	
3	Type	164	1	164	a	78.5	
4	Curing	20157	1	20157	a	9623.0	
5	Block	15	1	15	a	7.3	
6	Cm x Rp	357	4	89	a	42.6	
7	Cm x Ty	120	2	60	a	28.6	
8	Cm x Cu	692	2	346	a	165. 1	
9	Cm x Bk	9	2	4	a	2.1	
10	Rp x Ty	88	2	44	a	20.9	
11	Rp x Cu	523	2	262	a	124.9	
12	Rp x Bk	2	2	1	a	0.5	
13	Ty x Cu	50	1	50	a	24.0	
14	Ty x Bk	0	1	0	a	0.0	
15	Cu x Bk	15	1	15	a	7 .1	
16	Cm x Rp x Ty	63	4	16	a	7.6	
17	Cm x Rp x Cu	82	4	20	a	9.8	
18	Cm x Rp x Bk	29	4	7	a	3.4	
19	Cm x Ty x Cu	1	2	0	a	0.1	
20	Cm x Ty x Bk	11	2	5	a	2.6	
21	Cm x Cu x Bk	10	2	5	a	2.4	
22	Rp x Ty x Cu	26	2	13	a	6.1	
23	Rp x Ty x Bk	0	2	0	a	0.0	
24	Rp x Cu x Bk	7	2	3	a	1.6	
25	Ty x Cu x Bk	1	1	1	a	0.6	
26	Cm x Rp x Ty x Cu	30	4	8	a	3.6	
27	Cm x Rp x Ty x Bk	14	4	3	a	1.6	
28	Cm x Rp x Cu x Bk	15	4	4	a	1.8	
29	Cm x Ty x Cu x Bk	5	2	3	a	1.2	
30	Rp x Ty x Cu x Bk	1	2	0	a	0.2	
31	Cm x Rp x Ty x Cu x Bk	27	4	7	a	3.2	>2 . 5
32	Within Cell	151	72	2			

Residual	Factor Number	DF	MS
a	32	72	2.1

Tab B.4.2.C : 4-Factor analysis of variance of the 3-day compressive strength data under 20°C wet and dry curing, split by cementitious content.

Cement Content 200 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	352.62	2	176.31	b	3060.39	
2	Type	5.39	1	5.39	b	93.62	
3	Curing	7.18	1	7.18	b	124.71	
4	Block	0.03	1	0.03	b	0.50	
5	Rp x Ty	3.90	2	1.95	b	33.86	
6	Rp x Cu	3.94	2	1.97	b	34.19	
7	Rp x Bk	0.22	2	0.11	b	1.91	
8	Ty x Cu	0.00	1	0.00	b	0.06	
9	Ty x Bk	0.16	1	0.16	b	2.70	
10	Cu x Bk	0.01	1	0.01	b	0.09	
11	Rp x Ty x Cu	0.09	2	0.04	a	—	
12	Rp x Ty x Bk	0.08	2	0.04	a		
13	Rp x Cu x Bk	0.80	2	0.40	b	6.92	> 0.5
14	Ty x Cu x Bk	0.03	1	0.03	a	—	
15	Rp x Ty x Cu x Bk	0.02	2	0.01	a		
16	Within Cell	1.57	24	0.07			

Residuals		DF	MS
a	16	24	0.07
b	a + 15,14,12,11	31	0.06

Cement Content 300 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	1715.93	2	857.96	c	1420.94	
o	Type	18.00	1	18.00	c	29.80	
3	Curing	143.35	1	143.35	c	237.41	
4	Block	22.48	1	22.48	c	37 .23	> 0.1
5	Rp x Ty	9.51	2	4.75	c	7.87	> 0.5
6	Rp x Cu	61.26	2	30.63	c	50.73	> 0.1
7	Rp x Bk	1.61	2	0.81	b	—	
8	Ty x Cu	0.37	1	0.37	b	—	
9	Ty x Bk	0.60	1	0.60	b	—	
10	Cu x Bk	0.84	1	0.84	b	—	
11	Rp x Ty x Cu	0.21	2	0.10	a	—	
12	Rp x Ty x Bk	0.31	2	0.15	a		
13	Rp x Cu x Bk	3.97	2	1.99	b	3.96	
14	Ty x Cu x Bk	0.75	1	0.75	a	—	
15	Rp x Ty x Cu x Bk	0.57	2	0.28	a		
16	Within Cell	13.71	24	0.57			

Residuals		DF	MS
a	16	24	0.57
b	a + 15,14,12,11	31	0.50
c	b + 13,10,9,8,7	38	0.60

Cement Content 400 kg/m

	Factor	ss	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	4136.5	2	2068.3	c	2870.58	
L	Type	16.3	1	16.3	c	22.64	
3	Curing	389.3	1	389.3	c	540.33	
4	Block	1.5	1	1.5	c	2.03	
5	Rp x Ty	26. 1	2	13.1	c	18. 13	>0.1
6	Rp x Cu	109.7	2	54.8	c	76.11	> 0.1
7	Rp x Bk	18.0	2	9.0	c	12.48	> 0.1
8	Ty x Cu	0.0	1	0.0	b	—	
9	Ty x Bk	0.7	1	0.7	b	—	
10	Cu x Bk	1.7	1	1.7	b	----	
11	Rp x Ty x Cu	0.1	2	0.1	d	----	
12	Rp x Ty x Bk	2.8	2	1. 4	b	2. 09	
13	Rp x Cu x Bk	0.2	2	0.1	a	—	
14	Ty x Cu x Bk	0.0	1	0.0	a	—	
15	Rp x Ty x Cu x Bk	1.0	2	0.5	a		
16	Within Cell	19.4	24	0.8			

Residuals		DF	MS
a	16	24	0.81
b	a + 15,14,13,11	31	0.67
c	b + 12,10,9,8	36	0.72

Tab B.4.2.d : 4-Factor analysis of variance of the 91-day compressive strength data under 20°C wet and dry curing, split by cementitious content.

Cement Content 200 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	217.0	2	108.5	b	98.0	
2	Type	45.1	1	45.1	b	40.7	
3	Curing	2445.2	1	2445.2	b	2208.8	
4	Block	0.0	1	0.0	b	0.0	
5	Rp x Ty	26.4	2	13.2	b	11.9	
6	Rp x Cu	227 .2	2	113.6	b	102.6	
7	Rp x Bk	2.1	2	1.1	b	1.0	
8	Ty x Cu	21.5	1	21.5	b	19.4	
9	Ty x Bk	1.0	1	1.0	b	0.9	
10	Cu x Bk	0.0	1	0.0	b	0.0	
11	Rp x Ty x Cu	10.8	2	5.4	b	4.9	> 2.5
12	Rp x Ty x Bk	0.9	2	0.5	a	—	
13	Rp x Cu x Bk	0.5	2	0.2	a	—	
14	Ty x Cu x Bk	0.6	1	0.6	a	—	
15	Rp x Ty x Cu x Bk	0.3	2	0.2	a		
16	Within Cell	32.0	24	1.3			

Residuals		DF	MS
a	16	24	1.3
b	a + 15,14 ,13,12	31	1.1

Cement Content 300 kg/m

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	996.1	2	498.0	a	496.2	
2	Type	239.1	1	239.1	a	238.2	
3	Curing	8277.4	1	8277.4	a	8246.1	
4	Block	9.8	1	9.8	a	9.7	
5	Rp x Ty	124.6	2	62.3	a	62.1	
6	Rp x Cu	62.3	2	31.2	a	31.0	
7	Rp x Bk	10.9	2	5.5	a	5.4	
8	Ty x Cu	12.7	1	12.7	a	12.6	
9	Ty x Bk	3.3	1	3.3	a	3.3	
10	Cu x Bk	5.2	1	5.2	a	5.2	
11	Rp x Ty x Cu	25.1	2	12.6	a	12.5	
12	Rp x Ty x Bk	5.7	2	2.9	a	2.9	
13	Rp x Cu x Bk	16.5	2	8.2	a	8.2	
14	Ty x Cu x Bk	5.6	1	5.6	a	5.5	
15	Rp x Ty x Cu x Bk	12.5	2	6.3	a	6.2	>2.5
16	Within Cell	24.1	24	1.0			

Residuals		DF	MS
a	16	24	1.00

Cement Content 400 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	1439.9	2	720.0	c	142.2S	
2	Type	0.0	1	0.0	c	0.0	
3	Curing	11126.4	1	11126.4	c	2198.9	
4	Block	14.3	1	14.3	c	2.8	
5	Rp x Ty	0.0	2	0.0	b		
6	Rp x Cu	315.5	2	157.7	c	31.2	>0.1
7	Rp x Bk	17 .7	2	8.9	b	—	
8	Ty x Cu	16 .8	1	16.8	b	—	
9	Ty x Bk	6.6	1	6.6	b	—	
10	Cu x Bk	19.8	1	19.8	b		
11	Rp x Ty x Cu	20.2	2	10.1	b	2.6	
12	Rp x Ty x Bk	6.9	2	3.5	a	—	
13	Rp x Cu x Bk	4.5	2	2.3	a	—	
14	Ty x Cu x Bk	0.1	1	0.1	a	—	
15	Rp x Ty x Cu x Bk	14.9	2	7.5	a		
16	Within Cell	94.7	24	3.9			

Residuals		DF	MS
a	16	24	3.9
b	a + 15,14,13,12	31	3.9
c	b + 11,10,9,8,7,6	40	5.1

Tab B.4.2.e : F-Ratios from the analysis of variance of compressive strength under 40°C and 20°C wet curing, split by age, GGBS level and cementitious content.

Tab B.4.2.f : F-Ratios from the analysis of variance of compressive strength under 20°C wet and dry curing, split by age, GGBS level and cementitious content.

Tab B.4.2.g : F-Ratios from the analysis of variance of compressive strength under 10°C and 5°C wet curing, B.4.3 <u>Water Absorption data</u>

Tab	B.4.3.a	5-factor analysis
Tabs	B.4.3.b-c	4-factor, split analyses

Tab B.4.3*a : 5-Factor analysis of variance of the water absorption data, under 10°C and 5°C wet curing.

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Cement	2716.6	2	1358.3	d	77.44	
2	Replacement	207.3	2	103.6	d	5.91	
3	Type	11.7	1	11.7	c	---	
4	Curing	29.3	1	29.3	c	---	
5	Block	106.9	1	106.9	d	6.09	
6	Cm X Rp	138.8	4	34.7	b	---	
7	Cm X Ty	12.1	2	6.0	b	---	
8	Cm X Cu	4.8	2	2.4	b	—	
9	Cm X Bk	10.6	2	5.3	b	---	
10	Rp X Ty	38.5	2	19.3	b	---	
11	RP X Cu	80.6	2	40.3	c	2.42	
12	Rp X Bk	40.8	2	20.4	b	---	
13	Ty X Cu	10.0	1	10.0	b	---	
14	Ty X Bk	1.2	1	1.2	b	---	
15	Cu X Bk	7.6	1	7.6	b	---	
16	Cm X Rp X Ty	51.8	4	13.0	a	---	
17	Cm X Rp X Cu	53.9	4	13.5	a	---	
18	Cm X Rp X Bk	118.7	4	29.7	a	---	
19	Cm X Ty X Cu	4.3	2	2.2	a	---	
20	Cm X Ty X Bk	17.5	2	8.8	a	---	
21	Cm X Cu X Bk	14.7	2	7.3	a	---	
22	RP X Ty X Cu	86.1	2	43.1	b	2.72	
23	Rp X Ty X Bk	3.0	2	1.5	a	--	
24	Rp X Cu X Bk	44.6	2	22.3	a	---	
25	Ty X Cu X Bk	4.0	1	4.0	a	---	
26	Cm X Rp X Ty X Cu	55.2	4	13.8	a	---	
27	Cm X Rp X Ty X Bk	21.5	3	7.2	a	---	
28	Cm X Rp X Cu X Bk	153.2	4	38.3	a	--	
29	Cm X Ty X Cu X Bk	28.8	2	14.4	a	--	
30	Rp X Ty X Cu X Bk	33.0	2	16.5	a	--	
31	Cm X Rp X Ty X Cu x Bk	28.8	2	14.4			

Residual	Factor Number	DF	MS
a	31	2	14.4
b	a + 30 to 23,21 to 16	40	15.8
c	b + 22,15 to 1 to 6	59	16.7
d	c + 11,3,4	63	17.5

Tab B.4.3.b : U-Factor analysis of variance of the water absorption data, under 40°C and 20°C wet curing.

Cement Content 200 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	517.33	2	258.67	c	9.13	
2	Type	150.00	1	150.00	c	5.30	
3	Curing	240.67	1	240.67	c	8.50	1.0
4	Block	8.17	1	8.17	c	0.29	
5	Rp x Ty	804.00	2	402.00	c	14.19	> 0.1
6	Rp x Cu	58.33	2	29.17	b	—	
7	Rp x Bk	120.33	2	60.17	b	—	
8	Ty x Cu	10.67	1	10.67	b	—	
9	Ty x Bk	1.50	1	1.50	b	--	
10	Cu x Bk	1.50	1	1.50	b	--	
11	Rp x Ty x Cu	126.33	2	63.17	b	3.29	
12	Rp x Ty x Bk	13.00	2	6.50	a	—	
13	Rp x Cu x Bk	37 .00	2	18.50	a	--	
14	Ty x Cu x Bk	48.17	1	48.17	a	—	
15	Rp x Ty x Cu x Bk	36.33	2	18.17			

Residuals		DF	MS
a	15	2	18.17
b	a + 12,13,14	7	19.21
c	b + 11,10,9,8,6,7	16	28.33

Cement Content 300 kg/m

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	99.75	2	49.88	e	1.50	
2	Type	92.04	1	92.04	e	2.76	
3	Curing	92.04	1	92.04	e	2.76	
4	Block	2.04	1	2.04	d	—	
5	Rp x Ty	79.08	2	39.54	d	—	
6	Rp x Cu	115.58	2	57.79	d	--	
7	Rp x Bk	65.58	2	32.79	d	—	
8	Ty x Cu	5.04	1	5.04	d	—	
9	Ty x Bk	51.04	1	51.04	d	—	
10	Cu x Bk	0.38	1	0.38	d	—	
11	Rp x Ty x Cu	140.58	2	70.29	d	2.84	
12	Rp x Ty x Bk	64.58	2	32.29	b	11.93	
13	Rp x Cu x Bk	100.75	2	50.38	c	3.46	
14	Ty x Cu x Bk	2.04	1	2.04	a	--	
15	Rp x Ty x Cu x Bk	6.08	2	3.04			

Residuals		DF	MS
a	15	2	3.04
b	a + 14	3	2.71
c	b + 12	5	14.54
d	c + 13	7	24.78
e	d + 11,1 to 4	19	33.30

Cement Content 400 kg/m^3

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	621.58	2	310.79	d	29.05	
2	Type	7.04	1	7.04	d	0.66	
3	Curing	0.04	1	0.04	d	0.00	
4	Block	2.04	1	2.04	d	0.19	
5	Rp x Ty	5.08	2	2 .54	c	---	
6	Rp x Cu	7 .58	2	3.79	c	---	
7	Rp x Bk	125.08	2	62.54	d	5.85	> 2.5
8	Ty x Cu	22.04	1	22.04	c	---	
9	Ty x Bk	9.38	1	9.38	c	---	
10	Cu x Bk	30.37	1	30.37	c	3.24	
11	Rp x Ty x Cu	11.08	2	5.54	a	---	
12	Rp x Ty x Bk	5.25	2	2.63	a	---	
13	Rp x Cu x Bk	1.75	2	0.88	a	---	
14	Ty x Cu x Bk	45.37	1	45.37	b	7.07	
15	Rp x Ty x Cu x Bk	33.25	2	16.63			

Residuals		DF	MS
a	15	2	16.63
b	a + 13,12,11	8	6.42
c	b + 14	9	10.74
d	c + 5,6,9,8,10	16	10.70

Tab B.4.3.C : 4-Factor analysis of variance of the water absorption data, under 20°C wet and dry curing.

Cement Content 200kg/m 3

	Factor	SS	DF	MS	Residual U6ed	F-ratio	Significance Level %
1	Replacement	3961.3	2	1980.6	d	25.57	
2	Type	245.7	1	245.7	d	3.17	
3	Curing	16897.4	1	16897.4	d	218 .20	
4	Block	125.4	1	125.4	d	1.62	
5	Rp x Ty	261.3	2	130.6	c	—	
6	Rp x Cu	3329.2	2	1664.6	d	21.49	> 0.1
7	Rp x Bk	62.1	2	31.0	c	—	
8	Ty x Cu	110.0	1	110.0	c	—	
9	Ty x Bk	23.4	1	23. 4	c	—	
10	Cu x Bk	78. 1	1	78.1	c	—	
11	Rp x Ty x Cu	320.2	2	160. 1	c	3. 13	
12	Rp x Ty x Bk	17.7	2	8.8	a	—	
13	Rp x Cu x Bk	189.9	2	95.0	b	3.25	
14	Ty x Cu x Bk	66.1	1	66.1	a	—	
15	Rp x Ty x Cu x Bk	33.1	1	33.1			

Residuals		DF	MS
a	15	1	33.1
b	a + 12,14	4	29.2
c	b + 13	6	51.1
d	c + 11,9,7,10,8,5	15	77.5

Cement Content 300kg/m 3

	Factor	SS	DF	MS	Residual U6ed	F-ratio	Significance Level %
1	Replacement	8879.3	2	4439.6	d	38.54	
2	Type	805.0	1	805.0	d	6.99	> 2.5
3	Curing	18205.0	1	18205.0	d	158.01	
4	Block	45.4	1	45.4	d	0.39	
5	Rp x Ty	735.6	2	367 .8	c	4.65	
6	Rp x Cu	6803.6	2	3401.8	d	29.53	> 0.1
7	Rp x Bk	405.8	2	202.9	b	5.21	
8	Ty x Cu	273.4	1	273.4	b	—	
9	Ty x Bk	0.4	1	0.4	a	—	
10	Cu x Bk	22.0	1	22.0	a	—	
11	Rp x Ty x Cu	137.3	2	68.6	a	—	
12	Rp x Ty x Bk	0.8	2	0.4	a	—	
13	Rp x Cu x Bk	56. 1	2	28.0	a	—	
14	Ty x Cu x Bk	84 .4	1	84.4	a	—	
15	Rp x Ty x Cu x Bk	127.8	2	63.9			

Residuals		DF	MS
a	15	2	63.9
b	a + 14 to 9	11	39.0
c	b 4 7,8	14	79 .1
d	c + 5	16	115.2

Cement Content 400kg/m

	Factor	SS	DF	MS	Residual used	F-ratio	Significance Level %
1	Replacement	2830.6	2	1415.3	d	28 .16	
2	Type	28.2	1	28.2	d	0.56	
3	Curing	5460.2	1	5460.2	d	108.64	
4	Block	4.2	1	4.2	d	0.08	
5	Rp x Ty	30.1	2	15.0	a	—	
6	Rp x Cu	2492.6	2	1246.3	d	24.80	> 0.1
7	Rp x Bk	70.6	2	35.3	a	—	
8	Ty x Cu	160.2	1	160.2	b	5.10	
9	Ty x Bk	204.2	1	204. 2	c	5.10	
10	Cu x Bk	37.5	1	37 .5	a	—	
11	Rp x Ty x Cu	105. 1	2	52. 5	a	—	
12	Rp x Ty x Bk	103.1	2	51.5	a	—	
13	Rp x Cu x Bk	54.3	2	27. 1	a	—	
14	Ty x Cu x Bk	20.2	1	20.2	a	—	
15	Rp x Ty x Cu x Bk	19. 1	2	9 .5			

Residuals		DF	MS
a	15	2	9.5
b	a 4 14 to 11,5,7	14	31. 4
C	b 4 8	15	40.0
d	C 4 9	16	50 .3

C.1 Workability

C.1.1 Calculation of £ and h

For the two-point test operating in the low-medium workability mode, with a 20:1 right-angle reduction gear and a 1:2.25 planetary gear. At each speed:

1. Total and Idling pressures are measured in lbf/in^2 and coupling speed is measured in RPM (1 lbf/in^p r 6.9 kPa).
2. Net Pressure = Total Pressure - Idling Pressure lbf/in^2
3. Axial Torque = 0.0680 x Net Pressure (Fig A.1.a) Nm
4. Impeller Torque = Axial Torque / 2.25 Nm
5. Impeller Speed = Coupling Speed x 2.25 / (20 x 60) Hz
6. g and h, in the equation T = g + hN, are calculated by regressing impeller torque upon speed.

Example:-

Speed	Pressure (lbf/in2)		N	T
(RPM)	Total	Idling	(Hz)	(Nm)
597	521	129	1 .119	11.85
497	485	121	0.932	11.00
396	438	116	0.742	9.73
348	424	111	0.653	9.46
296	390	108	0.555	8.52
247	366	102	0.463	7.98
199	350	96	0.373	7.68
152	327	92	0.285	7.10
93	293	88	0.174	6.20

r = 0.997 g = 5.32 h = 5.97

C.1.2 Confidence Interval on £ and h (17)

The standard errors are:

$$seh = h\sqrt{\frac{(1-r2)}{r2}\left(\frac{1}{n-2}\right)}$$

$$seg = seh\left(\frac{\sqrt{N2}}{n}\right)$$

where n is the number of speeds used.

For the nine speed settings used (6,5,4,3.5,3,2.5,2,1.5,1) the root mean square of the speeds lies around 0.64.

Thus $se_g = 0.64\ se_h$.

The confidence interval is formed by multiplying the standard error by the appropriate value of Students t.

$$h \pm seh \times t_{n-2} \quad \text{and} \quad g \pm seg \times t_{n-2}$$

C.1.3 Rule-of-thumb interval on £ and h

This is calculated assuming that the upper and lower 90% limits on g and h are independent observations from the population. For example, four blocks of workability results give rise to eight observations.

	1	1	3	4
upper limits	6.90	6.83	6.42	4.28
lower limits	5.61	6.06	6.00	3.60

using $se = \frac{sd}{\sqrt{2}}$ and interval = mean +/- se x $t_{2.5\%,7}$

mean = 5.72, sd = 1.19, se = 0.84, t = 2.36,

therefore interval = 5.72 +/- 1.99

C.2 Strength and Elasticity

C.2.1 Maturity (76)

Compressive strength is shown plotted against the equivalent age in Fig 8.3.3-k. Two maturity functions were used to calculate the age,

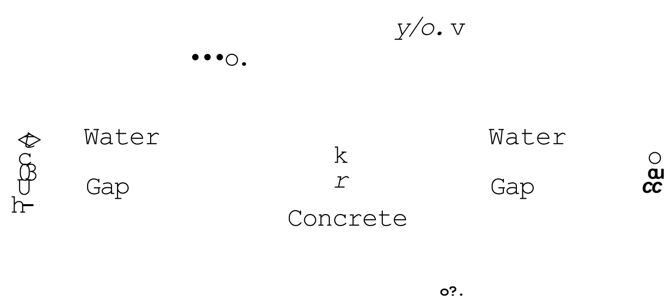
Nurse-Saul $\frac{(T+10)}{30}$ and Sadgove $\left(\frac{T+16}{36}\right)^2$

where T is the mean concrete temperature (°C).

Work by the author elswhere (.78) has indicated that the Sadgrove function is more universal than the Nurse-Saul function. The equivalent ages in days at 20°C are shown below for the curing temperatures employed.

Age (days)	40°C	20°C	10°C	5°C
1	2.4	1	0.5	0.3
3	7.3	3	1.6	1.0
7	16.9	7	3.7	2.4
28	67.8	28	14.6	9.5
91	220.2	91	47.5	31.0

underwater



I - Transit time (ps)
L - Path length (mm)
V - Pulse velocity (km/s)

w - Water
g - Water gap
c - Concrete
m - Mixture

In order to obtain the pulse velocity in the concrete cube the transit times with and without the cube in the tank of water must be measured.

$$T_m = T_g + T_c$$

thus $$T_c = T_m - T_g$$

but $$T_g = T_w - L_g$$

substituting for a 100mm cube,

$$T_c = T_m - (T_w - \frac{100}{1.48})$$

therefore $T_c = T_m - T_w + 67.7$ and $V_c = \frac{100}{T_c}$

C.2.3 Poisson's ratio

$$E_{cq} = \frac{\rho V^2 (1 + \mu)(1-2\mu)}{1-\mu} \quad \text{GPa}$$

but ρV^2 is the Stiffness Constant (E_u) GPa. (82).

let $\frac{E_{cq}}{E_u} = T$

substituting and rearranging,

$$T(1-\mu) = (1+\mu)(1-2\mu)$$

and $$0 = 2\mu^2 + (1-T)\mu + (T-1)$$

using the formulae $x = \frac{-b \pm \sqrt{(b^2 - 4ac)}}{2a}$

$$\mu = \frac{(T-1) \pm \sqrt{[(1-T)^2 - 8(T-1)]}}{4}$$

for positive values of μ

$$\mu = \frac{(T-1) + \sqrt{[T^2 - 10T + 9]}}{4}$$

Poisson's ratio can easily be calculated from the stiffness constant.

If $E_{cq} = aE_u + c$ then $T = a + c/E_u$

or $E_{cq} = aE_u^b$ then $T = aE_u^{(b-1)}$

C.3 Hydration and Durability

C.3.1 First-order correction of vacuum flask calorimetry results

COOLING CURVE

CORRECTION

c.

Actual

Recorded,^

-kt

Te

time

time

t t

The temperature profile can be approximated by a number of thin trapezoidal strips. The cooling over each strip (C) can be taken to be a function of the mean temperature (Tm), cooling coefficient (k) and the strip width (t). Applying Arrehnius law, with all the temperatures measured relative to the base temperature Te:

therefore $$C = T_m(1-e^{-kt})$$

and $$T_a = C + T_r$$

The coefficient k is 0.0018-0.0012 °C/min and the subscripts r and a denote the recorded and actual temperatures respectively; ignoring the effect of temperature upon the reaction rate and heat evolved by it. For a sequence of slices the corrections for cooling must be added together.

thus $$T_{a_i} = \sum_{1}^{i} C_s + T_{r_i}$$

C.3.2 Activation Energy

Several researchers (34) have calculated apparent activation energies using the Arrhenius relationship

$$\frac{t_1}{t_2} = \exp\left\{\frac{Ea}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right\}$$

where E_a is the apparent activation energy KJ/mol;

R is the molar gas constant (0.008314 kJ/mol K°);

T is the curing temperature K; and

t is the equivalent age to reach a certain degree of hydration.

rearranging, $$Ea = R\,\frac{\{\ln(t_1/t_2)\}}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

The degree of hydration can be judged from strength or calorimetry measurements. The following values of Ea were calculated from the equivalent ages to reach compressive strengths of 10, 20 and 30 MPa in the 200, 300 and 400 kg/m^3 cementitious content mixes, under 20 and 5°C wet curing.

Mix	Mean	sd
OPC	49.5	4.2
40$ Type 1	57.5	4.9
40$ Type 2	54.8	7.3
70$ Type 1	66.7	2.7
70$ Type 2	57.5	4.2

C.3.3 Water Absorption

The water absorption can be simply calculated by dividing the mass of water absorbed by the area and time of contact.

$$\text{specific water absorption} = \frac{\text{mass}}{\text{area x time}}$$

Area of cross section $= \frac{75^2}{4} \times \pi = 4418$ mm^2

thus $WA_{60} = \frac{\text{mass} \times 10^6}{4418 \times 3600} = \frac{\text{mass}}{15.90}$ $ml/m^2.s$

```
   10 REM A PROGRAM TO ANALYSE THE DATA OF THE TWO-POINT WORKABILITY R16 OK A BBC B* WITH GRAPHICS AND PRINTMASTER ROMS FITTED
   110 INPUT   TAB(0.9)"CHOOSE RIG"*BUILDING=1 OR CIV. ENG.=2 ? "RIG
a  120 INPUT          TAb(0,12) CHOOSE MOTION"*CONCENTRIC=1 OR PLANETARY=2 ?       MOTION
   130 INPUT   TAB(0,15)"CHOOSE GEAR BOX"" FIVE TO ONE =1 OR TWENTY TO       ONE=2? GEAR
   140 INPUT   TAb(0,18)"COUPLING SPEED FACTOR*" 1 OR 2 ? "SPOTS
   150 INPUT   TAB(0,21)"CONFIDENCE LEVEL"" 90%=1 OR 95%=2 ? "CL
   160 A(1,1)=0.019:A(1,2)=0.066:A(2,1)=A(1,1):A(2,2)=0.068:A(3,1)=1/(4.75*60):A(3,2)=1/(20*60)
   170 T(1.1)=2.920:T(2,1)=2.353:T(3,1)=2.132:T(4,1)=2.015:T(5,1)=1.943:T(6,1)=1.895:T(7,1)=1.860:T(8,1)=1.833:T(1,2)=4.303:T(2,2)=3.128:T
       (3,2)=2.776:T(4,2)=2.571:T(5,2)=2.447:T(6,2)=2.365:T(7,2)=2.306:T(8,2)=2.262
   180 HINRINE=0.1:HINTINE=0.2:NINISINE=0.2
   200 DIM COUPSPEEDZ(12):DIM PRESSZ(12):DIM IDLEPRESSZ(12):DIM IMPSPEED(12):DIM TRQUE(12):DIM RESIDUAL(12):DIM INDRESD(12)
   260 REPEAT
   270 CLS:INPUT TAB(0,2) "MIX LABEL "MIX*
   290 CLS:INPUT TAB(0,2) NUMBER OF POINTS "POINTS
   300 FOR J=1 TO POINTS
L  310 INPUT TAB(0,5)"COUPLING SPEED(RPM) .TOTAL PRESSURE(PSI) AND IDLING PRESSURE(PSI)" TAB(10,(6+J)) COUPSPEED,PRESS,IDLEPRESS
   320 IF PRESS<IDLEPRESS THEN 310 ELSE COUPSPEEDZ(J)=INT(COUPSPEED/SPOTS+0.5):PRESSX(J)=INT(PRESS+0.5):IDLEPRESSX(J)=INT(IDLEPRESS+0.5)
   330 NEXT J
   350 CLS:INPUT TAB(8,10)"HARDCOPY-Y/N "DISPRIN*
   360 FOR J=1 TO POINTS
c  370 IMPSPEED(J)=COUPSPEEDZ(J)*A(3,GEAR):TRQUE(J)=(PRESSX(J)-IDLEPRESSZ(J))*A(RIG,GEAR)
   375 IF MOTION=2 THEN IMPSPEED(J)=IMPSPEED(J)*2.25:TRQUE(J)=TRQUE(J)/2.25

   380 NEXT J
   381 FOR T=1 TO POINTS+1
   382 IF POINTS<5 THEN T=POINTS *1
U  384 PROCREGRESSION:NEXT T
   385 IF POINTS<4 THEN GW=0:HW=0:GOTO 410
   390 STDERROR=SQR( (1-R^2)/(R^24(POINTS-2)))
e  400 HW=ABS(H*STDERROR*T((POINTS-3),CL)):GW=ABS(K*HW)
   410 ULIMITH=H+HW:LLIMITH=H-HW:ULIMITG=G+GW:LLIMITG=G-GW:1STYLE "N H"
   420 IF DISPRIN*="Y" THEN VDU 2
   430 S2=4000002:4INDERLINE
   440 PRINT:PRINT:PRINT:PRINT:PRINT MIX$:VDU3:>INITALISE
   450 MAXRESIDUAL=0:MAXTRQUE=0:MINTRQUE=G:MAXSPEED=0
   460 FOR J=1 TO POINTS
f  470 RESIDUAL(J)=TRQUE(J)-(H*IMPSPEED(J)+G)
   480 IF ABS(RESIDUAL(J))>MAXRESIDUAL THEN MAXRESIDUAL=ABS(RESIDUAL(J))
   490 IF TRQUE(J)>MAXTRQUE THEN MAXTRQUE=TRQUE(J)
   500 IF TRQUE(J)<MINTRQUE THEN MINTRQUE=TRQUE(J)
   510 IF IMPSPEED(J)>MAXSPEED THEN MAXSPEED=IMPSPEED(J)
   520 SOS=SOS+(RESIDUAL(J)^2)
   530 NEXT J:SDPRL=SQR(SOS/(POINTS-2))
   750 SR=INT(RESIDUAL(J)/SDPRL+0,5):IF POINTS > 4 THEN SIR=INT(ABS(INDRESD(J)/SDPRL+0,5))

   860 DEF PROCREGRESSION
9  870 ASUM=0:BSUM=0:ASQSUM=0:BSQSUM=0:PRODSUM=0:SOS=0:N=0:FOR J=1 TO POINTS
   871 IF J=T THEN 873 ELSE N=N+1:A=IMPSPEED(J):B=TRQUE(J)
   872 ASUM=ASUM+A:BSUM=BSUM+B:PRODSUM=PRODSUM+A*B:ASQSUM=ASQSUM+(A^2):BSQSUM=BSQSUM+(B^2)
[redacted]873 NEXT J
   874 V=(PRODSUM-(ASUM*BSUM)/N):K=SQR(ASQSUM/N):U=(ASQSUM-(ASUM^2)/N):Z=(BSQSUM-(BSUM^2)/N):R=V/(SQR(U*Z)):H=V/U:G=(BSUM-H*ASUM)/N
   875 IF T>POINTS THEN G=C:H=H ELSE INDRESD(T)=TRQUE(T)-(H*IMPSPEED(T)+C)
   880 ENDPROC

,  1170 DEF PROCSTORE
"  1180 FOR T=1  TO1000:F=T MOD 100
   1190 IF F=0 THEN PRINT TAB(8,10)"INSERT DATA DISC IN DRIVE 1" ELSE IF F=50 THEN PRINT TAB(8,10)"
   1200 NEXT T
   1210 INPUT TAB(0,15)"GIVE FILE LABEL".LABEL*
   1220 IF LABEL$="" THEN 1210
   1230 FILENO=OPENOUT(LABEL*):PRINT# FILENO.POINTS,R,H,ULIMITH,LLIMITH,G,ULIMITG,LLIMITG
   1240 FOR J=1  TO POINTS:PRINT# FILENO,IMPSPEED(J),TRQUE(J):NEXT J
   1250 FOR J=1  TO POINTS:PRINT# FILENO,COUPSPEEDZ(J),PRESS!(J),IDLEPRESS!(J):NEXT J:CLOSE# FILENO:VDU 2:PRINT LABEL*" STORED1
       . . . . . VDU 3:ENDPROC
```

I f ELLER SPEED H M E

ft
0)
I
8
v

A
m
m
1
A

,8 11,8 12,1 13,8 14,8
TORQUE (HR)

nt 1.6 2.4 3,2 4,1 4,8 5.6 6,4 9 m PIS r g h

1 4-
2 ▪4
3 - 4

1	9	8,979	2,11	2,88
2	9	8,989	3,78	3,41
3	9	8,988	6,67	4,65

m 2,8 2,1 2,8 3,2 3,6 4,8 4,4 <,8 h

1 - 1
2 - 1
3 --- 1--

Fig D.1 : Example of the computer presentation of the two-point workability test results (a=4S0, b=4P4, c=4P7).

D.2. Temperature Monitoring

```
10 REM ft TEMPERATURE MONITORING SYSTEM FOR UPTO 10 THERMOCOUPLES CONNECTED TO A COLD JUNCTION
170 lNPUTTAB(0,13)*Please enterthe proposed numberof Thermocouples ' TCS
180 INPUTTAP(0,15)*Please enterthe DURATION of thetest(hours) 'DURATION
185 lNPUTTAB(0,17)'Please enterthe time INTERVAL between readinQs(minutes)'TIC
190 FILE5=INT(DURAT10NI(TCS+1)/(25tT1C)+1):X=INT(350ITIC/(TCS<-1)):IF FILES>14 OR TIC<0.5 THEN PRINTTAB(30,15)" ':B0T0 180
200 lNPUTTAB(0,19)'Please enter the UPFER and LONER temperature limits 'UPPERT,LONERT
210 IF UPFERT<L0NERT THEN 200
220 INPUTTAB(0,21)*Please enter the title and the date "TITLE*,DATE,MONTH,YEAR

240 CTRL4(1)=ІC11G'':CTRLt(2)='C12G':CTRL4(3)='C136":CTRL$(4)='C146':CTRL4(5)='C15G':CTRL$(6)='C16G':CTRL4(7)=,C17G,':CTRLt(B)='C18G'
    CTRL*(9)="C196*
241 CTRL<(10)=*C1AG*:CTRL*(11)=,C1BB':CTRL*(12)=*C1CG*:CTRL*(13)=*C1DB':CTRL*(14)='C1EB':CTRL*(15)="C1FB*
250 GOSUB 1400
330 DURATION=INT<DURAT10NI3.6E5):TIC = INT (TIC I 6E3)

340 REM TEST FOR REMOTE CONTROL CONNECTED
350 TEST = 0
360 FOR I = 1 TO 4
370 IF ADVAL(l) > 30000 THEN TEST = TEST ♦ 1
380 NEXT I
390 IF TEST = 0 THEN 450
400 IF TEST > 0 THEN PRINTTAB(15,17)'Remote Control NOT Connected -- Please CONNECT ';
410 7* = 1NKEY$(50)
420 PRINTTAB(15,17)' ';
430 24 = INKEY*(20)
440 GOTO 340

450 REM START TEST FROM REMOTE
460 R=TIME MOD 100
470 IP R>0 AND R<5 THEN PRINTTAB(0,19)"Press BUTTON 1 to start test'
480 IF R>45 AND R<50 THEN PRINTTAB!0.19)'
490 IF ADVAL(1) > 30000 THEN 520
500 GOTO 450
520 FOR 1=1 TO TCS:MIN(11=10000:TATAL(I)=0:ALLSAM=0:MAX(I)=-10000:NEXT I:TIK=0:TIHE=-500:A=0:B=A:F*='0FF":F=1:P=0
530 CLS
535 PR1NTTAB(50,3)"TIME INTO TEST*:PRINTTAB(50,4)'Hrs Mins Secs'
540 TALLY=0 :SAMPLE=0
550 GOSUB 990
560 REM ALARM/FAULT SEQUENCE
570 IF Ft='ON" THEN PRINTTAB(20,5) '- FAULT- '’"LABEL*"NOTSTORED BECAUSE'iREPDRT:PR1NTTAB(17,8) 'PRESS 'C KEY TO RETRY STORE'
620 REM CONTROL FROM REMOTE
630 PRINTTAB(0,19)'Press BUTTON 1 to END test'"Press BUTTON 2 to PRINT VALUES*"press BUTTON 3 to RESTART test'"press BUTTON 4 to
    EXIT to BASIC'
650 DPROMP*=INKEY*(10):IF DPR0MP4='C' THEN F*='0FF':P=0;PRINTTAB(17,8)*
655 IF TIME MOD 100=0 THEN PROCTIME(TIME)
656 IF A 0 B THEN $2=1r00000A:PRINTTAB(17,10)"TEMPERATURE LIMITSEXCEEDED!'sFOR DELAY =1 TO70:NEXT DELAY:PR1NTTAB(17,10)*

660 IF ADVAL(l) > 30000 THEN 950
670 IF ADVAL(2) > 30000 THEN P=20
680 IF ADVAL(3) > 30000 THEN 520
690 IF ADVAL(4) ) 30000 THEN MODE 135:PRINT'BYE":END
691 IF TIME>TIK THEN 730 ELSE IF F*='0N' GOTO 720
700 IF TALLYM500 THEN PROCSTORE(LABEL4(F)):G0T0 540
710 IF TIME > DURATION THEN 950
720 GOTO 650

730 REM START SAMPLE RUN HERE
740 PRINTTAB(0,19)"

750 MINUTE5=TIME DIV 6000:NEWTALLY=TALLY 1:TEMP(NENTALLY)=NINUTES :B=A:MAXDIFF=0
760 FOR 1=1 TO TCS:GOSUB 1220:NEXT I
770 FOP 1=1 TO TCS
```

```
D  780 IF VOLTS!I}<0.39 THEN TEMP*VOLTS(I)/0.039
^  790 IF VOLTS!I)>=0.39 ANDVOLTS(1)<1.19  THENTEMP=(VOLTS(I)-0.39)/0.04 +10
   800 IF VOLTS(I)>=1.19 ANDVOLTS!I) (2.03  THENTEMP=(VOLTS!I)-1.191/0.042 *30
   810 IF VOLTS!I!'=2.03 ANDVOLTS!I) (2.91  THENTEMP=(VOLTS(I)-2.03)/0.044 +50
   820 IF VOLTS!1)>=2.91 ANPVOLTS!I)<3.81  THENTEMP=(VOLTS(I(-2.911/0.045 +70
   830 IF VOLTS!I)>=3.01 THEN TE«P=(VOLTS(D-3.81)/0.047 +90
   840 IF TEMF > MA)((I) THENMAX(I)=TEMP
   850 IF TEMP < MIN(I) THENKIN(I)=TEMP
   860 IF TEMf >UPPERT OR TEMP (LOWERT THEN A=A+1
   870 TATAL(I) = TATAL(I) + TEMP
   880 NEWTALLY=NEWTALLY+1:TEMP(NEWTALLY)=TEMP
   081 DIFF=ABS(TEMF'-PRETEMP(1))
   882 IF DIFF>MAXDIFF THEN MAXDIFF=DIFF
   890 NEXT I
   900 IF p>0 THEN VDU2
   910 PRINTTAF(0,25)'                                  ":*7=&000006:PRINTTAB(0,25)iMINUTES;
n      «7=4020105:FOR J=(TALLY+2) TO NEWTALLY:PRINT,TEMP(J);
   920 NEXT J:PRINT:VDU 3
   925 IF MAXDIFF<0.2 THEN NEWTALLY=NEWTALLY-TCS-1  ELSE FOR 1=TCS TO 1 STEP -1:PRETEMP(I)=TEMP(NEWTALLY-TCS+I):NEXT I
   930 IF F$='OFF" THEN TALLY=NEWTALLY:SAMPLE=SAMPLE+1
   940 TIK=m+TIC:GOTO 620
   950 PROCSTORE(LABELS(F))
   960 GOSUB 1310
   980 END

r   990 REfl SUB IEEE STARTUP
   1000 tIEEE
   1010 c»d?=OPENlN("COMMAND")
   1020 data?=OPENIN("DATA")
   1030 PRINTfc»d?,"BBC DEVICE NO",0
   1040 FRlNTEcmd?,"CLEAR"
   1050 FRINTEcir.dX,"REMOTE ENABLE"
   1060 PPINTEcidX,"END OF STRING".CHR$(13)+CHR*(10)
   1070 dv»7=0PENIN(*16')
   1080 PRINTfcmd?.,"LOCAL LOCKOUT"
   1090 PRINTEcudX,"DEVICE CLEAR"
   1100 FRlNTfc»d7,"UNLISTEN"
   1110 PRINTfcmdl,"LISTEN",dv#7.,"EXECUTE"
   1120 PRINTEdata7.,*F1H0R0K1HON100D2TOG'
   1130 PRINTEcid?, "UNLISTEN'1
   1140 PRINTfcEd7.,"TALK',dv*X
   1150 PRINTEcsdX."TIMEOUT ON*
   1160 PRJNTfc*dX,"STATUS*
   1170 INFUTEctdX,state!
   1180 IF state?, <> 8445444 THEN PRINT TAB(0,2) state?
   1190 INPUTEdataX,volts$
   1200 PRlNTEcifdi."UNTALK"
   1210 RETURN

   1220 REM READ CHANNELS ROUTINE
   1230 PRlNTEcaid?."LISTEN",dv#?,"EXECUTE"
   1240 PRINTfdata?,CTRL4(I)
   1250 PRlNTfc»d?."UNLI5TEN"
   1260 PRINTEcid?, "TALK",dv*7.
   1270 INPUTfdata7,volts*
   1280 PRINTfc*d7,"UNTALK"
   1290 VOLTS!1) = 1000»(VAL(voIts$))
   1300 RETURN
```

```
     10 REM ft PROGRAM 10 PROCESS THE DATft FROM THE TEMPERATURE MONITORING ROUTINE ON A BBC WITH GRAPHICS AND PRINTMASTER ROMS FITTED
     60 DIM TEMP(1500):DIM K(4):DIH LABELS(15)
S    65 DIM TME{200):DIM ITEHP(200):DIH ADJTEMP(200):D1M 6ENTENPI200)
     70 K(1)=0.0018 :K(2)=0.0012:K(3)=0.0013:K(4)=0.0011

     110 1NPUTTABI10,10) 'Please enter LONER and UPPER  tiae liaits (hours)   *HINT1NE,MAXTINE
*.   120 IF MINTIME>MAXTIME THEN 110 ELSE NINT1NE*M1NTIHEI60:MAXTINE=HAXTIHEI60
     130 CLS:F1LES=-1:REPEAT:F1LES=F1LES+1:1NPUTTAB|0,5*F1LES)'FILE NAMES 'LABELS(F1LES+1):UNTIL LABELS(FILES+1)=*F'
     140 FOR I- 1 TO FILES;VDU 2:CLS:VDU 3
     ISO PROCFEEDILABELS(I))
     190 TCS=(TALLY-SAMPLE)/SAMPLE:MINTIMT=0.5
     205 PROCHEADIN6|LABELS(I),0)
     210 PROCHEfiDlNGCTIME',0)
     220 FOR S=1 TO SAMPLE;PROCSORT(1);THE(S)=VAR1:MEXT S
     230 FOR T=1 TO TCS:CLS
     240 PROCHEADING('THERMOCOUPLE-',T)
     250 FOR S=1 TO SAMPLE:PROCSORT((T+l)):ITEMP(S)=VARI;NEXT S:VDU 3

     250 FOR S=1 TO SAMPLE;PROCSORT((T+1)):ITEMP(S)=VAR1sNEXT S:VDU 3
     260 PROCSTAT(1500)
U    270 PROCADJ:PROCSCALE
     290 FOR J=1 TO SAMPLE;PROCPLOT(69,TME(J),ITEMP(J)):NEXT J
     290 FOR 0=1 TO SAMPLE:PROCPLOT(69,TME(J),ADJTEHP(J)):NEXT J
V    295 FOR J=1 TO SAMPLE:PRDCPLOT(5,THE(J),GENTEHP(J))iNEXT J
     300 IGDUMP 3 1 3 1 20
     310 VDU 3
     320 NEXT T
     325 NEXT 1:END
w    330 DEF PROCFEEDILABELS)
     410 FILENO=OPENIN(LA8EL$)
     420 INPUIE FILENO,TALLY.SAMPLE
     430 VDU2;PRINT,TALLY,SAMPLE:VDU3
     440 FOR J=1 TO TALLY
     450 INPUIE FILENO,TEMP(J)
     460 NEXT J
     470 CLOSED FILENO
     490 VDU 3;ENDPROC

X    570 DEF PROCSORT(F1LESTART)
     580 F1LEPOS=FILESTART+((S-DKTCS+l))
     590 VARI=TENP(F1LEPQS)
     600 VDU2:§2=i02010B:PRINT,VAR1;;VDU3
     610 ENDPROC

y    620 DEF PROCADJ
     630 VDU2.-PRINT:PRINT :PRINTiVDU3
     640 CH6SUH=0;F0R S=1 TO SAMPLE
     650 GRAD=EXP(-K(T)I(TME(S)-TME(S-1)))
     660 DIFF=ABS(1-GRAD)
     670 MID=(ITEMP(S)tITEMP(S-1))/2
     680 CHG=(MID-20)SDIFF
     690 CHGSUM=CHG+CHGSUM
     700 ADJTEMP(5)=ITEMP(S)+CHGSUM-MIN
     705 6ENTEMP(S)=600*(ADJTEMP(S)-ADJTEMP(S-1))/(TME(S)-TME(S-1)>
     710 VDU 2:eX=i020208:PRINT,ADJTEHP(S);:VDU 3
     720 NEXT S
     730 ENDPROC
```

```
740 DEF PROCSTATfCUTOFF)
Z    750 DUTSUM=0:INSUM=0:INSAHPLE=0:MAX=-1000:HIW=1000:SOS=0
760 FOR      TO SAMPLE
770 IF ITEMP(J)7CUTOFF THEN OUTSUM=DUTSW+ITEKP(J):GOTO 820
780 IF TMEUKMINTIHE OR TME(J)>MATT1ME THEN 820
790 IF 1TEHP(J)>MAX THEN MAT-1TEMP IJ):TTPEAF=TMEIJ)
800 IF ITEHPfJKMlN THEN HIN=ITEMP(J)
BIO 1NSAMPLE=INSAMPLE+1:1NSUM=INSUM+1TEMP(J)
820 NETT J:AVE=INSUM/INSAMPLE
830 FOR J=1 TO SAMPLE
040 IF ITEMPLJ)CUTOFF THEN 860
850 RES1DUAL*ITEMP(J)-AVE:SDS=SOS+(RES1DUAL"2)
860 NETT J:SD=(INT(SBR(SOS/INSAHPLE)41000))/1000
870  CLS:VDU 2:PR1NT:PRINT:PRINT,READIN6S^;INSAMPLE,',MA7INUH=,;HAT,',AVERA6E*,;AVE)"MINIHUH=„;HIN:PRINT,T1HE TO  PEAK=*;TTPEAK:VDU 3
880 ENDPROC
```

NOTES

a - experimental conditions
b - experimental results
c - calculation of impeller torque and speed
d - analys is
e - calculation of interval on g and h
f - residua] statistics
g - regression procedure
h - procedure for storing data from the analysis
i - experimental conditions
j - setting up the analogue scanner
k - check on the remote control
1 - start of sampling
m - alarm for errors in data or its storage
n “ remote control options
o - data storage and end of test
p - thermocouple calibration equations
q - optional hard copy of results
r - subroutines for interfacing with scanner and voltmeter
s - flask cooling coefficients
t - data retrieval and presentation
u - analys is
v - graph plotting
w - procedure for data retrieval
x - procedure for data sorting
y - procedure for first-order correction
z - procedure for statistical analysis