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Applicability of No-Fines Concrete as a Road Pavement

A dissertation submitted by

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ABSTRACT

Considerable research has been conducted on environmentally sustainable development. This has lead to the use of no-fines concrete in place of conventional concrete and asphalt surfaces. This material dramatically reduces environmental degradation and the negative effects associated with urban sprawl. No-fines concrete has been used as an effective method for treating and reducing negative environmental impacts.

Problems plagued the initial development, with the pores becoming clogged and stopping the water from passing through, causing ponding and reducing the skid resistance of the road surface. The second problem was concerned with the unsightly ravelling that occurs on the surface shortly after construction and the unsafe perception that this creates.

This thesis analyses the effectiveness of no-fines concrete in pavement applications. This was achieved by analysing the properties and characteristics of no-fines concrete. The performance of no-fines concrete was compared with a concrete sample that is comparable to the material used for the construction of conventional concrete road pavements.

The analysis was undertaken by conducting a number of standard concrete tests and comparing the characteristics of the no-fines and conventional concrete samples. The tests included both fresh and hardened concrete tests to obtain a complete picture of its properties during the construction and working phase.

The tests conducted to determine the fresh concrete properties were the slump, VEBE and compacting factor tests. These were complimented by hardened concrete tests including the following: compressive strength, indirect tensile strength, modulus of rupture and elasticity and skid resistance.

It was found that no-fines concrete pavements possess some positive features like increased skid resistance and high permeability but lacks the high strength required for highly trafficked areas. No-fines concrete has proven to have properties suitable for use in low volume traffic areas. The properties found may change depending on the aggregate particle chosen, however this aspect requires further investigation. Nonetheless, if no-fines concrete pavements can be implemented, it will have numerous positive affects on the environment.

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CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

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Date

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CHAPTER 1

1. INTRODUCTION

1.1 INTRODUCTION TO NO-FINES CONCRETE

No-Fines concrete is a mixture of cement, water and a single sized coarse aggregate combined to produce a porous structural material. It has a high volume of voids, which is the factor responsible for the lower strength and its lightweight nature. No-fines concrete has many different names including zero-fines concrete, pervious concrete and porous concrete.

No-Fines concrete consists of an agglomeration of coarse single sized aggregate covered with a thin layer of cement paste approximately 1.3 mm thick (Neville 1997). This form of concrete has the ability to allow water to permeate the material which reduces the environmental problems associated with asphalt and conventional concrete pavements. The most common application of no-fines concrete is in low traffic volume areas, for example: parking lots, residential roads, driveways and footpaths.

The force exerted on the foundations by no-fines concrete is approximately one third of that produced by the same structure constructed from conventional concrete. This difference may be of critical importance when considering structures on ground with a low bearing capacity (Fulton 1977).

No-fines concrete has been predominantly used in non-pavements applications, with only a limited use in pavements applications. The purpose of this project is to assess the suitability for no-fines concrete to be used for the construction of road pavements. This assessment will include investigating current literature on the topic and conducting some mix designs and standard concrete testing on conventional concrete and no-fines concrete to determine and compare their properties. From the tested data a conclusion as to the usefulness of no-fines concrete pavements will be drawn and it may be determined that further testing is required.

1.2 HISTORICAL BACKGROUND

The use of no-fines concrete as a pavement material has been extremely limited and has only recently been developed for this particular application. However, no-fines concrete has been used extensively as a structural building material in Europe, Australia and the Middle East for over 70 years (Macintosh et al. 1965). The earliest known application of no-fines concrete occurred in England in 1852 with the construction of two residential houses and a sea groyne 61 m long and 2.15 m wide (Francis 1965). The use of no-fines concrete became considerably more widespread during the material shortages after World War II, for cast-in-place load bearing walls of single and multistorey buildings.

The early use of no-fines concrete was primarily for two-storey structures, however this expanded to five-storey buildings in the 1950's and continues to expand. In recent years no-fines concrete has been used as a load bearing material in high rise buildings up to ten-storeys. The most remarkable use of this form of concrete was undertaken in Stuttgart, Germany where a high rise building was constructed using conventional concrete for the six bottom storeys and no-fines for the remaining thirteen upper storeys (Malhotra 1976).

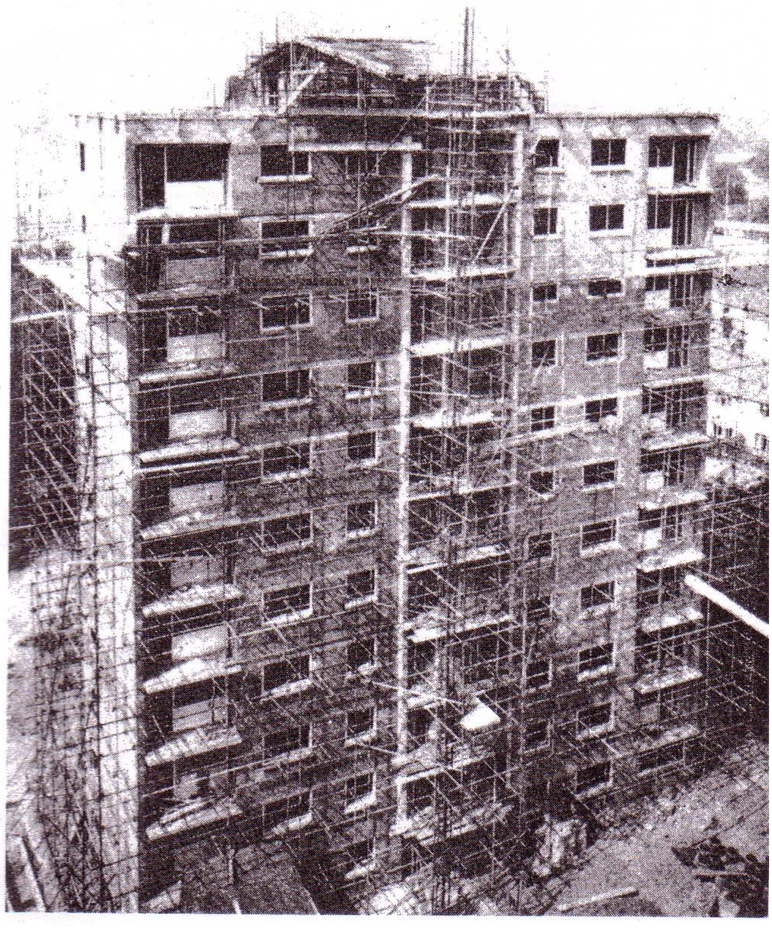


Figure 1.1 – The partly completed 19 storey high-rise building in Stuttgart, Germany (Source: Malhotra 1976).

The only reported use of no-fines concrete in Canada was the construction of a number of multistorey residential houses in the Toronto area around 1960.

No-fines concrete has been used in south-eastern America for the past 20 years in pavement applications. It was originally developed in Florida as a method of recharging the Everglade aquifers while controlling the water and reducing some of the detrimental effects caused by urban sprawl.

1.3 AIMS AND OBJECTIVES

No-fines concrete has been predominantly used in non-pavements applications with only a limited use in pavements applications. The purpose of this project is to assess the suitability of no-fines concrete to be used for the construction of road pavements. This assessment will include investigating current literature on the topic and also conducting some mix designs and standard concrete testing on conventional concrete and no-fines concrete to determine and compare their properties.

In order to achieve these aims, the following objectives had to be met:

1. Research background information relating to the use of no-fines concrete in pavement and non-pavement applications.
2. Conduct some initial mix design test to evaluate some possible alternatives. This will include using different water/aggregate/cement ratios.
3. Investigate some existing no-fines concrete pavement designs, construction specifications and maintenance procedures.
4. Determine suitable tests to assess the strength, durability, skid resistance and cost of the above found mix design and normal concrete road surfaces.

5. Conduct the tests and analyse the results to form a conclusion as to the effectiveness of no-fines concrete as a road pavement.

1.4 CURRENT STATUS OF NO-FINES CONCRETE

Although there is very little documented use of no-fines concrete in Australia, it was first utilised as early as 1946. No-fines concrete was used in the construction of a residential house in Ryde, New South Wales. The Department of Works and Housing undertook this project as a method of investigating new cost effective construction materials (Ghafoori et al 1995).

Developers and government organisations have been using no-fines concrete more readily as a method of pollution control in America. Pervious surfaces are in greater demand as planners, public works officials and developers search for methods to adequately and efficiently manage storm water in an economical and environmentally friendly method (Frentress et al 2003). This form of concrete allows the water to penetrate the soil, reducing the runoff and stopping the movement of pollutants.

The predominant usage of no-fines concrete in America is low volume residential roads and ground level parking lots. The concrete can be placed up close to trees and vegetation without comprising their health as the porous nature of the concrete allows water and air to penetrate the surface.

1.5 NON-PAVEMENT APPLICATIONS OF NO-FINES CONCRETE

No-fines concrete has had numerous useful non-pavement applications including buildings, tennis courts, drains and draintiles and floors in greenhouses.

No-fines concrete has been utilised by European countries in many different building situations. It has been used for cast-in-place load-bearing walls in houses, multi-storey and high-rise buildings, as prefabricated panels and steam-cured blocks.

A prominent use of no-fines concrete in Europe is in tennis court applications. The only variation from a normal mix is the slightly smaller aggregate used to provide a smoother playing surface. The permeability of the no-fines concrete reduces the time taken for water to drain and the surface to be playable (Ghafoori et al 1995).

Water and Power Resources Services in America successfully tested the use of drains and draintiles constructed from no-fines concrete beneath hydraulic structures. This application made it possible to reduce the uplift pressure on the structures and to drain ground water from beneath infrastructure like sewer pipes (Ghafoori et al 1995).

Researchers at Rutgers University used no-fines concrete as a floor surface in a plastic greenhouse as part of a solar heating system. This application provided a suitable hard surface capable of withstanding the movement of heavy equipment, while preventing water from ponding on the surface and discouraging weed growth (Ghafoori et al 1995).

1.6 PAVEMENT APPLICATIONS OF NO-FINES CONCRETE

The majority of pavement applications for no-fines concrete are low volume road surfacing, parking lots and pavement edge drains.

No-fines concrete pavements were developed after some success with open graded asphalt and their applications in parking lots and service roads. Open graded asphalt is a mix of even graded aggregate, small amounts of fines and a bituminous material. This road surfacing has a relatively high void ratio, normally ranging between 18 and 25 percent (Ayers 2004).

Many road pavement trials were conducted throughout the world, initially with little or no success. One of these tests was conducted in England, where a group of engineers experimented with the monolithic casting of a no-fines wearing course over a conventional rigid pavement. This road was considered a failure after the ponding of water and the occurrence of ravelling 10 years after construction. Many factors had an influence on the results here, not least the clogging of the voids with dirt caused by the movement of farm machinery along the road (Ghafoori et al 1995).

Finally, Parking lots are another application for no-fines concrete, made using a no-fines concrete wearing course and several underlying porous layers. The underlying porous layers consist of three layers varying from a sandy material to a 37 mm aggregate. The primary task of all the porous layers is to act as a reservoir for retaining water until it permeates into the soil. This is an effective method of controlling water runoff in situations where flash flooding frequently occurs. The reduced runoff eliminates the problems of downstream flooding caused by traditional impervious concrete surfaces (Ghafoori et al 1995).

The use of no-fines concrete as an edge drain or porous hard shoulders has been undertaken extensively in France. Excessive uplift pressures produced in concrete pavements lead to the development of methods to rapidly drain water from the pavement base (Ghafoori et al 1995).

1.7 MERITS AND DEMERITS OF USING NO-FINES CONCRETE

1.7.1 ECONOMICAL BENEFITS

The initial costs of no-fines concrete pavements are higher than those for conventional concrete pavements. This is due to two factors, the materials used are slightly more expensive and the increased thickness of the no-fines pavement compared to conventional pavements. However, in the long term, no-fines concrete pavements are more cost effective.

There are lower installation costs associated with the use of no-fines concrete because the need for underground piping and storm drains are eliminated. No major earthworks are required since the pavement does not need to slope to gutters and drains for adequate water control methods. The system does not require the upgrading of existing storm sewer systems, as there is little or no runoff.

No-fines concrete pavements effectively double as a stormwater management system and eliminate the need to purchase additional land for retention basins, as the pavement works as one. This helps developers maximise their profits and utilise the land more efficiently.

The concrete has another cost saving benefit in terms of the amount of lighting required for the no-fines pavement. This is due to the light colour of the pavement, which reflects light, thereby reducing the installation and operating costs.

No-fines concrete is a sustainable material that has a life expectancy similar to that of conventional concrete. Correctly constructed no-fines pavements should have a life expectancy of 20 to 40 years and thus a lower life-cycle cost, according to the *Southern California Mixed Concrete Association*.

1.7.2 ENVIRONMENTAL BENEFITS

The benefits to the environment are many when using no-fines concrete. No-fines concrete pavements are light in colour, which helps to reduce the ground level ozone by lowering the temperatures in and around major cities. This is achievable due to the open cell structure of the concrete, which does not absorb and store heat and later radiate it back into the environment the way asphalt surfaces do. The open structure also draws on the cooler earth temperatures below the pavement to keep the pavement temperatures down.

Stormwater is one of the leading causes of pollutants entering waterways. No-fines concrete pavements reduce runoff by storing a large volume of water within the pavement until it seeps into the ground. Most of the pollutants are carried by the first 12 to 25 mm of rain. Since this initial water is contained within the pavement it reduces the quantity of polluted water from reaching the waterways. The no-fines pavements allow the water to recharge the underground water supply and channel water to tree roots.

1.7.3 WATER HAZARDS

Standing water is a common problem associated with concrete pavements. This is compounded by torrential rain, which makes the pavement surface slippery. Aquaplaning becomes a real danger for cars and can cause damage to the road users and public. No-fines concrete does not suffer from these inadequacies since a large volume of water will be stored instantly within the pavement (http://www.perviouspavement.com).

1.7.4 LIMITATIONS OF USE

Although no-fines concrete is a versatile material able to be used in many situations there are times when its use is not a viable choice. No-fines concrete pavements have a rough-textured, honeycomb like surface, which lacks the high bonding strength on the wearing course. Moderate amounts of ravelling are normal with little or no problems but this becomes a major issue on highly trafficked roadways. This problem is being investigated with the top 12 mm being ground away so the exposed aggregate have stronger bonds with the surrounding material.

Pavement design is of critical importance, as the substructure of the pavement is required to hold water until it permeates into the soil without failing. This requires the use of stormwater management principles to determine what happens to the water once it penetrates the surface and pavement design principles to design a pavement structure that is capable of withstanding the internal pressures caused by the water in the pavement (http://www.concretenetwork.com/pervious).

1.7.5 CLOGGING OF PAVEMENT VOIDS

Clogging of the no-fines concrete pavement can occur in areas where water will run from grassed or dirt areas and below highly vegetated areas. Soil is capable of clogging the pores and reducing the effectiveness of the pavement. These problems can be reduced or eliminated by correct design and routine maintenance of the pavement. The maintenance includes regular sweeping or vacuuming and the addition of supplements to help break down organic materials. Pressure washing may be required if the dirt has been washed from the surface into the underlying material. This procedure has been shown to restore the concrete to near new condition (www.pervious.info).

1.8 GENERAL DIFFICULTY PERTAINING TO THE USE OF NO-FINES CONCRETE

No-fines concrete has been recently introduced into the pavement applications. Like any new product there are difficulties or uncertainties faced by the supplier as to the correct situations it can be applied in and the correct laying and compacting procedures. The benefits of no-fines concrete pavements are not known by the wider community and its life expectancy is not fully understood.

1.8.1 LACK OF EXPERIENCE

The lack of experience existing with the use of no-fines concrete pavement stems from it being a relatively new product. The difference between the properties of no-fines concrete and conventional concrete requires it to be placed and compacted in a different manner. The low workability and self-compacting nature of the no-fines concrete results in only a minimal amount of rodding and compaction and no vibrating.

The different placement and compaction methods required are not widely understood. When these important procedures are not correctly undertaken it can have a detrimental affect on the strength, appearance and effectiveness of the pavement. This can affect the water permeating capacity of the pavement, reducing the environmental benefits associated with its use.

1.8.2 LACK OF PUBLIC AWARENESS

Before a product is accepted and implemented by the public, there must be an awareness of its benefits. The environmental and economic benefits of the no-fines concrete are not yet widely recognised. In terms of the environment, this product can potentially eliminate the negative impacts to the environment associated with the use of conventional concrete. No-fines concrete has the ability to make driving conditions safer by eliminating standing water and the problems associated with the lack of grip on roads. In economic terms, the lack of need of extensive earthworks and the upgrade of existing sewer systems means saving time and money but this benefit is not widely recognised.

This lack of public awareness is limiting the use of no-fines concrete in pavement applications in Australia. This is because it is a recently developed material that has not been widely used in Australia. Developers and homeowners would more readily use this product if its benefits were publicised. In a society with an emphasis on supporting the environment, greener products should be encouraged and possibly enforced by the government in an attempt to reduce the negative impacts associated with urban sprawl.

1.9 DISSERTATION OVERVIEW

The dissertation has the following structure:

Chapter 1 provides an introduction and background relating to no-fines concrete and the objectives that will be covered in the project.

Chapter 2 provides a review of the relevant literature and a discussion of the general engineering properties of no-fines concrete.

Chapter 3 covers existing no-fines concrete pavement designs, specifications and maintenance requirements.

Chapter 4 explains the tests and testing methodology to be used and the processes and results involved with the preliminary mix design.

Chapter 5 explores the procedures, results and analysis from the sieve analysis and flakiness index tests.

Chapter 6 covers the workability tests conducted on the no-fines and conventional concrete samples before the test specimens were made.

Chapter 7 covers all the hardened concrete testing that occurred on the no-fines and conventional concrete specimens.

Chapter 8 discusses the achievement of objectives, conclusions made from the testing and recommendations for further studies.

CHAPTER 2

2. LITERATURE REVIEW

2.1 INTRODUCTION

Through researching no-fines concrete for this project, it was found that there has only been a limited amount of work completed on this topic. There is some information relating to no-fines concrete in general but very little relating to its use in pavement applications. Nonetheless, the different applications do not significantly affect the properties of no-fines concrete. The following sections relate to the properties of no-fines concrete that have already been investigated.

2.2 LITERATURE REVIEW OF NO-FINES CONCRETE

The initial use of no-fines concrete was in the United Kingdom in 1852 with the construction of two residential houses and a sea groyne. It was a further 70 years before any further recorded use of no-fines concrete occurred when it was reintroduced into the United Kingdom in 1923 from Holland. The use of no-fines concrete became more important after the conclusion of World War II with the associated material shortages (Malhotra 1976).

Malhotra (1976) found that the density of no-fines concrete is generally about 70 percent of conventional concrete when made with similar constituents. The density of no-fines concrete using conventional aggregates varies from 1602 to 1922 kg/m^3. A clinker aggregate was trialled and the no-fines concrete produced a density of 961 kg/m^3.

Adequate vibration is imperative for strength of conventional concrete. The use of no-fines concrete is different and is a self-packing product. Malhotra (1976) suggests that the use of mechanical vibrators and ramming is not recommended with no-fines concrete. A light rodding should be adequate and used to ensure that the concrete reaches all sections of the formwork. This is not a problem with conventional concrete since it has greater flow ability than no-fines concrete. The light rodding ensures that the concrete has penetrated all the areas impeded by reinforcing steel.

Malhotra (1976) stresses that in situations where normal conditions are not achieved during placement and curing, the formwork should not be removed after 24 hours as with conventional concrete. No-fines concrete has very low cohesiveness and formwork should remain until the cement paste has hardened sufficiently to hold the aggregate particles together. However, this is more of a consideration in low temperature conditions and when used in non-pavement applications where the concrete is not sufficiently supported by the ground or other means.

Ghafoori et al (1995) undertook a considerable amount of laboratory investigation to determine the effectiveness of no-fines concrete as a paving material. The curing types were investigated to determine if there was any difference between wet and sealed curing. There appeared to be only a negligible difference in strength between the different curing methods. It was clear from the test results that the strength development of no-fines concrete was not dependent upon the curing conditions.

The indirect tensile test conducted by Ghafoori et al (1995) found that the sample tests varied between 1.22 and 2.83 MPa. The greater tensile strength was achieved with a lower aggregate-cement ratio. Ghafoori et al (1995) explained the more favourable properties obtained by the lower aggregate-cement ratio by an improved mechanical interlocking behaviour between the aggregate particles.

Abadjieva et al determined that the compressive strength of no-fines concrete increases with age at a similar rate to conventional concrete. The no-fines concrete specimens tested had aggregate-cement ratios varying from 6:1 to 10:1. The 28 day compressive strength obtained by these mixes ranged from 1.1 and 8.2 MPa, with the aggregate-cement ratio of 6:1 being the strongest. He concluded that the most plausible explanation for the reduced strength was caused by the increased porosity of the concrete samples. This strength is sufficient for structural load bearing walls and associated applications. Ghafoori et al (1995) produced no-fines concrete with a compressive strength in excess of 20 MPa when using an aggregate-cement ratio of 4:1.

Abadjieva et al investigated the influence of the aggregate-cement ratio on the tensile and flexural strength of no-fines concrete. This study only assessed aggregate-cement ratios ranging from 6:1 to 10:1. The highest strengths were obtained with an aggregate-cement ratio of 7:1 and the strength decreased with an increasing aggregate-cement ratio. He found that the tensile and flexural strengths of no-fines concrete were considerably lower than those obtained from conventional concrete, but he could not explain why the sample with the highest strength had a ratio of 7:1.

A study conducted by Krishna Raju et al (1975) focused on the optimum water content for no-fines concrete. It was determined that for the particular aggregate-cement ratio there is a narrow range for optimum water-cement ratio. This water-cement ratio was imperative to gain the maximum possible compressive strength. A higher than ideal water-cement ratio would cause the cement paste to drain from the aggregate particles. Alternatively, a water-cement ratio too low would stop the cement paste from adhering sufficiently to the aggregate. When the optimum water-cement ratio was not obtained, sufficient compaction could not be achieved, further compounding the loss of compressive strength.

The large air voids in no-fines concrete does not allow water to penetrate using capillary action. Malhtora (1976) noted that the depth of penetration in no-fines concrete by this method under conditions of high humidity and no air movement is generally no greater than two or three times the largest aggregate diameter. The penetration of moisture was higher in no-fines concrete made from conventional aggregates than clinker aggregate.

Meininger (1988) investigated the effect on the properties of no-fines concrete with the addition of sand. He found that when a small amount of sand was added to the mixture, the compressive strength of the concrete increased from 10.3 MPa to 17.2 MPa. The sand added was between 10 and 20 percent of the aggregate by weight. The increased fines filled some of the voids, reducing the air content from 26 to 17 percent. A decrease in the voids causes the concrete to bond more effectively, thus increasing the compressive strength. With more than 30 percent sand the concrete started to display the properties of conventional concrete and did not have sufficient voids necessary for water flow.

No-fines concrete possessed good engineering properties for non-pavement applications such as buildings. Development of this material in pavement applications did not take off until the late 1970's, where it was first used as a wearing course for a parking lot. The first no-fines concrete pavement design was patented as a 'porous pavement' and a following no-fines pavement design was called a 'pervious pavement.' Ghafoori et al (1995) found 53 no-fines concrete parking lots within the east and western coastlines of Florida, USA.

The demand for no-fines concrete for pavement applications continued to increase and an institute called 'Portland Cement Pervious Institute' was formed in 1991 to continue the research. Ghafoori et al (1995) documents the development of permeable base materials capable of storing a greater volume of water until it dissipates into the surrounding soil.

Ravelling can occur in no-fines concrete pavements when there is a deficiency in the curing process or improper compaction and seating of the top aggregate particles. Meininger (1988) found that poor curing techniques allowed the cement paste to dry too rapidly and did not allow the hydration process to finish. It could be seen by the roughness of the pavement surface that no compaction was undertaken. All these factors affected one particular parking lot studied and started ravelling one year after construction. Another pavement was constructed and it was made sure that sufficient compaction was provided to ensure the top aggregate was correctly seated and covered with plastic to establish proper curing conditions.

2.3 GENERAL ENGINEERING PROPERTIES OF NO-FINES CONCRETE

The physical properties of the individual components and the no-fines concrete as a whole are extremely important and should be explored further. The rheology of the concrete and the individual materials determine properties like the strength, void ratio, durability and the chemical properties. All these properties need to be known and assessed to make the most appropriate choice for a particular application.

The strength and permeability of the no-fines concrete are the important properties that will be shown in later chapters. However, the following properties are critical to the performance of the no-fines concrete. By ensuring the desirable properties of no-fines concrete components a stronger material with good permeability and improved durability will be achieved.

2.3.1 STRUCTURE

The structure of no-fines concrete varies significantly from conventional concrete in the sense that a small fillet of cement paste holds the materials together. The aggregate is covered with a thin layer of cement paste. When the compaction is undertaken it forces the aggregate particles together until they are in contact with each other. This squashes the cement paste out from the point of contact causing a fillet of cement paste to appear and bond the particles.

The no-fines concrete has an open structure with a high void ratio that relies on the bonding of the aggregate for strength. The structure is most easily explained as rice bubbles bonded together to produce a porous material.

2.3.2 SHAPE

The ideal shape of the aggregate particles to be used in no-fines concrete is spherical. This shape allows the greatest number of bonding points and will produce concrete with the most strength. Flaky or elongated particles should be avoided for use in no-fines concrete as local crushing can occur more readily with these particles.

2.3.3 MIX PROPORTIONS

The mix proportions for no-fines concrete depends predominantly on the final application. In building applications, the aggregate-cement ratio used is leaner, usually ranging from 6:1 to 10:1. This leaner mix ensures that the void ratio is high and prevents capillary transport of water. However, in pavement applications the concrete strength is more critical and aggregate-cement mixes as low as 4:1 is used. This lower ratio ensures an adequate amount of bonding between the aggregate and cement to withstand the higher loads.

2.3.4 WATER CONTENT

The water content is imperative for the bonding to occur between the aggregate. A water-cement ratio higher than the optimum will not create an adequate bond between the cement paste and aggregate causing the cement paste to run off the aggregate particles. If the water-cement is lower than the optimum, the cement paste will not be sufficiently adhesive to bond the aggregate. The general range for water-cement ratio is between 0.38 and 0.52 (Neville 1997). The absorption rate of the aggregate will also affect the water content and this should be taken into account for design mixes.

2.3.5 AGGREGATE GRADING

The aggregate generally used in no-fines concrete applications usually ranges from 10 mm to 20 mm. Five percent oversized and ten percent undersized materials are acceptable for use but there should be no particles smaller than 5 mm (Neville 1997). If there are too many small particles it will tend to fill the voids, affecting the porosity of the concrete and the associated properties.

2.3.6 DENSITY

The density of no-fines concrete is dependent upon the void content in the concrete. Due to the high air content it is a lightweight concrete with a density of about two thirds of conventional concrete. The density of no-fines concrete normally ranges between 1600 and 1900 kg/m^3. This is dependent upon the shape, size and density of the aggregate, the aggregate-cement-water ratio and the compaction exerted on the concrete.

2.3.7 AIR-VOID CONTENT

The cement paste is only a thin layer and does not contain air bubbles, so the voids are obtained mostly through the interconnected spaces of the aggregate particles. The air content is by definition the sum of the available voids between the aggregate particles and any entrained or entrapped air within the cement paste. The void content is dependent upon the aggregate-cement ratio and thus varies greatly. The air content of no-fines concrete ranges from 13 to 28 percent for aggregate-cement ratios between 4:1 and 6:1.

2.3.8 SHRINKAGE

Drying shrinkage in no-fines concrete is relatively small but does vary depending on the aggregate-cement ratio. The difference in the amount of shrinkage can be attributed to the following factors. A reduction in the aggregate-cement ratio means there is more cement paste available to undergo volumetric contraction and shrinkage. At the same time, the decrease in aggregate-cement ratio causes the aggregate particles to induce a restraint on the drying shrinkage since they are in contact (Fulton 1977).

2.4 SUMMARY

No-fines concrete has properties capable of being used in road pavement applications. It suffers from a number of problems like lower compressive strength and ravelling but still has favourable properties that can be utilised in road pavement applications. The mix proportions and water content are critical when obtaining a sufficient bond between the aggregate particles.

The following chapter looks in detail at the maintenance, design and constructions specifications for no-fines concrete pavements.

CHAPTER 3

3. NO-FINES CONCRETE PAVEMENT DESIGN & MAINTENANCE

3.1 INTRODUCTION

This chapter includes a brief explanation of the difference between flexible and rigid pavements. This is followed by the existing no-fines concrete pavement construction specifications and maintenance procedures used by Stoney Creek Materials, *L.L.C.*

3.2 ROAD PAVEMENTS

Roads can be broadly classified into two different types – flexible and rigid. Flexible pavements consist of a sub-grade, a sub-base, an unbound granular base and a bituminous surfacing. Figure 3.1 shows the cross-section of a typical flexible pavement.

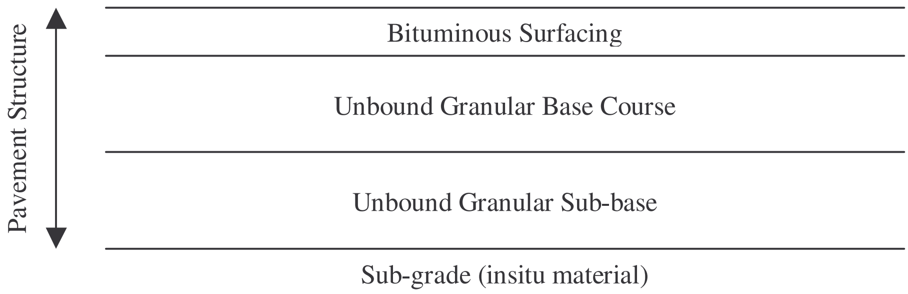


Figure 3.1 – Cross Section of a Flexible Pavement

Traditional rigid pavements consist of a concrete slab on top of an unbound granular sub-base and a sub-grade consisting of insitu materials. A typical cross-section of a rigid pavement is shown below in Figure 3.2.

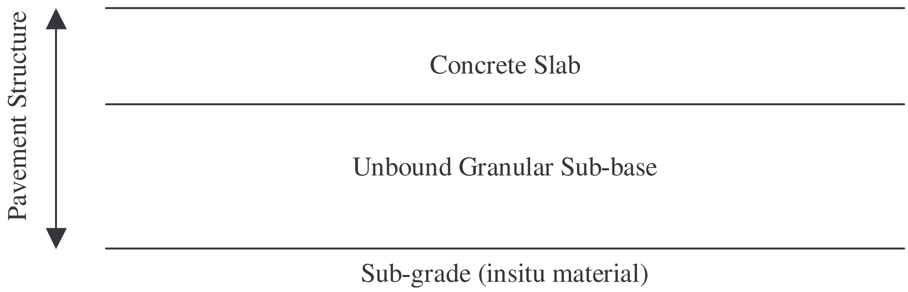


Figure 3.2 – Typical Cross Section of a Rigid Pavement

3.3 NO-FINES CONCRETE PAVEMENTS

No-fines concrete pavements are a form of rigid pavement but differ substantially due to the materials used during construction. The no-fines pavements consist of a concrete slab over a clean aggregate sub-base, a filter fabric and a permeable sub-grade. This insitu material is important, as it is required to be permeable to allow the water in the sub-base to penetrate the soil. The following sections will set out some guidelines relating to the construction and maintenance required for no-fines concrete pavements.

Stoney Creek Materials, *L.L.C.* have set out the following guidelines in relation to their Pervious Pavement System (www.stoneycreekmaterials.com). They are one of many companies with their own set of guidelines and were chosen as they provided the most useful and detailed information.

3.3.1 SUB-GRADE AND SUB-BASE REQUIREMENTS

The sub-grade material has to contain a set of favourable properties relating to the permeability, support and moisture content, while the sub-base requires a homogenous material with set properties.

3.3.1.1 SUB-GRADE PERMEABILITY

The permeability of the sub-grade is important as it dictates the effectiveness of the no-fines pavement. Prior to the placement of the no-fines pavement the sub-grade has to be tested for the rate of permeability with a suitable sub-grade permeability test. The minimum sub-grade percolation rate acceptable for no-fines concrete pavements is 2.5 mm per hour, providing local water quality regulations relating to sedimentation, filtration and detention are met.

3.3.1.2 SUB-GRADE TREATMENT

The organic material in the sub-grade is required to be scarified to a minimum depth of 75 mm. This material requires a proof roll to identify any weak or wet areas that may cause premature pavement failures. Fill material may be incorporated if it is clean and free from deleterious materials as specified by a geotechnical study.

The sub-grade is required to be in a moist condition before the construction of the pavement sub-base. The moisture content should be within 3 percent of the optimum moisture content as determined by a compaction test.

3.3.1.3 FILTER FABRIC

The entire area of the pavement requires the placement of a non-woven geo-textile filter fabric. This has two purposes – firstly to separate the sub-grade from the sub-base material and secondly to stop the solids from rising upwards into the pavement and reducing its water holding capabilities.

3.3.1.4 SUB-BASE MATERIAL

The sub-base is made up of a clean aggregate that is retained on a 37 mm sieve and passes through a 50 mm sieve. It must not contain any fines, as this will affect the performance of the pavement. A washed riverbed rock or crushed stone would be the most appropriate material for this situation.

Compaction on the sub-base will occur in a single pass with the use of a plate or roller compactor to provide a smooth uniform working surface. Any irregularities in the sub-grade will be smoothed during this phase of construction. This aggregate is required to be saturated before the concrete is poured to minimise the loss of moisture from the concrete.

The thickness of this sub-base layer is dependent upon the underlying sub-grade and the intended use for the pavement. This layer ranges in thickness from 100 mm for footpaths to 250 mm for heavily trafficked areas.

3.3.2 MIXING, PLACING AND FINISHING REQUIREMENTS

This phase of the pavement construction is the most important, as the placing and finishing methods for no-fines concrete are considerably different to conventional concrete. It is this treatment that determines the overall life of the pavement.

3.3.2.1 MIX TIME

The time for mixing no-fines concrete is the longer of either 75 revolutions or 10 minutes. When using a high mix speed the addition of admixture to increase the flow ability of the aggregate/cement mix is required to ensure adequate strength. Most standard cement mixers do not require the addition of admixtures when mixing no-fines concrete.

3.3.2.2 CONCRETE DISCHARGE METHOD

The concrete discharging mechanism should be continuous for conformity of the pavement. The concrete must be discharged as close as possible to the final placement. This placement must overlap the previously discharged concrete and the concrete should not be pulled or shovelled to the final resting place as this will disturb the underlying material and affect the pavement strength.

3.3.2.3 JOINTING REQUIREMENTS

Transverse contraction joints are to be installed to a depth between 5 and 10 mm at approximately 6 metre intervals. Longitudinal joints should be constructed down the centre of the pavement if the concrete strip exceeds 4.5 metres in width. The joints will reduce the amount of ravelling and uncontrollable cracking if it is undertaken while the concrete is wet because the aggregate will still achieve maximum strength at these points.

3.3.2.4 PLACING AND FINISHING EQUIPMENT

The placing and finishing equipment required for the placement of the no-fines concrete is a mechanical machine similar to a paving machine used in asphalt applications which is capable of providing 69 kPa (10 psi) of vertical force. The only vibration applied to the pavement will be from the screed that is providing the compaction. The vibration must be stopped whenever the machine or screed is not moving. Vibration should be limited, as excessive vibration negatively impacts on the strength of the concrete.

3.3.2.5 CURING REQUIREMENTS

The curing process begins within 20 minutes of placement and it is at this time that a curing agent must be applied to all surfaces. A second application may be appropriate and can be applied when the first has dried. In extreme weather conditions it is recommended that the surfaces be covered with a polyethylene sheet. This can be done as soon as the curing agent has become tacky and should remain on the surface for a minimum of 72 hours (http://www.stoneycreekmaterials.com).

3.3.3 NO-FINES CONCRETE PAVEMENT MAINTENANCE

No-fines concrete pavements require continual maintenance to maintain its pervious characteristics. The minimum maintenance should include 4 surface vacuums per year and 2 high pressure washings per year.

The vacuuming removes any surface silt or debris that is capable of clogging the pavement. The frequency of vacuuming should be increased in situations where there is overhanging vegetation, excessive surrounding dirt areas and other pollutants that reduce the voids of the pavement.

The high-pressure washing is required to flush contaminants from the no-fines concrete into the underlying sub-base. The excess material in the sub-base has not been shown to reduce the effectiveness of the no-fines pavement.

3.3.3.1 HYDROCARBON CLEAN-UP

Hydrocarbons are broken down by naturally occurring micro-organisms present in most soils. The micro-organisms will aerobically break down the hydrocarbons provided there is a sufficient amount of oxygen and nutrients. Supplements can be provided to ensure sufficient nutrients and the proper functioning of these organisms.

3.3.3.2 ORGANIC BUILD-UP

Breaking down organic materials is achieved with the use of a sludge busting microbiological material. This should be applied during the leaf drop season. The proper conditions for this breakdown to occur must be maintained until the organic matter has completely broken down.

3.3.3.3 SIGNAGE

In cases where the pavement is used by a large number of people it is important to provide signage informing everyone of the ecological sensitivity of the pavement. It should set out some guidelines that need to be adhered to. This includes no piling of any material without covering the surface and contacting the owner to treat any spills example to prevent pavement contamination.

3.4 PAVEMENT SPECIFICATIONS

The previous sections set out the requirements for the sub-grade, sub-base and no-fines wearing course. The following section assesses some of the designs that have been used in different situations.

3.4.1 FOOTPATHS AND BIKEWAYS

The following figure has been used in the construction of footpaths and bikeways. It consists of 200 mm of clean aggregate and a 60 mm thick no-fines concrete surface. This large amount of sub-base material probably makes this design uneconomical since it will be considerably more expensive than conventional footpaths (www.stoneycreekmaterials.com).

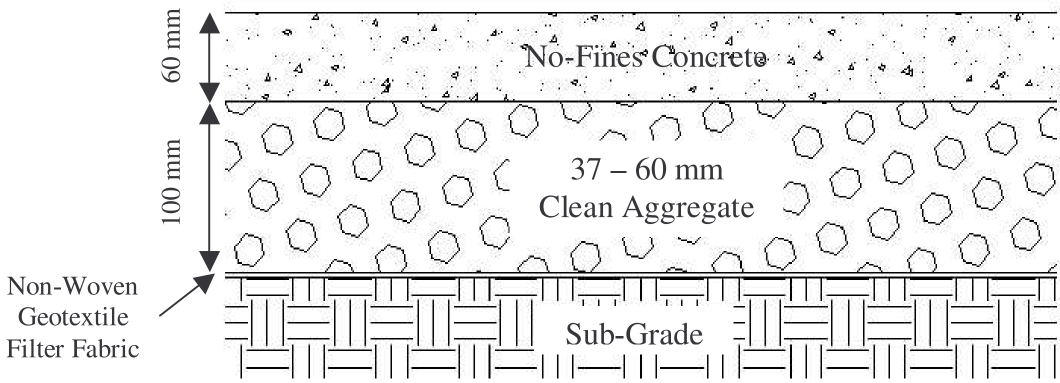


Figure 3.3 – A typical cross section for a no-fines concrete footpath or bikeway

3.4.2 STANDARD PAVEMENTS

There are a number of pavements that have been classified as standard pavements that can be used in situations such as residential driveways and footpaths. These differences are predominantly concerned with the sub-grade type.

This pavement consists of a non-woven geotextile fabric over the sub-grade and a 200 mm thick clean aggregate for the sub-base. This is covered by 100 mm of no-fines concrete and is shown in figure 3.4 (www.stoneycreekmaterials.com).

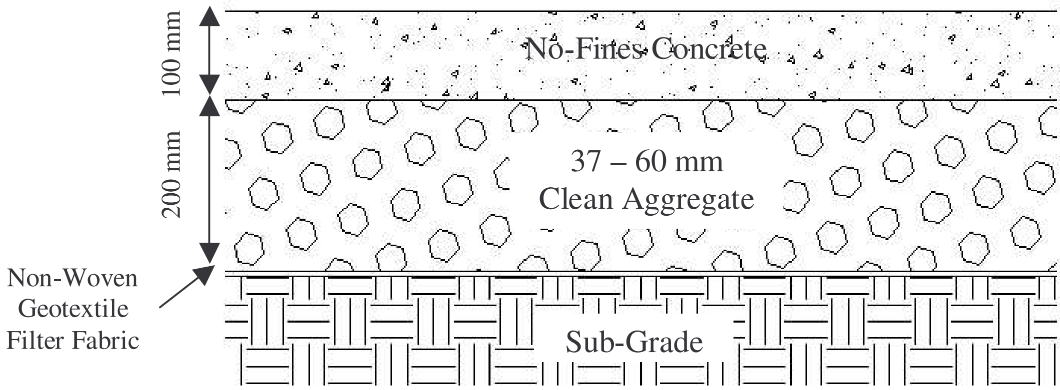


Figure 3.4 – Typical cross section of a no-fines pavement for driveways and parking lots

The following figure shows the pavement cross-section with a sub-grade made from an expansive soil. This consists of an impervious layer of polyethylene between the sub-grade and sub-base. The 200 mm sub-base and 100 mm no-fines concrete are the same as the previous standard pavement. It requires a number of 300 to 500 mm cased borings that continue through the expansive soil filled with riprap. The spacings required for these borings will be specified in the geotechnical study to assess the permeability (www.stoneycreekmaterials.com).

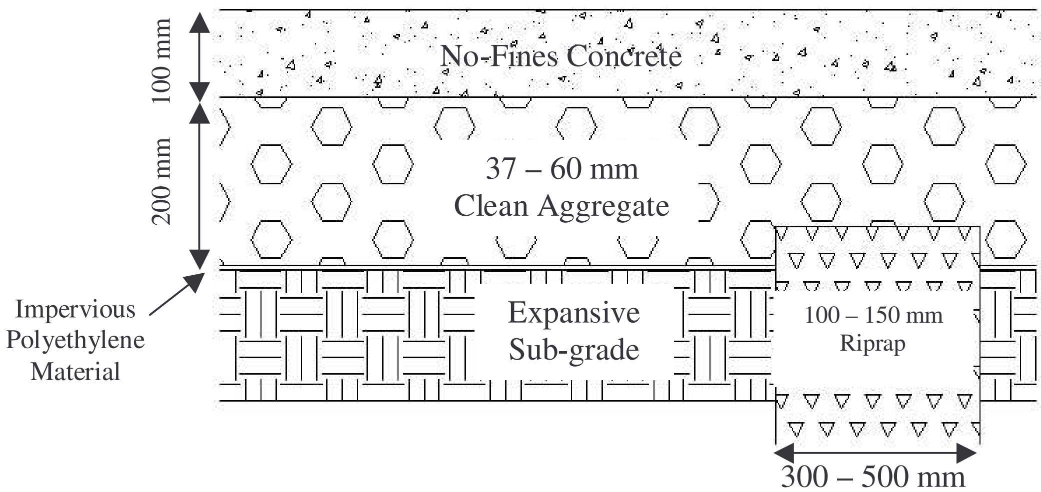


Figure 3.5 – The cross section for a no-fines concrete pavement with expansive soils

The final standard pavement consists of an impervious sub-grade. This requires boring holes through the impervious layer into a permeable layer that allows the water to dissipate. The size of the borings will range between 300 and 500 mm in diameter and spacings will be determined from a geotechnical study. The sub-base required is 200 mm and the no-fines concrete is 100 mm thick. Figure 3.6 shows the cross section of the standard pavement with an impervious sub-grade (www.stoneycreekmaterials.com).

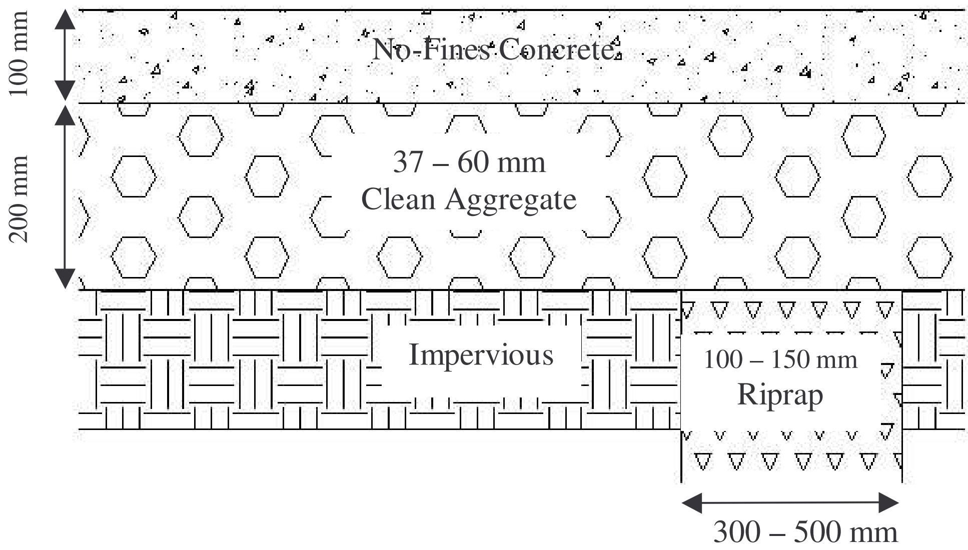


Figure 3.6 – A typical cross-section for a pavement with an impervious sub-grade

3.4.3 HEAVY TRAFFIC PAVEMENT

The pavement for heavy and large traffic volumes consists of a 150 mm layer of no-fines concrete and a 250 mm thick layer of 37 to 50 mm clean aggregate. A non-woven geotextile fabric is placed between the clean aggregate and the sub-grade. This arrangement is shown diagrammatically in the figure below.

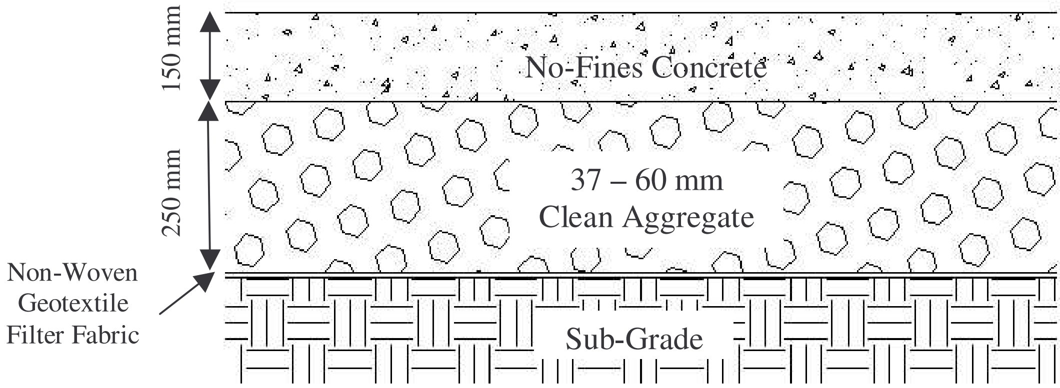


Figure 3.7 – No-fines concrete pavement cross-section for heavily trafficked areas

The no-fines concrete pavements shown in the previous sections have been designed on the performance of previously constructed roads. It has been based on empirical evidence collected from the pavements that have failed and those that have been successful. Currently there is no theoretically based pavement design method for no-fines concrete pavements. This means that the pavements currently in use may be over designed and the pavement cost could be reduced if there was a better understanding of how the various components interact. With a greater understanding of the critical characteristics of all the components, new or improved materials may be found to increase the performance of the pavement.

3.5 SUMMARY

This chapter covered the construction and maintenance procedures that Stoney Creek Materials recommend to be used in conjunction with their no-fines concrete pavements. A number of different pavements were discussed, ranging from pedestrian footpaths to highly trafficked roadways. The different treatments available to be used in unfavourable soil conditions were also discussed.

The following chapter looks at the testing methodology and the tests to be conducted. This is followed by the preliminary mix design procedure, results and analysis.

CHAPTER 4

4. METHODOLOGY & PRELIMINARY MIX DESIGN

4.1 INTRODUCTION

The following sections of this chapter describe in detail the testing that follows and the methodology used to produce the results to be analysed. A discussion of the preliminary mix design that was conducted during the early stages of this project follows.

To provide uniform results and conformity with the concrete testing, an aggregate sample was chosen to be used for the remainder of the project. 20 mm crushed basalt was chosen as it appeared to be the most spherical aggregate available.

4.2 TEST METHODOLOGY

This project is focused predominantly on the use of no-fines concrete as a road pavement material. As this is a comparison between no-fines concrete pavements and conventional concrete pavements, there is a requirement that the tests being conducted can occur on both samples.

The test procedure included the initial steps of deciding on the tests to be conducted and choosing a number of aggregate-cement ratios for the no-fines concrete. This was followed by conducting the preliminary mix design and compressive strength tests on these samples to determine the mix that performed most successfully.

With the mix ratio known, the remaining testing began. This included determining the properties of the aggregate being used with a sieve analysis and a flakiness index test. After mixing, the workability testing was conducted on the wet concrete before the test specimens were constructed.

The no-fines concrete samples were placed in the fog room for 28 days before testing occurred. The samples were tested using standard hardened concrete tests. The same workability and hardened concrete tests were undertaken on a 32 MPa ready mixed concrete that was used in conjunction with another project. With both sets of data, a comparison of the properties of the no-fines concrete could be assessed and conclusions relating to its usefulness reached.

4.3 CONCRETE TESTS

The tests that were conducted had to provide a complete picture of all the characteristics of the concrete in both the wet and hardened state.

For this reason, it was proposed that the testing incorporate aggregate testing to determine the potential effect of the aggregate shape on the performance of the no-fines concrete. This was followed by conducting workability tests like the slump, VEBE and compacting factor tests on the wet concrete sample.

The hardened concrete tests proposed for the project were compressive strength and indirect tensile tests, modulus of rupture and elasticity and the skid resistance test. This testing includes determining the void ratio and assessing the permeability of the no-fines concrete.

4.4 MIX DESIGN

The mix design in this case was the determination of the ratio of aggregate, cement and water that possessed the most favourable properties. For this particular situation four trial mixes were designed. The mixes were determined from previous literature and particular mixes used by some companies. There are only three constituents of no-fines concrete that can be considered and varied: aggregate, cement and water content.

4.4.1 CONVENTIONAL CONCRETE

There was no mix design undertaken for conventional concrete, since the strength of certain mixes is readily known. This meant that no trials were required to be carried out. When conducting the tests to determine the properties of a conventional concrete, a 32 MPa ready-mixed concrete was used in conjunction with another concrete project.

4.4.2 NO-FINES CONCRETE

The mix designs for no-fines concrete were obtained from printed articles. There were a large number of different mixes that are currently being used for a whole range of applications. For this reason four different mixes were trialled. The aggregate-cement-water ratio mixes were:

Aggregate	Cement	Water
8	1	0.4
6	1	0.4
4.5	1	0.4
4.8	1	0.36

Table 4.1 – Mix Proportions used for No-fines Trial Mixes

These different mixes will test the effect of increasing the cement content for the same amount of aggregate. The fourth mix is the ‘Stoney Creek Pervious Pavement System’ design mix. This particular mix has been developed for use in Texas, USA.

4.4.3 TRIAL MIX

The trial mixes were used to determine the most suitable mixture for the analysis. The four different samples were mixed and tested for compressive strength and indirect tensile strength at 14 days. From these results, the most appropriate mix was determined and used for the remainder of the analysis. The 28 day strength was tested later to ensure that the chosen concrete mix possessed the highest ultimate compressive strength of the concrete mixes.

4.4.3.1 APPARATUS

Wheelbarrow – capable of resisting chemical attack from the cement and of sufficient size to allow hand mixing.

Shovel – capable of resisting chemical attack and abrasion during the mixing process.

Balance – capable of weighing the required mass with an accuracy of 0.1 g and complying with AS 1141.2.

4.4.3.2 MIXING PROCESS

1. Weigh aggregate, cement and water for the mix.
2. Moisten the working surface of the wheelbarrow to prevent the materials from sticking to the sides.
3. Add the aggregate to the wheelbarrow and add approximately half the water and mix until all the aggregate is wet.

4. Spread the cement and water uniformly over the surface of the aggregate.
5. Mix the concrete until the aggregate is evenly covered with cement paste.

4.4.3.3 COMPACTING AND CURING

Rodding was adopted for the compaction of no-fines concrete. The concrete samples were tamped 25 times and split into three layers. This procedure ensures sufficient compaction has been produced.

The curing process starts with the moulds being left in place for 2 or 3 days, to allow sufficient bonding between the aggregate particles. After the specimens were removed from the mould they were placed in the fog room until the time of testing. This process was used to ensure that optimum curing was achieved.

4.4.3.4 RESULTS AND ANALYSIS

Half the specimens were tested for compressive strength and indirect tensile strength at 14 days. The remaining small and large specimens were tested for 28 day compressive strength. The results of those tests can be found in the table below.

Aggregate-Cement-Water Ratio	14 Day Strength		28 Day Strength	
	Compressive Strength (MPa)	Indirect Tensile Strength (MPa)	Compressive Strength (MPa)	Compressive Strength of Large Cylinders (MPa)
8:1:0.4	4.33	1.19	3.06	6.00
	4.33		3.82	
6:1:0.4	5.60	1.58	7.51	5.49
	8.02		7.64	
4.5:1:0.4	7.77	2.32	11.20	7.70
	7.89		12.99	
4.8:1:0.36	7.89	1.08	6.37	5.32
	7.26		6.24	

Table 4.2 – The data collected from the trial mixes

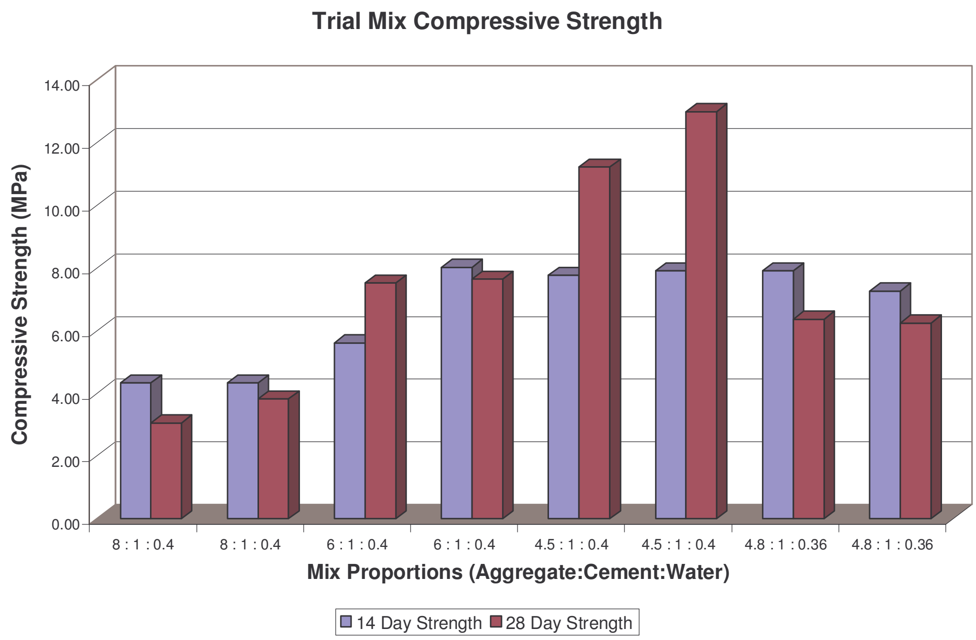


Figure 4.1 – Shows the comparison between the different mix proportions and between 14 and 28 day strength for the no-fines concrete cylinders

From the 14 day testing, the aggregate-cement-water ratio of 4.5:1:0.4 was chosen as the most suitable mix since it produced the highest average compressive strength and possessed the greatest indirect tensile strength. The rest of the analysis will be completed using this mix design.

The large variation in the values obtained was caused predominantly by the inability to adequately seat the specimens. Rubber capping was used to try and overcome this problem but the aggregate size made providing a smooth surface hard to achieve. It was determined that the use of sulphur capping or similar methods would be more suitable to eliminate the problem of tilting and failing due to the dislodging of the edge aggregate.

The specimens tended to fail slightly and then regain strength before failing again. This process continued until the ultimate failure occurred. At times this failure was catastrophic and can be seen in the figure below, which shows the failure of the specimens on completion of 28 day compression testing. This anomaly can be explained by the poor bonding of the top aggregate particles and should be eliminated by sulphur capping, as it will strengthen the bond of these particles.

Figure 4.2 – The failure of Mixes 1 and 2

Figure 4.3 – Shows the failure of Mixes 3 and 4

The failure shown in the previous two figures vary from slight shear failure with only small amounts of the concrete missing from the edges, to nearly complete disintegration with only small fragments still visible.

A compressive test was undertaken on the large specimens at 28 day strength to assess if the same repeated failing and strengthening occurred. The tested samples appeared to exert the same failure characteristics but did not fail in a catastrophic manner like some of the smaller samples. A photo of the failure of these specimens is shown below.

Figure 4.4 – Shows the failure of the four mixes on the large cylinders

All the edges in contact with the moulds provided a reasonably smooth surface. The problem of failure with this form of compressive testing lead to the consideration that cube strength testing may more accurately determine the true compressive strength of no-fines concrete. The cube testing does not rely on providing a smooth surface on the top as the sample is tested on its side. This method of testing should provide a better result as it will test the strength along the entire length of the sample. The shape of the sample should reduce the problem of the tested sample leaning and falling before failure.

4.5 SUMMARY

The no-fines concrete mix design found that an aggregate-cement-water mix of 4.5:1:0.4 produced the highest compressive strength out of the different mix proportions trialled. Since the highest compressive strength was found in the 4.5:1:0.4 mix, it was used for the remainder of the testing in this project.

The following chapter is primarily concerned with the testing and analysis of the aggregate sample used for making the no-fines concrete.

CHAPTER 5

5. PROPERTIES AND TESTING OF AGGREGATE

5.1 INTRODUCTION

This chapter investigates the properties of the aggregate used to make the no-fines concrete test samples. A sieve analysis and flakiness index of the aggregate sample was determined, so the characteristics of the aggregate could be assessed.

The results of these tests will help explain any differences that occurred during the testing phase. These results are useful when trying to explain differences in the compressive strength of the no-fines concrete when a different aggregate sample of the same size is used.

5.2 SIEVE ANALYSIS

Sieve analysis is a method of determining the grading of a particular aggregate or a mixture of aggregates. The sieve analysis is carried out in a mechanical sieving machine to provide a more consistent result and achieve much greater accuracy. The sieves used vary in size but consecutive sieves used are smaller in aperture as you move down the stack. There are three different methods for undertaking a sieve analysis. Two wet analysis methods can be used, one with alcohol and the other with water. The third method is dry analysis, which can only be used for granular particles larger than 125 μm.

The aggregate was dry sieved due to the large particle size. Before sieving began the aggregate particles were air dried to ensure that no lumps or small particles contaminated the larger sieves and to prevent the smaller sieves from becoming clogged. The test sample was reduced from a large quantity by the method of 'sample reduction'. The aggregate was riffled and collected in boxes at the bottom of the chutes. Half was discharged and the other half was riffled again. This process was continued until the specifications for sampling were met and an adequate quantity of material collected for the sieve analysis.

5.2.1 APPARATUS

The following apparatus complying with the appropriate Australian Standards were used in all cases.

Drying Oven – capable of maintaining a temperature of 110 ± 5ºC and complies with AS 1141.2.

Balance – capable of weighing the required mass with an accuracy of 0.1 g and complies with AS 1141.2.

Sample Divider – capable of handling the size aggregate to be passed, usually the slot width is 10% wider then the aggregate and complies with AS 1141.2.

Test Sieves – a certified set of sieves with a lid and collection pan to comply with AS 1152.

Brush – capable of removing all aggregate from the sieves, without damaging the sieves.

Shaking Device – a machine capable of providing lateral and vertical movement that ensures the continuous movement of the aggregate over the sieves.

Figure 5.1 – The shaking device and stack of sieves used to conduct the sieve analysis

5.2.2 PROCEDURE

A brief outline of the procedure, which complies with AS 1774.19 – 2003, follows:

1. The mass of the dry sample obtained from the riffler was measured with an accuracy of 0.1 g.
2. Dry, clean sieves were stacked in order with the largest sieve on the top and collection pan on the bottom.
3. The sample was placed on the top sieve, the lid replaced and the nest of sieves positioned on the shaking device which was operated for 10 minutes.
4. The contents of each sieve were removed separately and the mass of aggregate retained by each sieve weighed.

5.2.3 RESULT OF SIEVE ANALYSIS

The results of the sieve analysis conducted on the 20 mm aggregate used to prepare the test samples are shown below in Table 5.1.

Sieve Size (mm)	Mass Retained (g)	Sum Mass Retained (g)	Percentage Retained (%)	Percentage Passing (%)
19	160.2	160.2	3.56	96.44
16	855	1015.2	22.59	77.41
9.5	3235.4	4250.6	94.56	5.44
6.7	153.1	4403.7	97.97	2.03
4.75	38.2	4441.9	98.82	1.18
< 4.75	53.1	4495	100.00	0.00
TOTAL	**4495**			

Table 5.1 – Results of the Sieve Analysis

The results of the sieve analysis show that this 20 mm aggregate sample is not completely single sized but reasonably close. Almost 95 percent of the aggregate was retained on or above the 9.5 mm sieve. There were small amounts of fines and small aggregate, which should not affect the strength of the no-fines concrete but could affect the void ratio.

A sieve analysis was also undertaken on the second sample of 20 mm aggregate obtained to make the no-fines concrete samples. This second sieve analysis was conducted as there was a large variation in the strength of the two concrete samples. The details of this test can be found in Appendix C along with a grading curve for both aggregate samples. Both aggregate samples appeared to be a single-sized aggregate.

5.3 FLAKINESS INDEX

The purpose of determining the Flakiness Index is to find the quantity of flaky or thin aggregate particles. The flakiness of the aggregate particles is of critical importance to the strength of no-fines concrete. The flaky particles can crush under load causing premature failure of the concrete. The flaky particles will tend to lie flat on each other reducing the void content and the permeability of the concrete. If the voids are not large enough it will suffer from internal stress caused by the capillary action of the water.

A flaky particle is defined as an aggregate particle with its least dimension less than 0.6 times its mean dimension (determined by sieving). The Flakiness Index gives the amount of flaky particles expressed as a percentage of the total sample.

5.3.1 APPARATUS

The following apparatus used in testing complies with the appropriate Australian Standards.

Drying Oven – capable of maintaining a temperature of 110 ± 5ºC and complies with AS 1141.2.

Balance – capable of weighing the required mass with an accuracy of 0.1 g and complies with AS 1141.2.

Sample Divider – capable of handling the size aggregate to be passed, usually the slot width is 10% wider then the aggregate and complies with AS 1141.2.

Slotted Gauge – capable of withstanding abrasion from aggregate particles and having slots with a width of 0.6 times the sieve sizes.

Figure 5.2 – Shows the slotted gauge used to determine the Flakiness of the aggregate particles

5.3.2 PROCEDURE

1. The mass of the sample retained on each sieve was weighed separately and the test fraction recorded to the nearest gram (m_1).
2. With the test fraction and corresponding slotted gauge, attempt to pass the particles through the gauge. Determine the mass of the particles passing through the slotted gauge to the nearest gram and record as (m_2).

3. Calculate the flakiness index (FI) from the following equation:

$$FI = \frac{\Sigma m_2}{\Sigma m_1} \times 100$$

where

Σm_2 = sum of the masses of selected entire size fractions passing the slotted gauge, in grams

Σm_1 = sum of the masses of selected entire size fractions, in grams.

4. Report the flakiness index obtained from the previous calculation to the nearest whole number.

5.3.3 RESULT OF FLAKINESS INDEX

The Flakiness Index obtained from testing the aggregate sample is shown in Table 5.2.

Aggregate Size (mm)	M_1 (g)	M_2 (g)	Flakiness Index
19	160	22	13.75
16	855	115	13.45
9.5	616	70	11.36
6.7	153	33	21.57
4.75	59	13	22.03
Σ	**1843**	**253**	**13.73**

Table 5.2 – Data collected from the Flakiness Index test

The aggregate sample has a Flakiness Index of 13.73 percent by weight. This means that the amount of flaky particles in the sample is 13.73 percent. Flaky particles are not wanted when making no-fines concrete as it initiates aggregate crushing and promotes poor contact between particles.

This amount of flaky particles will slightly reduce the ultimate strength of the no-fines concrete. A spherical aggregate shape is most desirable for no-fines concrete applications. The flaky particles are probably causing a small loss of strength but this quantity should not affect the outcome dramatically.

The flakiness index from the second aggregate sample is 10.97, which is different to the previous sample. It can be deduced from this that the flakiness of the aggregate particles affects the compressive strength of no-fines concrete, as the concrete made from this sample was considerably stronger.

5.4 SUMMARY

It was found that there was a discrepancy in the flakiness of the two aggregate samples used. The lower amount of flaky particles meant that a higher compressive strength could be obtained. This upholds what is stated in the literature.

The workability tests, results and analysis are explained in detail in the following chapter.

CHAPTER 6

6. WORKABILITY TEST OF CONCRETE SAMPLES

6.1 INTRODUCTION

This chapter includes the no-fines concrete mix preparation procedure and the workability tests. The workability tests include the slump, VEBE and compacting factor tests. These tests were chosen as they will provide a clear indication of the workability and fresh concrete characteristics.

No-fines concrete is said to have self compacting properties. This will be tested with the compacting factor test. The slump and VEBE tests are not good for testing no-fines concrete due to the low cohesion between the aggregate particles.

6.2 PREPARING CONCRETE MIX

The preparation of the no-fines concrete mixes were made in accordance with AS 1012.2. It was imperative that this standard be adhered to, to ensure different mixes had similar properties when made at different times.

The only method to test uniformity in mixes was achieved by undertaking the workability tests on the fresh concrete. The workability test used to test the concrete mixes included the slump, VEBE and compacting factor tests.

The concrete used for the testing on conventional concrete samples was supplied by Wagners Concrete. It had a compressive strength of 32 MPa.

6.2.1 APPARATUS

The apparatus used for preparing the concrete mixes was a motor-driven mixer. A Hallweld Bennett Pan Mixer model 03UE was used to perform the mixing requirements. This is shown in the figure below.

Figure 6.1 – The Hallweld Bennett Pan Mixer used for the no-fines concrete mixes

6.2.2 OPERATIONAL PROCEDURE

The following operating procedure was undertaken when using the pan mixer:

1. The inside surface of the mixer was moistened.
2. The aggregate and half of the required water was added.
3. The mixing was started and the cement and remaining water was added slowly.
4. The mixing continued until the aggregate was sufficiently covered with cement paste.
5. The mix was discharged into the wheelbarrow by fully opening the trap.
6. The motor was turned off.
7. The power at wall was isolated.
8. The inside of the pan mixer was cleaned with water.

6.3 SLUMP TEST

The slump test is a method of testing the fresh concrete for particular characteristics including workability. It is a simple method of determining if different batches of concrete are the same. This is determined if the same constituents in the same proportions do not vary the characteristics of the concrete sample.

The slump is determined by filling a slump cone with fresh concrete in three layers. Each layer is rodded 25 times. The slump cone is removed and the vertical subsidence of the fresh concrete sample is measured. No-fines concrete has very little cohesion due to its structure and may collapse on removal of the cone resulting in a poor result with little or no value. The values obtained from the slump test were compared with results obtained by compressive strengths and other related tests in an attempt to be able to describe the characteristics of the concrete. This is a simple test that can be performed simply in the field without requiring any special training.

6.3.1 APPARATUS

Slump Mould – manufactured from galvanised steel sheet with a wall thickness of 1.5 mm and internal dimensions as follows: bottom diameter = 200 mm, top diameter = 100 mm and vertical height = 300 mm.

Rod – constructed of 16 mm diameter metal rod approximately 600 mm long with a tapered and spherical end with a radius of 5 mm.

Scoop – capable of withstanding chemical attack from cement paste.

Base Plate – smooth, rigid and non-absorbent.

Ruler – an appropriate steel ruler.

Figure 6.2 – The equipment required to conduct a Slump Test

6.3.2 PROCEDURE

A brief procedural outline of the steps taken is shown below and were completed in accordance with AS 1012.3.1 – 1998

1. Make sure the internal surface of the slump cone is free from hard concrete.
2. Wet the internal surface with a damp cloth before commencing test.
3. Place the mould on the base place and hold in place by standing on the foot pieces provided during the filling procedure.
4. Ensure that the remainder of the steps are carried out within 3 minutes.

5. Fill the mould in three equal layers and rod each layer 25 times. The rodding must occur uniformly over the entire cross section of the concrete.

6. Ensure that the top layer of the concrete is in line with the top of the mould on completion of the filling and rodding procedures.
7. Carefully remove the slump mould without disturbing the concrete sample.
8. Measure the slump by determining the difference in height between the mould and the average height of the top surface of the concrete.
9. Measure the slump to the nearest 5 mm if slump is less than 100 mm or to the nearest 10 mm if the slump is greater than 100 mm.

6.3.3 RESULTS AND ANALYSIS

This test was undertaken on each sample of concrete used for the hardened concrete tests. The slumps obtained on the concrete samples are as follows:

	No-Fines Concrete	Conventional Concrete
Slump (mm)	170	70
	160	70

Table 6.1 – The Slump of the different concrete samples

The no-fines concrete had an extremely high slump caused by the low amount of cohesion between the aggregate particles. This particular workability test appears to be of little use when considering no-fines concrete.

The no-fines samples momentarily held the shape of the slump cone before collapsing and producing the high slump found in the table above. From the results obtained from the slump test it could be deduced that the no-fines concrete has high workability but this is not the case. The low cohesion between the aggregate particles produced a poor result making the Slump Test useless for assessing the workability of the no-fines concrete.

The slumps found for the no-fines concrete appears to be highly variable and does not in anyway correlate with the water content of the samples.

The ready mixed conventional concrete used for this section of the testing had a slump of 70 mm. This concrete was used in conjunction with another project and the slump and strength characteristics were dictated by the requirements of the other testing.

The slump produced by the conventional concrete exhibited the traditional failure. This is a good method for determining and predicting the workability properties of the concrete sample. No unusual failure mechanisms were observed which further validates the workability characteristics of the concrete sample.

6.4 VEBE TEST

The VEBE test is another consistency test that is conducted on a fresh sample of concrete. A sample of concrete is made and a standardised vibratory action is applied and vibrated until total compaction is achieved. This is done by making a mould similar to that used previously in the slump test and vibrated with an applied load until the compaction is achieved. This particular test is measured by the time taken for total compaction to occur.

The time taken for total compaction to occur should not vary between samples if all the constituents and mix proportions do not differ. Vibration is not recommended for use on no-fines concrete as there is a low amount of cohesion and it makes the cement paste run off the aggregate particles. This test may not be the most appropriate for testing the consistency of no-fines concrete.

6.4.1 APPARATUS

Consistometer – is made up of a number of components that will be detailed below.

Container – shall have an internal diameter of 240 mm and height of 200 mm and is water tight, rigid and possesses the ability to retain its shape with usage.

Mould – manufactured from galvanised steel sheet with a wall thickness of 1.5 mm and internal dimensions as follows: bottom diameter = 200 mm, top diameter = 100 mm and vertical height = 300 mm.

Disc – a transparent horizontal disc with a diameter of 230 mm attached to a funnel and a guide arm with a total weight of 2750 grams

Vibrating Table – shall be 380 mm in length and 260 mm in width and vibrates with a frequency of 50 Hertz and amplitude of 0.5 mm.

Rod – constructed of 16 mm diameter metal rod approximately 600 mm long with a tapered and a spherical end with a radius of 5 mm.

Scoop – capable of withstanding an attack by cement.

Stopwatch – capable of measuring time to the nearest 0.5 second.

Figure 5.3 – Shows the Consistometer and other major components used in the VEBE Test

6.4.2 PROCEDURE

1. Make sure the internal surface of the slump cone is free from hard concrete.
2. Wet the internal surface with a damp cloth before commencing test.
3. Attach the container securely to the vibrating table and place the mould in container.
4. Fill the mould in three equal layers and rod each layer 25 times. The rodding must occur uniformly over the entire cross section of the concrete and throughout the entire layers of concrete.
5. Ensure that the top layer of the concrete is in line with the top of the mould on completion of the filling and rodding procedures.

6. Remove the mould carefully without disturbing the concrete and place the transparent disc on the sample.
7. Start the vibrating machine and stopwatch simultaneously. Observe the concrete sample through the transparent disc and stop the timing when total compaction has occurred and the disc is completely covered with cement paste.
8. The VEBE value is the vibration time in seconds measured to the nearest 0.5 seconds.

6.4.3 RESULTS AND ANALYSIS

The VEBE test is related to the slump test, with the initial cone shape of the mould. The results for the VEBE test conducted on both types of concrete are shown in table 6.2.

	No-Fines Concrete	Conventional Concrete
Time (secs)	2.5	2.0
	3.0	2.0

Table 6.2 – The time elapsed for the completion of the VEBE Test

This test is also extremely sensitive to the type of concrete sample. When testing conventional concrete, it shows the consistency or workability of the concrete. The no-fines samples produced a result that would characterise it as a material with moderate to high workability. This is once again caused by the low cohesion between aggregate particles possessed by the no-fines concrete.

The no-fines concrete samples almost completely covered the plastic screen before the consistometer was started. From these tests it can be deduced that the VEBE test is not an effective method of testing the workability and other properties like the appropriateness of the water content of the no-fines concrete samples.

The size of the aggregate may have increased the time taken for compaction of the sample. The large aggregate would have resisted the movement from the consistometer. This test that should be conducted on no-fines concrete since the use of vibrating during compaction is not recommended for this particular type of concrete.

The VEBE test shows that the conventional concrete has higher workability properties than the no-fines concrete. From handling the concrete and making the test specimens it was seen that the workability of the conventional concrete was much higher than the no-fines concrete.

6.5 COMPACTING FACTOR TEST

The compacting factor test is used to determine the extent with which the fresh concrete compacts itself when allowed to fall without the application of any external compaction. The compaction obtained from the free falling is compared with the same sample under standard compaction practices (that is 3 layers, each rodded 25 times). The sample falls from the initial cone and is captured in a second cone. It is then allowed to fall into a test cylinder with a diameter of 150 mm and height of 300 mm.

This test is another test for consistency of a fresh concrete sample and as with the other tests it should not vary considerably for different batches with the same mix proportions. This is probably the most appropriate method for testing the consistency of no-fines concrete as it is considered to be a self compacting material and can be dropped from height without affecting its properties.

6.5.1 APPARATUS

Compacting Factor Apparatus – consists of 2 conical hoppers mounted above a cylinder.

Trowel – requires the use of two trowels.

Rod – constructed of 16 mm diameter metal rod approximately 600 mm long with a tapered and spherical end with a radius of 5 mm.

Scoop – capable of withstanding an attack by cement paste.

Balance – capable of measuring to an accuracy of 0.1 percent.

Level – a rigid piece of material able to withstand an attack by the cement paste.

Figure 6.4 – The apparatus used to conduct the Compacting Factor Test

6.5.2 PROCEDURE

1. Ensure the internal surfaces of the hoppers and cylinders are free from hardened concrete.
2. Moisten all the internal surfaces with a damp cloth before commencing each test.
3. Place the compacting factor apparatus on a level rigid surface free from vibration.
4. Gently fill the upper hopper with concrete using the scoop, then immediately open the trapdoors to allow the concrete to fall into the second hopper. Undertake this test 4 minutes after the mixing process is completed.

5. Immediately after the concrete has come to rest, open the lower trapdoor allowing the concrete to fall into the cylinder.
6. Level the top of the cylinder and wipe clean any concrete on the mould.
7. Determine the mass of the concrete in the cylinder to the nearest 10 grams. This mass is known as the 'mass of the partially compacted concrete (m_1)'.
8. Empty the cylinder and fill with a new sample of concrete and compact by rodding the concrete in three layers. Carefully strike off the top surface and clean the outside of the cylinder.
9. Determine the mass of the concrete in the cylinder to the nearest 10 grams. This mass is known as the 'mass of fully compacted concrete (m_2)'.
10. Calculate the compacting factor with the following equation:

$$\text{Compacting Factor} = \frac{(m_1)}{(m_2)}$$

6.5.3 RESULTS AND ANALYSIS

The results from the compacting factor test conducted on the concrete samples are found in table 6.3.

	Partially Compacted (m_1) kilograms	Fully Compacted (m_2) kilograms	Compacting Factor
No-Fines Concrete	10.925	11.435	0.96
	10.245	11.435	0.90
Conventional Concrete	13.095	13.565	0.97

Table 6.3 – Shows the Compacting Factor for all the samples of concrete used

No-fines concrete is a self-compacting material and this test determines its ability to compact itself dropping from a set height. No-fines concrete can be dropped from large heights and this test shows these properties by the amount of compaction obtained from simply allowing the concrete to drop.

The low cohesion between the aggregate particles helps the self compacting process of the no-fines concrete. This particular fresh concrete test is the most useful for determining the properties of no-fines concrete. The results obtained from this test will provide a method for assessing the amount of compaction required when placing a particular no-fines concrete mix.

The self-compacting properties of the conventional concrete sample were similar to that of the no-fines concrete. The only problem with conducting this test was that the conventional concrete sample required assistance to move from each of the cones to the final cylinder. This may be related to the dry nature of the concrete used in this particular situation. By helping the concrete pass through each cone, it may have affected the outcome and skewed the self-compacting factor results.

6.6 SUMMARY

The slump varied dramatically between the no-fines and conventional concrete samples due to the low cohesion between the aggregate particles. The VEBE test showed similar results for both samples and the compacting factor test was reasonably similar for both types of concrete. The compacting factor test appeared to be the most useful workability test as it illustrates the self compacting properties of the concrete.

The following chapter provides the details of all the hardened concrete tests undertaken, along with the results and analysis.

CHAPTER 7

7. TESTING HARDENED CONCRETE SPECIMENS

7.1 INTRODUCTION

This chapter explains the curing techniques and the sulphur capping used for all the concrete specimens being tested. The remainder of this chapter is involved with the procedures, results and analysis of all the hardened concrete tests that were conducted.

7.2 CURING

There are two curing times that are of critical importance for concrete specimens constructed in the laboratory. These include the initial curing and the standard moist-curing. The Australian Standard 1012.8.1 sets out the requirements for the correct curing procedures.

7.2.1 INITIAL CURING

The specimens need to be left undisturbed except when the early capping procedures are used. Apart from this the moulds should be set on a rigid horizontal surface for a period of between 18 and 36 hours. An ambient temperature ranging between 21 and 25ºC should be maintained during this initial curing period.

7.2.2 STANDARD MOIST CURING

The temperature range for moist curing laboratory specimens is 21 to 25ºC. The moist curing is achieved by storing the concrete specimens in a fog room which provides a high humidity environment.

The specimens require the fog room to keep them moist but it is imperative that they are not exposed to streams of running water. Mist spraying of the specimens may be required during the initial curing stages.

7.3 CAPPING

Moulded caps are required to be as thin as practicable and should not exceed 6 mm in depth. The capping process should occur in a single layer process on each of the surfaces requiring capping. Capped surfaces are required to be within 0.05 mm out of plane.

There is a wide range of capping materials capable of providing a smooth surface but sulphur capping will be used in this situation. The sulphur cap requires 1 hour of curing before testing when the expected compressive strength of the concrete is less than 50 MPa.

7.3.1 PLATES AND EQUIPMENT

The plates and equipment used for capping complied with the following requirements:

1. Sulphur caps were formed in a metal plate with a recess to hold the sulphur. The recess was required to be at least 10 mm deep and have a bottom diameter 5 mm larger than the test specimen. The side of the recess should slope to facilitate the removal of the specimen from the mould.
2. Capping plates require a thin coating with mineral oil to prevent adhesion of the sulphur to the plate.
3. An alignment device like a square should be used in conjunction with the plates to ensure that the cap and specimen axis are perpendicular.

Figure 7.1 – The capping mould used for sulphur capping

7.3.2 CAPPING PROCEDURE

The hardened concrete cylinders were capped in accordance with the following recommendations:

Ensure the surface to be capped is dry and free from loose objects. Only dry the specimen the minimum amount required for the contact of the sulphur. The dry surface is required to provide an adequate bond between the sulphur and concrete sample. This will help provide a more stable connection and may improve results.

7.3.3 CAP INSPECTION

The following procedures were undertaken on the moulded cap before testing commenced:

1. Tap the moulded cap before placing it in the compression machine.
2. Remove any caps that make a hollow sound and remould the cap before the specimen is tested.
3. Ensure the alignment of the cap is correct before the specimen is tested.

7.4 TESTING MACHINES

The machine used for testing complied with the following requirements:

1. The machine complied with the requirements for Grade A machines defined in AS 2193 for the required range of compressive forces.
2. The testing machine is capable of applying a compressive force that increases continuously as required.
3. The machine is fitted with a load pacer which allows the operator to apply the load in a correct manner.
4. Steel compression plates with at least 10 mm clearance around the test specimen and the top platen have a spherical seat capable of tilting at least 3º in all directions.
5. The bottom platen contains an accurate means of centring the test specimen by means of finely scribed markings.

Figure 7.2 – Avery machine used to conduct the concrete testing

7.5 COMPRESSIVE STRENGTH

The compressive strength tests are conducted to ensure a minimum strength is achieved by the particular mix. Cylinder and cube testing are methods of determining the compressive strength. The cylinder testing is an Australian Standard for testing compressive strength, while cube testing is a British Standard. Both methods of determining compressive strength will be used as it may be difficult to achieve a good result when using the cylinders.

The cube test, due to the method by which it is implemented, should give a more stable test specimen than the cylinders. This test will determine the strength of the sample along the entire length of the sample and eliminate problems encountered with the edge aggregate dislodging and failing. The cube method usually determines a concrete strength increased by 10 and 40 percent in comparison to the equivalent cylinder test.

This extra strength will be taken into account when testing and will be compared with equivalent conventional concrete samples. If there is a major difference then the cube test will be used for the determination of compressive strength.

7.5.1 CYLINDER TESTING

The procedure for the preparation of test specimens, capping and testing procedures for the testing of concrete cylinders are set out in the following sections. The Australian Standards for the compressive testing of concrete specimens were undertaken in accordance with AS 1012.9-1999. The test specimens were made, compacted and cured in accordance with AS 1012.8.

7.5.1.1 PREPARATION OF TEST SPECIMENS

The preparation of the test specimens includes assessing the test samples for defects, removing any loose materials and capping the cylinder when appropriate. Capping is only required when the top surface of the test specimens do not have end surfaces within 0.05 mm.

The no-fines concrete samples are extremely rough predominantly due to the large aggregate particles. Sulphur capping will be used to provide a smooth surface for testing the compressive strength of the no-fines concrete.

This same process will be undertaken on the conventional concrete samples to ensure the testing complies with AS 1012.9. The top surface of these test specimens should not be as rough as the equivalent no-fines specimens as it uses a wider range of aggregate sizes.

7.5.1.2 TESTING PROCEDURE

The following testing procedure was undertaken during the cylinder compression testing:

1. The measuring and testing of test specimens was undertaken as soon as possible after being removed from the fog room.
2. All specimens were tested in a wet condition and excess water removed from the surface.
3. The dimensions of the test specimens were measured and recorded.
4. The platens were cleaned when necessary to ensure no obstruction from small particles or grit.
5. Any loose particles were removed from the uncapped bearing surfaces of the specimens.
6. It was ensured there was no trace of lubricant on the bearing surfaces.
7. The specimens were centred on the bottom platen of the testing machine.
8. The upper platen was lowered until uniform pressure was provided on the specimen.
9. A force was applied at the required rate shown by the rotating disc on the testing machine.
10. The maximum force applied to the cylinder was recorded and the compressive strength calculated: $pressure = \frac{Force}{Area}$

7.5.1.3 RESULTS AND ANALYSIS

The maximum force determined in the cylinder compressive tests and the associated compressive strength is shown in Table 7.1.

Test No.	Specimen Type	Force (kN)	Cross Sectional Area (mm^2)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
1	No-Fines	123	7854	15.7	**18.2**
2	No-Fines	130	7854	16.6	
3	No-Fines	131	7854	16.7	
4	No-Fines	130	7854	16.6	
5	No-Fines	135	7854	17.2	
6	No-Fines	112	7854	14.3	
7	No-Fines	167	7854	21.3	
8	No-Fines	215	7854	27.4	
9	Conventional	317.5	7854	40.4	**39.8**
10	Conventional	318	7854	40.5	
11	Conventional	300	7854	38.2	
12	Conventional	311	7854	39.6	
13	Conventional	317	7854	40.4	

Table 7.1 – Shows the force determined from the testing machine and the cylinder compressive strength of the test specimens

The compressive strength of the no-fines concrete appeared to have a compressive strength much larger than that obtained during the trial mixes. The only difference between test methods was the use of sulphur capping in place of rubber capping. Sulphur capping effectively restrains the top aggregate particles, eliminating the ravelling effect on the surface. This caused the sulphur capped test specimens to yield a higher compressive strength.

This method of testing did not exhibit the same failing-strengthening characteristics found from rubber capping. Although the sulphur capping provides a more accurate measurement for the compressive strength, it does not include the effect of some of the prominent characteristics of the no-fines concrete. The no-fines concrete data obtained from these tests will evaluate the strength of the concrete after the ravelling has occurred or when methods of eliminating this problem are discovered.

There was a large amount of aggregate cracking found on completion of the compressive strength test. The aggregate cracking was more prominent in the no-fines concrete samples made from the first aggregate type. The no-fines concrete samples failed in shear and the following figure shows the test sample after testing. This failure did not appear as prominent in the conventional concrete samples.

Figure 7.3 – Shows the shear failure mechanism of the no-fines concrete (left) and conventional concrete (right) after compressive strength testing

The last mix undertaken was made with a new sample of the same sized aggregate. There is a large variation in the cylinder compressive strength from about 16.5 MPa to slightly more than 27 MPa. All samples had the same curing time and conditions and the only variable was the aggregate sample. Another sieve analysis was conducted on this new aggregate sample to try and explain the large variation in strength.

The compressive strength of the ready mixed concrete was approximately 40 MPa. Although these samples are considerably stronger then the no-fines concrete, a relationship between the two should still be seen.

The following three figures show how the no-fines and conventional concrete samples act under the action of compressive strength testing. It also shows the bonds and the internal actions between the cement and aggregate particles.

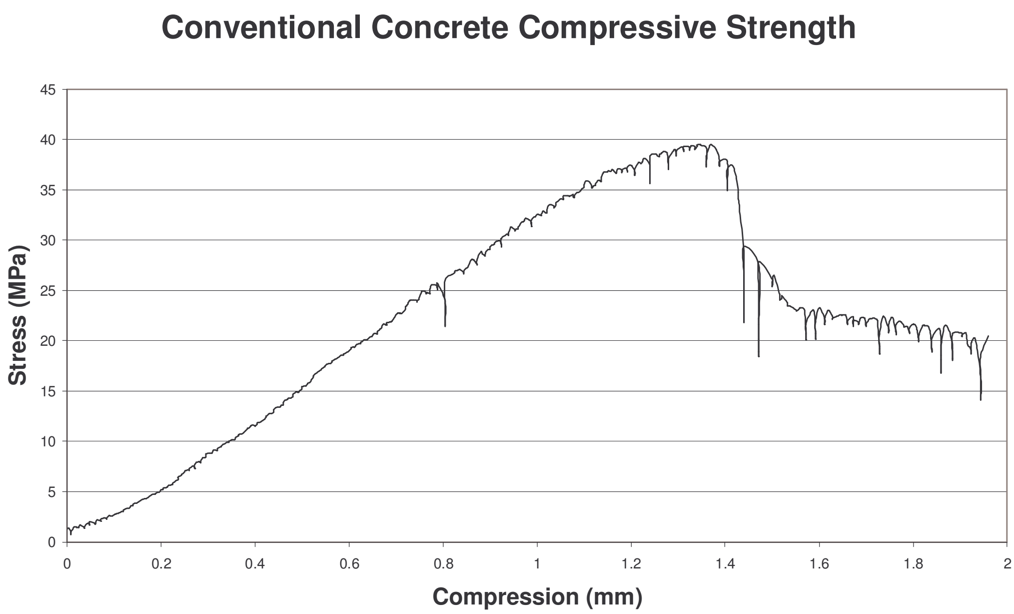


Figure 7.4 – The plot of stress versus compression for the conventional concrete sample

The maximum compressive strength of this plot is 39 MPa with a compression of 1.348 mm at peak stress and a strain of 0.009. The sample appears to lose a large amount of strength just after the maximum strength has been reached. It then flattens out before complete failure.

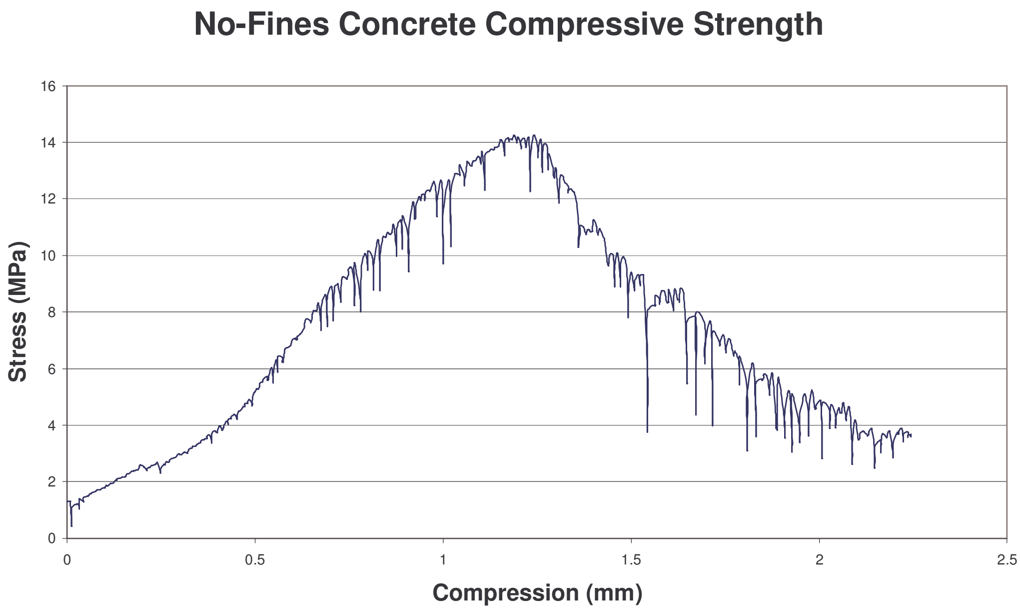


Figure 7.5 – The plot of stress versus compression for a no-fines concrete sample made from the first aggregate

The peak compression of 1.19 mm (strain = 0.0079) occurred when the stress reached 14 MPa. Once the maximum stress was reached, the stress dropped off in a reasonably linear fashion while the compression increased. There were large fluctuations in this section caused by the crushing and failing of the aggregate particles within the no-fines concrete sample.

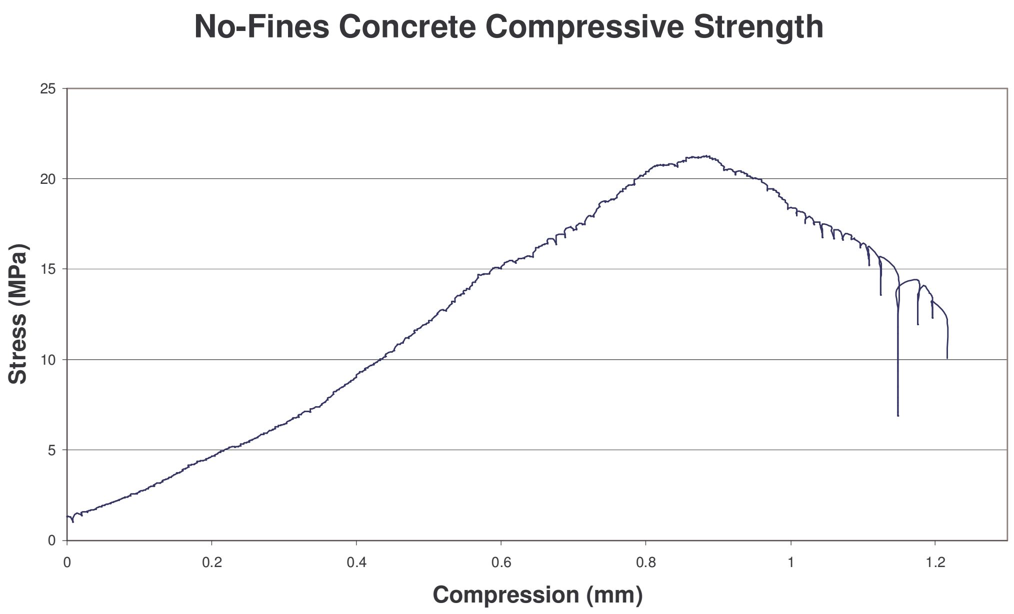


Figure 7.6 – The plot of stress versus compression for a no-fines concrete sample made from the second aggregate sample

The failure of this sample was much more catastrophic then the previous no-fines concrete sample but it also reached a higher compressive strength of 21 MPa. There was a compression of 0.88 mm when the maximum stress was applied. This equates to a strain of 0.0059.

The slopes of all three figures appear to be reasonably similar meaning that the compression capable by the sample is dependent upon the compressive strength of the concrete samples. The small fluctuations that appear in figures 7.4 and 7.6 may be caused by problems with the sulphur capping, internal bond breaking or machine error. The most likely cause is the breaking of the bonds between the aggregate particles. Figure 7.5 shows much larger fluctuations which are caused most probably by the flaky particles crushing under the applied force.

The no-fines concrete samples appear to retain much more strength and have the ability to elongate much greater then the conventional concrete samples. From this information it could be deduced that the no-fines concrete will have better durability properties providing the capacity of the concrete is not dramatically exceeded.

7.5.2 MODIFIED CUBE TESTING

The modified cube test uses the specimens obtained from the completion of the flexural test. The beams are broken approximately in half by the flexural test and tested for compressive strength with the use of two 150 by 150 mm metal plates. This method reduces the number of specimens required to perform the tests. The beam is placed on its side in the compression machine with a metal plate on top and bottom. The compression test is conducted the normal way with the area of interest being the square metal plates of 150 by 150 mm. Capping is not required for this test since the bearing surfaces are a moulded edge which is smooth enough to perform the test.

7.5.2.1 PREPARATION OF TEST SPECIMENS

Since the samples used for the cube test have been used in another test it is important that there are no defects that may affect the results. It was made sure before testing that all the bearing surfaces are clean from loose particles and free from any stress cracks.

The position of the contact points used during the flexural test should be avoided as some local cracking or failure may have occurred and this could dramatically affect the outcome of the compressive test.

7.5.2.2 TESTING PROCEDURE

The following testing procedure was undertaken during the modified cube compression testing:

1. The measuring and testing of test specimens was undertaken as soon as possible after being removed from the fog room.
2. All specimens were tested in a wet condition and excess water removed from the surface.
3. The dimensions of the test specimens were measured and recorded.
4. The platens were cleaned when necessary to ensure no obstruction from small particles or grit.
5. Any loose particles were removed from the uncapped bearing surfaces of the specimens.
6. It was ensured there was no trace of lubricant on the bearing surfaces.
7. The 150 by 150 mm plate was placed on top and bottom of the beam directly opposite each other.
8. The specimens were centred on the bottom platen of the testing machine.
9. The upper platen was lowered until uniform pressure was provided on the specimen.
10. A force was applied at the required rate shown by the rotating disc on the testing machine.
11. The maximum force applied to the cylinder was recorded and the compressive strength calculated: $pressure = \frac{Force}{Area}$

7.5.2.3 RESULTS AND ANALYSIS

The maximum force determined in the modified cube tests and the associated compressive strength is shown in Table 7.2.

Test No.	Specimen Type	Force (kN)	Cross Sectional Area (mm^2)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
1	No-Fines	464	22500	20.6	**23.1**
2	No-Fines	583	22500	25.9	
3	No-Fines	545	22500	24.2	
4	No-Fines	500	22500	22.2	
5	No-Fines	530	22500	23.6	
6	No-Fines	495	22500	22.0	
7	Conventional	797	22500	35.4	**35.7**
8	Conventional	812	22500	36.1	
9	Conventional	806	22500	35.8	
10	Conventional	801	22500	35.6	
11	Conventional	804	22500	35.7	
12	Conventional	802	22500	35.6	

Table 7.2 – Shows the force determined from the testing machine and the compressive strength determined from the modified cube test

It is recognised that the factor for reducing the cube strength to cylinder compressive strength ranges between 0.6 and 0.9. The no-fines concrete samples performed in a recognisable manner with the cube testing possessing 25 percent more compressive strength compared with the cylinders. This proves that the results obtained from the cylinder compressive strength tests are representative of the actual compressive strength of the no-fines concrete.

Figure 7.7 – The failure of the no-fines concrete sample on completion of the Modified Cube Test

The conventional concrete did not possess these same qualities. The cube compressive strength was approximately 10 percent weaker than the strength obtained from the cylinders. The only explanation for this is that the cubes were not able to completely cure due to the fact that they were used from the flexural testing beams.

7.6 INDIRECT TENSILE TEST

The tensile strength of concrete can not be measured directly. This leads to the need to determine the tensile strength through indirect methods. The indirect tensile test is also referred to as the 'Brazil' or splitting test, where a cylinder is placed on its side and broken in the compression machine. This test can also be used to determine the modulus of elasticity of the concrete sample.

7.6.1 APPARATUS

The following apparatus are required to successfully complete the indirect tensile test:

Testing Machine – complying with the appropriate requirements set out in section 6.2.

Testing Jig – will ensure that the specimen can be centred on the lower platen and loaded along the vertical plane.

Bearing Strips – require two tempered grade hardboard, 5 mm thick, 25 mm wide (must comply with AS 2458).

Vernier Calliper – complies with the requirements of AS 1984.

Ruler – 400 mm long, capable of reading to an accuracy of 0.5 mm.

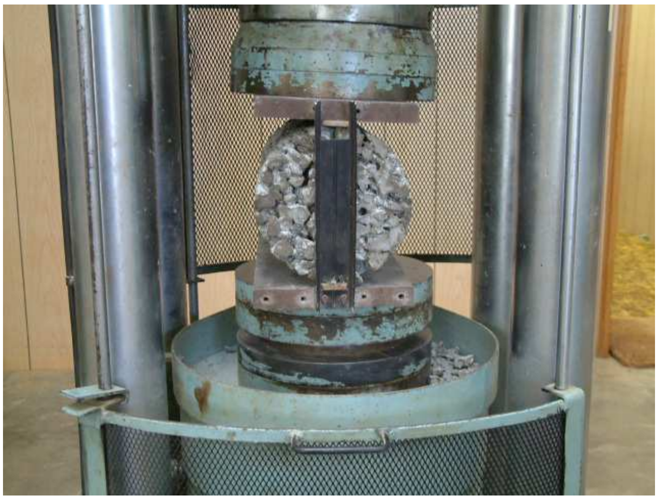


Figure 7.8 – The compression machine is set up for an indirect tensile test

7.6.2 TESTING PROCEDURE

The procedure used to conduct the indirect tensile test follows:

1. The diameter of specimen in the plane in which it is being tested as well as the lengths where the bearing strips are in contact were determined.
2. The bearing strips between the testing jig and the test specimen were aligned.
3. The testing jig was centred in the compression machine and the top platen was lowered.
4. A small force was applied to ensure correct seating was achieved.
5. The force was at the required rate without shock (shown on inner disc of machine).
6. The maximum force applied to the concrete before failure was recorded.
7. The fracture type and appearance of concrete was also recorded.
8. The indirect tensile strength of the specimen was calculated using the following equation: $T = \frac{2P}{\pi LD}$

7.6.3 RESULTS AND ANALYSIS

The results from the indirect tensile test are shown in Table 7.3.

Test No.	Specimen Type	Force, P (kN)	Length, L (mm)	Diameter, D (mm)	Indirect Tensile Strength, T (MPa)	Average Tensile Strength (MPa)
1	No-Fines	116	300	150	1.64	2.21
2	No-Fines	150	300	150	2.12	
3	No-Fines	188	300	150	2.66	
4	No-Fines	111	300	150	1.57	
5	No-Fines	182	300	150	2.57	
6	No-Fines	190	300	150	2.69	
7	Conventional	253	300	150	3.58	3.39
8	Conventional	226	300	150	3.20	
9	Conventional	232	300	150	3.28	
10	Conventional	248	300	150	3.51	

Table 7.3 – Shows the results from the indirect tensile test

The conventional concrete exhibited reasonably similar tensile strength ranging from 3.20 to 3.58 MPa. The no-fines concrete varied more, with tensile strength between 1.57 and 2.69. The no-fines concrete did not have as much tensile strength as the conventional concrete, due to the bonding mechanisms within the concrete samples.

The Characteristic Principle Tensile Strength for the concrete samples were calculated from the average compressive strength using the following code defined equation:

$$f'_{ct} = 0.4\sqrt{f'_c}$$

This produced a tensile strength of 1.7 MPa in the no-fines concrete, while the conventional concrete possessed 2.52 MPa. The average tensile strength determined in the testing were both found to be above the calculated values, so the use of this equation is relevant when considering no-fines concrete.

The following figures show the plots of the tensile strength versus the elongation of the concrete samples.

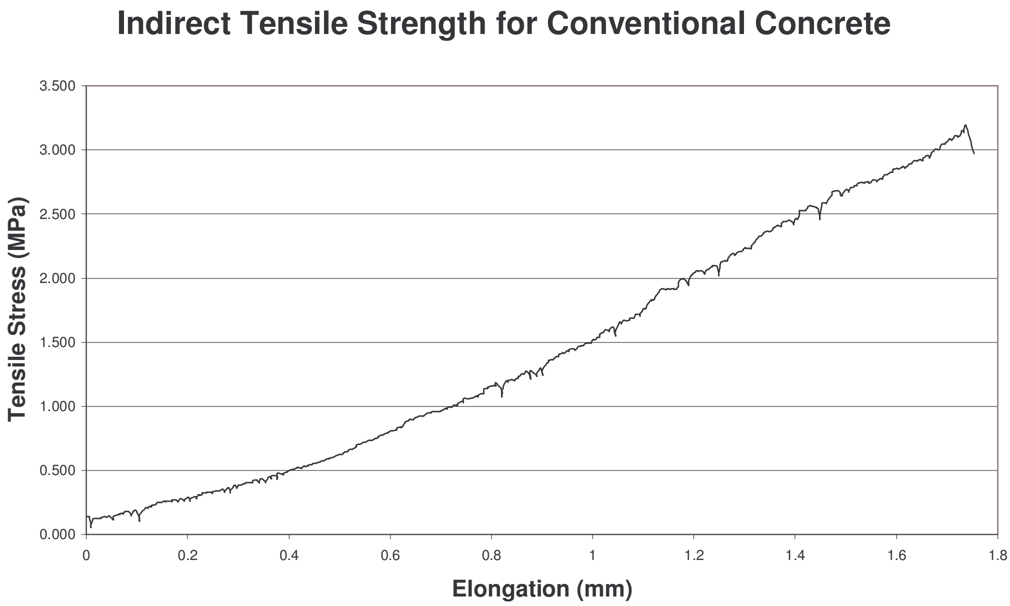


Figure 7.9 – Shows the elongation of the concrete sample under a tensile stress

The maximum tensile strength of the conventional concrete is 3.19 MPa. It deflected 1.753 mm before the specimen failed completely and split the specimen in half.

Figure 7.10 – The failure of the no-fines concrete after an Indirect Tensile Test

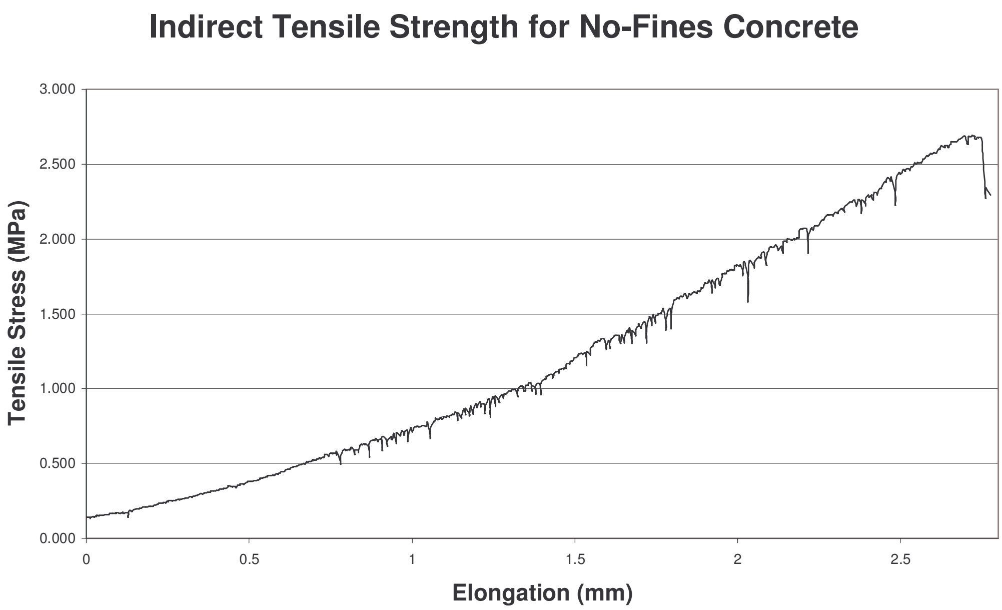


Figure 7.11 – Shows the elongation of the no-fines concrete under a tensile stress

The maximum tensile stress was 2.69 MPa and the no-fines sample elongated 2.776 mm at failure.

The fluctuations are caused by the breaking of internal bonds between the aggregate particles and possibly from aggregate cracking or crushing. This would explain why the variations appear to be larger in the no-fines concrete sample than the conventional concrete.

The no-fines concrete sample elongated more before failure than the conventional concrete. It could be deduced from these results that the no-fines concrete will have better durability than the conventional concrete because it flexes more before failure.

7.7 MODULUS OF RUPTURE

The modulus of rupture is a flexural test that uses a symmetrical four-point loading on a plain, un-reinforced concrete beam. The beams are tested on their side when the concrete is unsegregated as it is representative of the true modulus of rupture. The maximum tensile stress in the bottom fibres of the test beam is known as the modulus of rupture.

7.7.1 APPARATUS

The following pieces of equipment are required to successfully complete this test:

Testing Machine – complies with the appropriate requirements set out in section 6.2

Vernier Calliper – complies with the requirements of AS 1984.

Flexure Testing Apparatus – consisting of the double roller loading and the two roller supports. A diagram of the flexural testing apparatus is shown below.

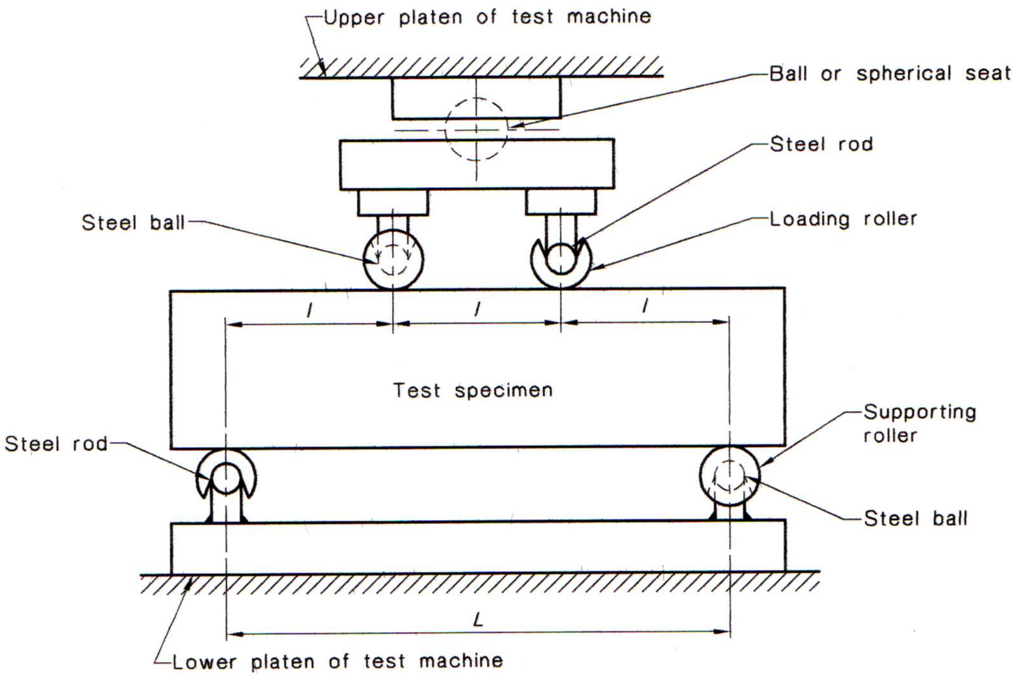


Figure 7.12 – Diagrammatic view of a standard flexure testing apparatus (source: AS 1012.11 – Figure 1)

7.7.2 TEST PROCEDURE

The following procedure used for determining the modulus of rupture complies with AS 1012.11.

1. All grit and excess water from the contact surfaces was removed from the test specimens.

2. The specimen was turned onto its side with respect to the way it was moulded and centred on the supporting rollers.
3. The loading rollers were lowered until they were in contact with the top of the test specimen.
4. A seating load not exceeding 100 N was applied and the roller positions on the side of the specimen were marked.
5. The load was applied without shock at the required rate until the specimen failed.
6. The maximum force applied to the test specimen was recorded.
7. The width and depth of the test specimen at point of fracture was measured.
8. The modulus of rupture was calculated using the following equation:

$$f_{cf} = \frac{PL}{BD^2}$$

7.7.3 RESULTS AND ANALYSIS

The results from the modulus of rupture test determined for the no-fines and conventional concrete is found in Table 7.4.

Test No.	Specimen Type	Force, P (kN)	Length, L (mm)	Depth, D (mm)	Width, B (mm)	Modulus of Rupture, f_{cf} (MPa)	Average Tensile Strength (MPa)
1	No-Fines	18.6	450	150	150	2.48	2.57
2	No-Fines	18.2	450	150	150	2.43	
3	No-Fines	18.8	450	150	150	2.51	
4	No-Fines	21.6	450	150	150	2.88	
5	Conventional	31.8	450	150	150	4.24	4.30
6	Conventional	31.3	450	150	150	4.17	
7	Conventional	33.6	450	150	150	4.48	

Table 7.4 – Shows the data collected and the calculated Modulus of Rupture

The modulus of rupture is a flexural test used to determine the tensile strength of the concrete. The conventional concrete has considerably more tensile strength than the no-fines concrete. This is due to the stronger bonds between the aggregate particles in the conventional concrete and the much higher compressive strength. The no-fines concrete relies on the contact between the aggregate particles and the bonding from the cement for strength.

The following figures are graphs showing the flexural stress versus strain of the conventional and no-fines concrete samples.

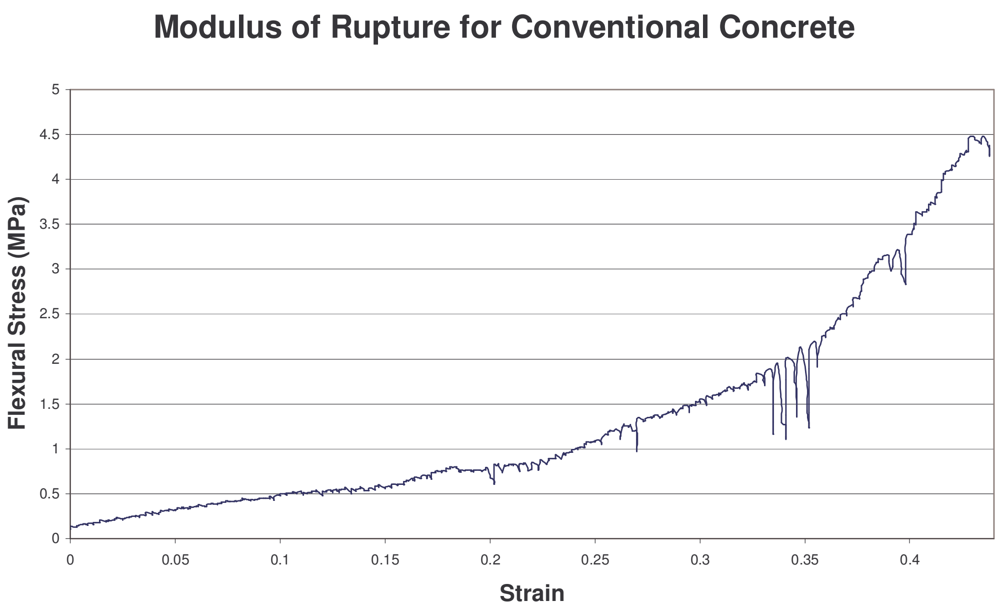


Figure 7.13 – The plot of stress versus strain for the modulus of rupture test on the conventional concrete sample

The maximum strain of 0.438 was obtained after the maximum flexural stress of 4.48 MPa was applied.

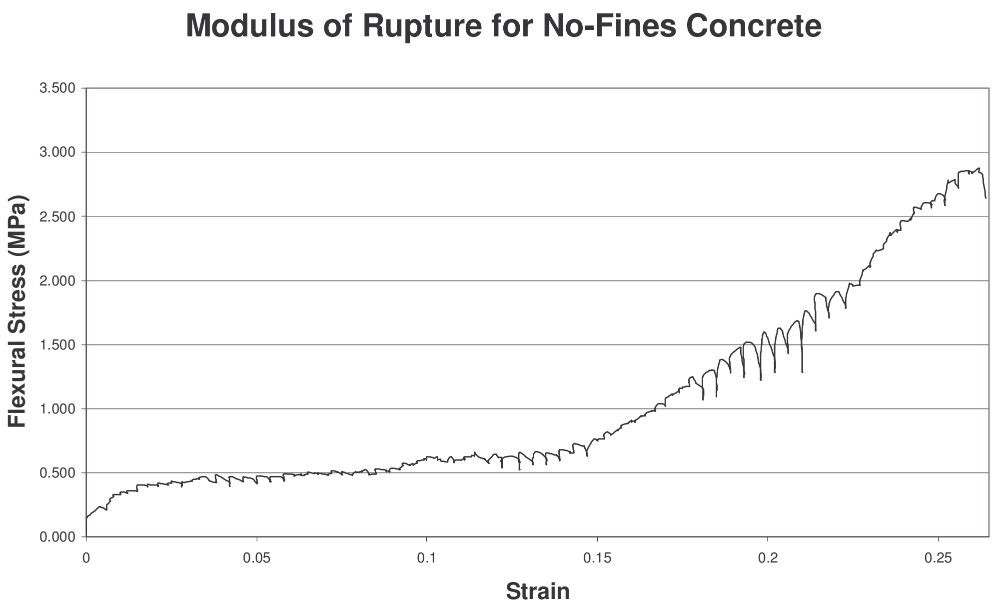


Figure 7.14 – The plot of stress versus strain for the modulus of rupture test on the no-fines concrete sample

The maximum flexural stress of 2.88 MPa was obtained shortly before failure, where a strain of 0.264 was reached.

The Characteristic Flexural Tensile Strength for the concrete samples were calculated from the average compressive strength using the following code defined equation:

$$f'_{cf} = 0.6\sqrt{f'_c}$$

This produced a tensile strength of 2.56 MPa in the no-fines concrete, while the conventional concrete possessed 3.79 MPa. The average tensile strength determined in the testing were both found to be above the calculated values, so the use of this equation is relevant when considering no-fines concrete.

The figures both appear to have flat sections at the start where the specimens are deflecting without a significant change in the load. This continues until the deflection slows down and requires a greater load and it is at this time that these values fluctuate. These fluctuations are occurring as the beam approaches failure, which would be best explained by the breaking of the bonds between the aggregate particles.

The fluctuations are more consistent within the no-fines concrete sample. There are two things that may be causing these variances. These are aggregate cracking, aggregate crushing or the cement bond breaking. The most probable of these is bond breaking as there appeared to be little or no aggregate cracking upon visual inspection.

Figures 7.13 and 7.14 show that no-fines concrete and conventional concrete act in a similar manner when placed under four-point loading. The following figure shows a broken flexural test beam constructed of no-fines concrete.

Figure 7.15 – The no-fines concrete Flexural Test failure on completion of the four-point loading test

7.8 MODULUS OF ELASTICITY

The modulus of elasticity is a method of representing the stress-strain relationship of the concrete sample. It shows how the concrete is reacting to a load and how it is affecting characteristics such as strength.

This is determined by applying a stress not greater than 40 percent of the compressive strength and measuring the strain or deformation on the specimen. The modulus of elasticity of the concrete is dependent upon the modulus of elasticity of the aggregate and the proportion of the aggregate making up the concrete sample.

7.8.1 APPARATUS

The following apparatus were required to complete the test for determining the modulus of elasticity.

Testing Machine – complies with the appropriate requirements set out in section 6.2.

Deformation-measuring apparatus – consisting of a sensing device capable of measuring the deformation to an accuracy of 10×10^{-6} m/m.

Figure 7.16 – Typical compressometer used to measure the longitudinal strain

7.8.2 TEST PROCEDURE

The following procedure was used for determining the modulus of elasticity of concrete complies with AS 1012.17.

1. **Determination of Test Load**

a) The test load was taken as 40 percent of the compressive strength found by averaging at least 2 compressive strength tests.

2. **Loading Procedure**

a) The test was conducted within 30 minutes of removal from the humidity room.
b) The diameter and length of the test specimen were measured.
c) The deformation-measuring device was attached and placed in the compression machine.
d) A small load was applied to ensure correct seating was obtained.
e) The load was applied at a rate of approximately 15 MPa/min.

f) The applied load and the associated deformation from the gauges were recorded.

g) The stress vs. strain was plotted.

7.8.3 RESULTS AND ANALYSIS

The modulus of elasticity is an indication of the concrete's ability to retain its original shape after being subjected to stresses and strains. The following figures show the plots of stress versus strain for conventional and no-fines concrete samples.

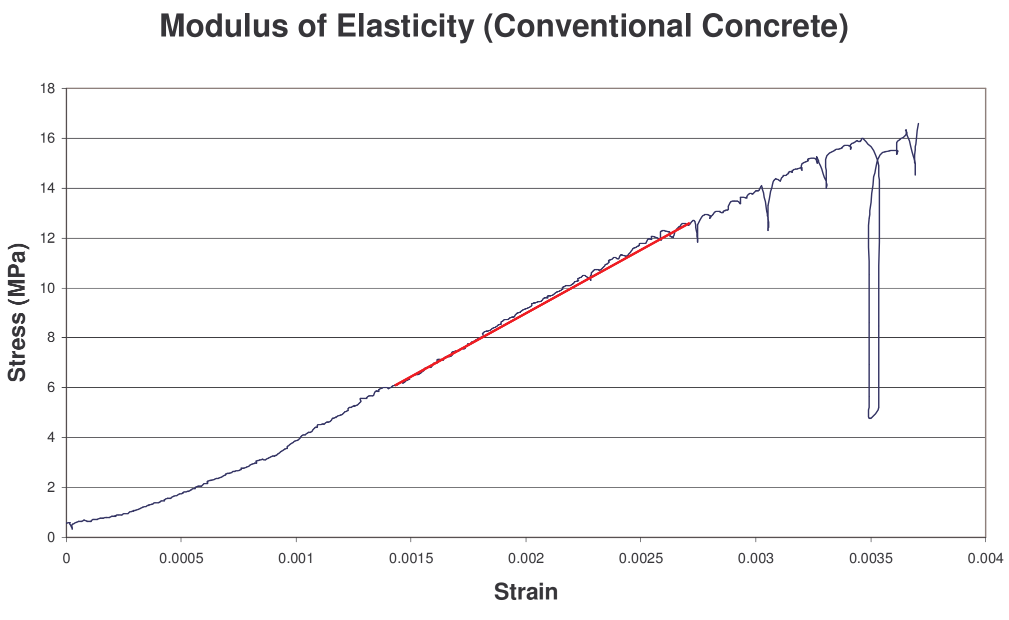


Figure 7.17 – The plot of stress versus strain for a conventional concrete sample used to conduct a Modulus of Elasticity test

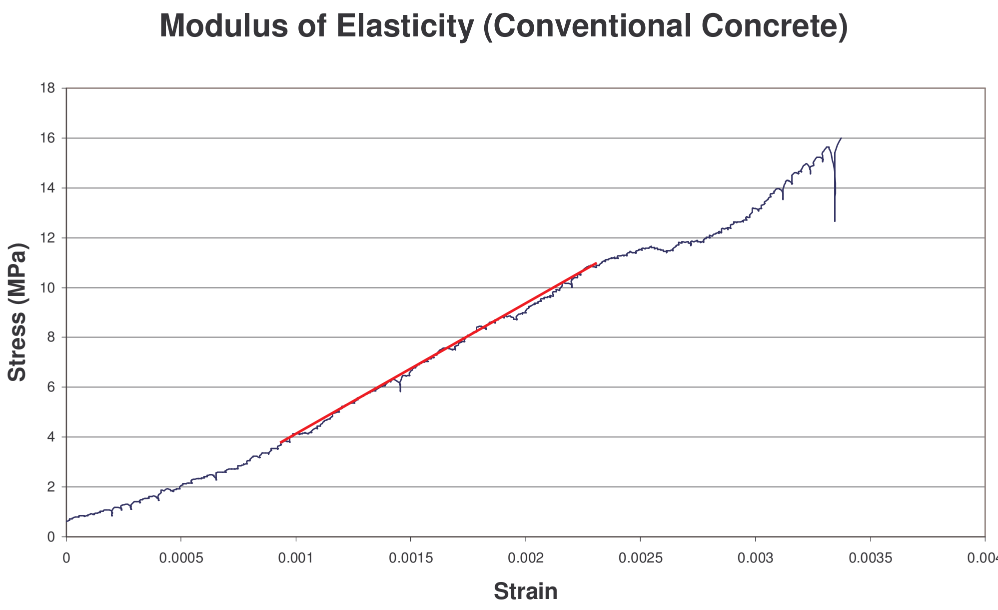


Figure 7.18 – The plot of stress versus strain for a conventional concrete sample used to conduct a Modulus of Elasticity test

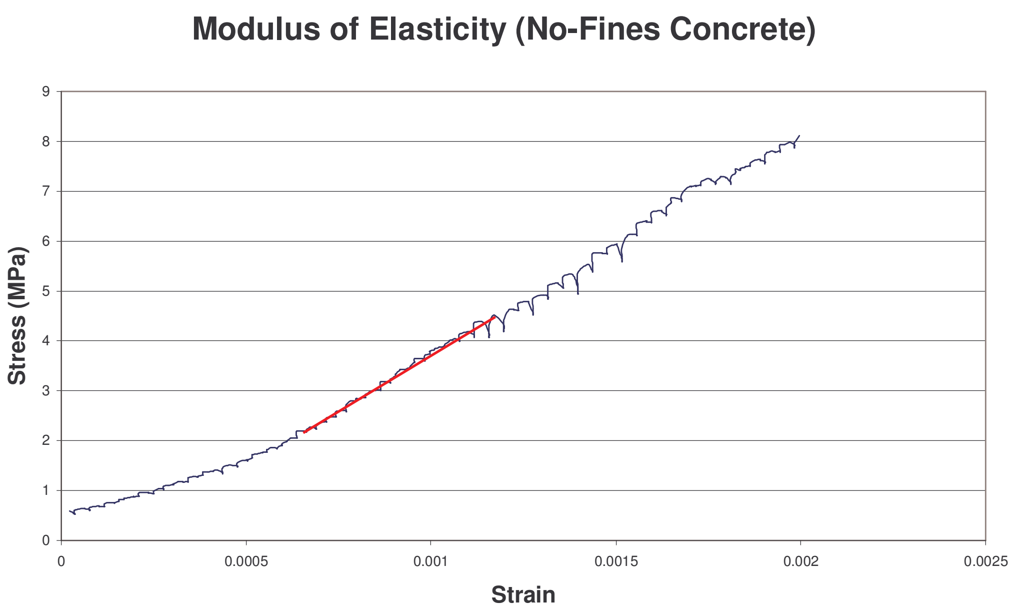


Figure 7.19 – The plot of stress versus strain for a no-fines concrete sample used to conduct a Modulus of Elasticity test

Figure 7.20 – The plot of stress versus strain for a no-fines concrete sample used for a Modulus of Elasticity test

The following results were obtained from the previous four graphs for the no-fines and conventional concrete samples.

Sample Type	E (MPa)
Conventional	5333
Conventional	5122
No-Fines	4425
No-Fines	4695

Table 7.5 – Shows the Modulus of Elasticity for the four previous graphs

The Modulus of Elasticity was higher for the conventional concrete sample than the equivalent no-fines concrete. The difference between the sample types was approximately 500 MPa. This equates to a 12.8 percent increase in the modulus of elasticity.

The lower value of *E* found in the no-fines concrete is due partly to the lower strength and partly to the higher associated strain. A low value of *E* means that the concrete sample is more forgiving or spongy than concrete samples with a high *E*.

This greater sponginess in the no-fines concrete may provide a surface capable of withstanding greater loads by allowing the concrete to act similarly to a flexible road pavement. The no-fines concrete will act in a flexible manner, providing the bonds between the aggregate particles are not being broken by the deformation in the concrete under loading.

The low values of *E* can be contributed to a discrepancy in the testing machine that most likely was not properly calibrated. A much larger extension was being measured by the machine than was actually occurring.

7.9 SKID RESISTANCE

The skid resistance is an important characteristic of every wearing course that is being used by the public. A high skid resistance means that there is sufficient grip for cars and trucks to stop effectively in poor conditions. The surfaces of pavements are most vulnerable in wet conditions as water acts as a lubricant, reducing the skid resistance.

The skid resistance of the no-fines concrete will be compared with that of the conventional concrete. This safety test is becoming more important in this day and age. It is vital that safe and effective road surfaces are provided for all road users. No-fines concrete has the ability to eliminate water from sitting on the surface of the road. This will reduce the risk of aquaplaning and other problems that are common with surface water such as water spray.

7.9.1 APPARATUS

The equipment required to undertake this test follows:

Water Bottle – used to wet the surface before testing.

Portable Skid Resistance Tester – capable of measuring the skid resistance to the required accuracy.

Figure 7.21 – The WF Stanley skid resistance testing machine used to determine the skid resistance of different surfaces

7.6.2 TESTING PROCEDURE

The procedure for determining the skid resistance of different surfaces follows:

1. The tester was placed on the surface to be tested.
2. The base was levelled by the means of three levelling screws.
3. The head was raised so the pendulum arm was clear of the surface.
4. The head of the tester was lowered until it just touched the surface and was able to be rotated until it reached the end of contact.
5. The length of contact was compared with the length of the measuring device provided and the pendulum length was adjusted until the correct length was obtained.
6. The pendulum was raised and clamped horizontally in place.
7. The test area and slider were watered.
8. The pointer was moved to the stop.
9. The pendulum was released and caught on the return swing before it struck the surface again.
10. The value shown by the pointer was recorded.
11. This process was repeated six times and the results averaged.

7.9.3 RESULTS AND ANALYSIS

The skid resistance results for the different concrete surfaces are shown below. The test was conducted three times on each sample in different directions to assess any differences caused by the orientation of the concrete.

Surface:	**No-Fines**	**No-Fines**	**No-Fines**	**Convent**	**Convent**	**Convent**
Reading 1	85	85	82	57	55	53
Reading 2	80	85	82	55	53	52
Reading 3	80	85	82	53	54	53
Reading 4	80	85	82	52	53	53
Reading 5	82	85	82	54	53	54
Reading 6	80	83	82	53	55	53
Average	**81.2**	**84.7**	**82**	**54**	**53.8**	**53**

Table 7.6 – Shows the results of the skid resistance test for the no-fines and conventional concrete surfaces

The values obtained from the skid resistance are a measurement of the resistance to movement. This means that the higher the value the greater the skid resistance.

The skid resistance tests showed that the no-fines concrete has a higher resistance to skidding. The no-fines concrete had an average skid resistance of approximately 83 while the conventional concrete surface provided only 53.5. There is considerable difference between these values and this has shown that the no-fines concrete surface provides a safer wearing course for road users.

This should be tested further in road trials with the recommended placement, compaction and curing procedures. These were adhered to as closely as possible but without the use of a paving machine it will be difficult to assess if the skid resistance will vary from testing to reality.

7.10 VOID RATIO AND PERMEABILITY

The void ratio and permeability of the no-fines concrete was assessed to gauge the effectiveness and extent of the voids.

The void ratio was determined by measuring the mass of water the mould was capable of holding and determining the mass of water with the concrete sample in place. The volume of voids was calculated to be 32 percent of the mould.

This percentage of voids appears quite large and is probably not a clear indication of the voids that will be obtained during construction since the construction pressures and vibration implemented by the paving machine could not be replicated in the laboratory.

The no-fines concrete slab has a reasonably good permeability with about half of the water being poured onto the concrete passing directly down while the remaining water spread out further until it was able to pass through.

7.11 SUMMARY

The cylinder compressive strength of the no-fines concrete samples were approximately 45 percent of the compressive strength in the conventional concrete samples. The average compressive strength for the no-fines and conventional concrete respectively were 18.2 and 39.8 MPa.

The modified cube test produced an average compressive strength of 23.1 MPa for no-fines concrete and 35.7 MPa for conventional concrete. This equates to no-fines concrete possessing approximately 65 percent of the compressive strength of conventional concrete. The relative difference in the compressive strengths found in the cylinder and modified cube test should be similar. However, the results did not show this. This can be explained by the conventional concrete samples used in the modified cube test possessing less strength than the equivalent cylinder test.

The average indirect tensile strength of the no-fines and conventional concrete samples are 2.21 and 3.39 MPa respectively. This equates to 35 percent less tensile strength in the no-fines concrete samples.

The modulus of rupture is another tensile strength test for concrete. The no-fines concrete had a tensile strength of 2.58 MPa and the conventional concrete had a tensile strength of 4.30 MPa. The no-fines concrete had a tensile strength reduction of 40 percent when compared with the conventional concrete. This tensile test produces an increase in strength of approximately 80 percent to the indirect tensile strength test.

The Modulus of Elasticity was higher for the conventional concrete sample than the equivalent no-fines concrete. The difference between the sample types was approximately 500 MPa. This equates to a 12.8 percent increase in the modulus of elasticity for the conventional concrete. The no-fines concrete sample is spongier or more forgiving than the conventional concrete. This characteristic may provide a pavement that performs more effectively than current concrete pavements.

The no-fines concrete has a skid resistance that is 35 percent higher than the conventional concrete sample. This difference is significant enough to allow motorists to stop safely in poor conditions.

The void ratio of the no-fines concrete is approximately 32 percent and it possesses excellent permeability properties that allow the water to flow through the concrete with great ease.

The following chapter assesses whether the objectives of the project have been achieved, the conclusions that have been made and recommendations for further studies.

CHAPTER 8

8. CONCLUSION AND RECOMMENDATIONS

8.1 ACHIEVEMENT OF OBJECTIVES

The objective of this thesis was to determine the applicability of no-fines concrete as a road pavement material. The performance of the no-fines concrete was determined by comparing its properties with those obtained from conventional concrete. The following section provides an overview of the objectives achieved that were set at the commencement of the project.

1. *Research background information relating to the use of no-fines concrete in pavement and non-pavement applications.*

A detailed literature review was undertaken at the commencement of this project (Chapter 2) to gain an understanding of the work previously completed on no-fines concrete in pavement and non-pavement applications. It was found that a limited amount of work had been undertaken assessing the properties of no-fines concrete and its current usage. The research found that no-fines concrete has favourable properties for road pavement applications.

2. *Conduct some initial mix design test to evaluate some possible alternatives. This will include using different water/aggregate/cement ratios.*

The research showed a wide range of aggregate-cement ratios previously used. The aggregate-cement ratios chosen to be trialed were 8:1, 6:1, 4.8:1 and 4.5:1. The concrete possessing the most strength was the 4.5:1 mix. The details of this testing is found in Chapter 4.

3. *Investigate some existing no-fines concrete pavement designs, construction specifications and maintenance procedures.*

Prior to the preliminary mix design being chosen research was undertaken to investigate existing no-fines concrete pavement designs and documented construction and maintenance procedures. Stoney Creek Materials from America provided details of the specifications they used for the construction and maintenance of the no-fines concrete pavements they have designed (Chapter 3).

4. *Determine suitable tests to assess the strength, durability, skid resistance and cost of the above found mix design and normal concrete road surfaces.*

The tests used had to provide a good indication of the properties of no-fines concrete. The tests chosen were compressive strength, tensile, skid resistance and modulus of elasticity tests on the hardened concrete specimens (Chapter 7). Workability and aggregate testing was included to gain a complete picture of the requirements of no-fines concrete, starting with the selection of the aggregate (Chapters 5 and 6).

5. *Conduct the tests and analyse the results to form a conclusion as to the effectiveness of no-fines concrete as a road pavement.*

After testing, the data was analysed and conclusions were drawn. These conclusions are discussed in the subsequent section of this chapter.

8.2 CONCLUSION

There was a considerable difference in the compressive strength between the concrete samples but this does not affect the outcome as it was the relationships between the characteristics that were assessed. The relationships showed that no-fines concrete acts in a manner similar to what was found in the conventional concrete sample.

A major difference found was that the no-fines concrete deformed more than the conventional sample before failure. This shows that a no-fines pavement has the ability to deform under the loading of traffic. The deformation should not affect the performance of the pavement providing its capacity is not exceeded.

No-fines concrete is a viable material that has the potential to replace the use of traditional concrete pavements in situations where heavy traffic is limited, such as car parks, residential streets and driveways. More widespread applications may be possible if methods of reducing the ravelling that occurs within the top aggregate are found.

The varying compressive strengths obtained from the different aggregate samples shows that the shape of the aggregate particles used can dramatically affect the strength of the concrete.

The increased skid resistance that the no-fines concrete possesses is an extremely valuable characteristic that increases the safety of all road users. No-fines concrete has many positive attributes that make its use beneficial to society. However, it is in its early stages of development and requires more research before it is readily available and used extensively.

8.3 RECOMMENDATIONS FOR FURTHER STUDIES

There are an unlimited number of possible topics for further studies but there are a small number that would be particularly useful. Investigation of these may affect the future design and specifications of no-fines concrete pavements.

The most critical element that should be investigated relates to the flakiness of the aggregate particles used. It was found during this project that a small change in flakiness can have a dramatic affect on the compressive strength of the no-fines concrete. The no-fines concrete gained 6 to 8 MPa with a drop in flaky particles of about 2 percent.

This could be taken further by investigating different aggregates like ridge gravels which would have close to no flaky particles, or to investigate the use of recycled aggregates. Alternative materials that can be readily used in no-fines concrete applications could reduce costs and make it more environmentally friendly.

Another line of investigation could entail finding the optimum aggregate size that will provide the greatest strength while not affecting the permeability of the concrete. However, this may be difficult to establish because different applications require different water management capabilities.

Methods of reducing or even eliminating the ravelling that occurs on the surface of no-fines concrete pavements should be investigated. This is one of the major drawbacks associated with the use of no-fines concrete. It is of critical importance that a solution is found that can be readily implemented.

As no-fines concrete pavements are designed by rule of thumb, it may be appropriate to create a design tool to determine the required depth of the different components that make up the pavement. A design graph similar to what is used for the design of asphalt pavements would be effective in reducing problems associated with a lack of knowledge.

REFERENCES

Abadjieva, T & Sephiri, P. Investigations on Some Properties of No-Fines Concrete. Department of Civil Engineering University of Botswana. http://buildnet.csir.co.za/cdcproc/docs/2nd/abadjieva_t.pdf

Australian Standard. AS 1012.2 – 1994. Method 2: Preparation of Concrete Mixes in the Laboratory. Standards Australia Committee.

Australian Standard. AS 1012.3.1 – 1998. Method 3.1: Determination of Properties related to the Consistency of Concrete – Slump Test. Standards Australia Committee.

Australian Standard. AS 1012.3.2 – 1998. Method 3.2: Determination of Properties Related to the Consistency of Concrete – Compacting Factor Test. Standards Australia Committee.

Australian Standard. AS 1012.3.3 – 1998. Method 3.3: Determination of Properties Related to the Consistency of Concrete – VEBE Test. Standards Australia Committee.

Australian Standard. AS 1012.8.1 – 2000. Method 8.1: Method for Making and Curing Concrete – Compression and Indirect Tensile Test Specimens. Standards Australia Committee.

Australian Standard. AS 1012.8.2 – 2000. Method 8.2: Method for Making and Curing Concrete – Flexure Test Specimens. Standards Australia Committee.

Australian Standard. AS 1012.9 – 1999. Method 9: Determination of the Compressive Strength of Concrete Specimens. Standards Australia Committee.

Australian Standard. AS 1012.10 – 2000. Method 10: Determination of Indirect Tensile Strength of Concrete Cylinders. Standards Australia Committee.

Australian Standard. AS 1012.11 – 2000. Method 11: Determination of the Modulus of Rupture. Standards Australia Committee.

Australian Standard. AS 1012.17 – 1997. Method 17: Determination of the Static Chord Modulus of Elasticity and Poisson's Ratio of Concrete Specimens. Standards Australia Committee.

Australian Standard. AS 1141.2 – 1999. Method 2: Basic Testing Equipment. Standards Australia Committee.

Australian Standard. AS 1141.15 – 1999. Method 15: Flakiness Index. Standards Australia Committee.

Australian Standard. AS 1774.19 – 2003. Method 19: The Determination of Sieve Analysis and Moisture Content. Standards Australia Committee.

Ayers, R. 2004. Transport Engineering – Study Book 1. University of Southern Queensland. pp 4.22.

Basavararajaiah, B. S. & Krishna Raju, N. 1975. Experimental Investigations on No-Fines Concrete. Journal of the Institution of Engineers (India. Part CV: Civil Engineering Division. Vol 55. No. Pt. CI 4. March. pp 137-140.

Concrete Network. 2005. Previous Concrete Pavements. http://www.concretenetwork.com/pervious/index.html

Francis, A. M. 1965. Early concrete buildings in Britain. Concrete and Constructional Engrg. London. England. pp 73-75.

Frentress, D., Guptill, N. & Germer D. 2003. Concrete Solutions. Glacier Northwest Inc. Seattle. USA. http://www.glaciernw.com

Fulton, F. S. 1977. Concrete Technology. Cape & Transversal Printers Limited. Republic of South Africa. pp 370-375.

Ghafoori, Nader & Dutta, Shivaji. 1995. Building and NonPavement Applications of No-Fines Concrete. Journal of Materials in Civil Engineering. Vol 7. No. 4. November. pp 286-289.

Ghafoori, Nader & Dutta, Shivaji. 1995. Development of No-Fines Concrete Pavement Applications. Journal of Transportation Engineering. Vol 121. No. 3. May/June. pp 283-288.

Ghafoori, Nader & Dutta, Shivaji. 1995. Laboratory Investigation of Compacted No-Fines Concrete for Paving Materials. Journal of Materials in Civil Engineering. Vol 7. No. 3. August. pp 183-191.

Ghafoori, Nader & Dutta, Shivaji. 1995. Pavement Thickness for No-Fines Concrete Parking Lots. Journal of Transportation Engineering. Vol 121. No. 6. November/December. pp 476-484.

Macintosh, H., Bolten, J. D. & Muir, C. H. D. 1965. No-fines concrete as a structural material. Proc. Instn. Of Engrs. London. England. 5(part I). pp 677-694.

Malhotra, V. M. 1976. No-Fines Concrete – Its Properties and Applications. Journal of the American Concrete Institute. Vol 73. No. 11. pp 628 – 644.

Meininger, Richard C. 1988. No-Fines Pervious Concrete for Paving. Concrete International: Design and Construction. Vol 10. No. 8. August. pp 20-27.

Neville, A. M. 1996. Properties of Concrete. John Wiley & Sons. Inc. New York. USA. pp 711-713.

Orchard, D. F. 1979. Concrete Technology, 4th Edition. Properties of Materials, Applied Science Publishers Ltd, London. pp 160-161.

Pervious Pavement. 2005. http://www.perviouspavement.com/defalt.html

Stoney Creek Materials, L.L.C. 2005. Stoneycrete – Pervious Pavement System. http://www.stoneycreekmaterials.com

APPENDIX A

PROJECT SPECIFICATION

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **PAUL HARBER**

TOPIC: Applicability of No-Fines Concrete as a Road Pavement

SUPERVISORS: Dr Thiru Aravinthan

SPONSORSHIP: Faculty of Engineering & Surveying, USQ

PROJECT AIM: This project involves the investigation of no-fines concrete as a possible safer replacement for existing concrete pavements. The properties will be assessed to determine the suitability of no-fines concrete in pavement applications.

PROGRAMME: **Issue B, 20th June 2005**

1. Research background information relating to the use of no-fines concrete in pavement and non-pavement applications.

2. Conduct some initial mix design tests to evaluate some possible alternatives. This will include using different water/aggregate/cement ratios.

3. Investigate some existing no-fines concrete pavement designs, construction specifications and maintenance procedures.

4. Determine suitable tests to assess the strength, durability, skid resistance and cost of the above found mix design and normal concrete road surfaces.

5. Conduct the tests and analyse the results to form a conclusion as to the effectiveness of no-fines concrete as a road pavement.

A time permits:

6. Consider the effects on the reinforcing steel when exposed to the moisture in the no-fines concrete pavement.

7. Determine methods to stop or reduce these problems, both existing and new innovations.

AGREED: ____________________ (Student) ____________________ (Supervisor)

Dated ___ / ___ / ___

APPENDIX B

RISK ASSESSMENT

RISK ASSESSMENT

Hazard	People at Risk	Probability	Exposure	Possible Consequences	Risk Score	Level of Risk	Controls	Risk after Controls
Hands & arms Catching in Pan Mixer	Operator	Remotely Possible	Occasional	Serious Injury	45	Moderate	Ensure all Safety Guards are in Place	Low
Breathing Cement Powder	People in Vicinity of Cement Powder	Quite Possible	Occasional	Respiratory Problems	90	Moderate to High	PPE (dust mask)	Low
Dropping Testing Equipment	Person Carrying Equipment	Remotely Possible	Frequent	Casualty Treatment	35	Low to Moderate	PPE (safety boots)	Low
Caught in Compression Machine	Operator	Remotely Possible	Frequent	Casualty Treatment	35	Low to Moderate	Ensure all Parts of Your Body are Clear of the Machine Before Operation	Low
Pieces of Flying Concrete During Testing	People in Vicinity of Cement Powder	Quite Possible	Frequent	First Aid Treatment	55	Moderate	Ensure all Safety Guards are in Place and People are Clear of Machine	Low

The above risks were calculated using a Tie Line Risk Calculator.

APPENDIX C

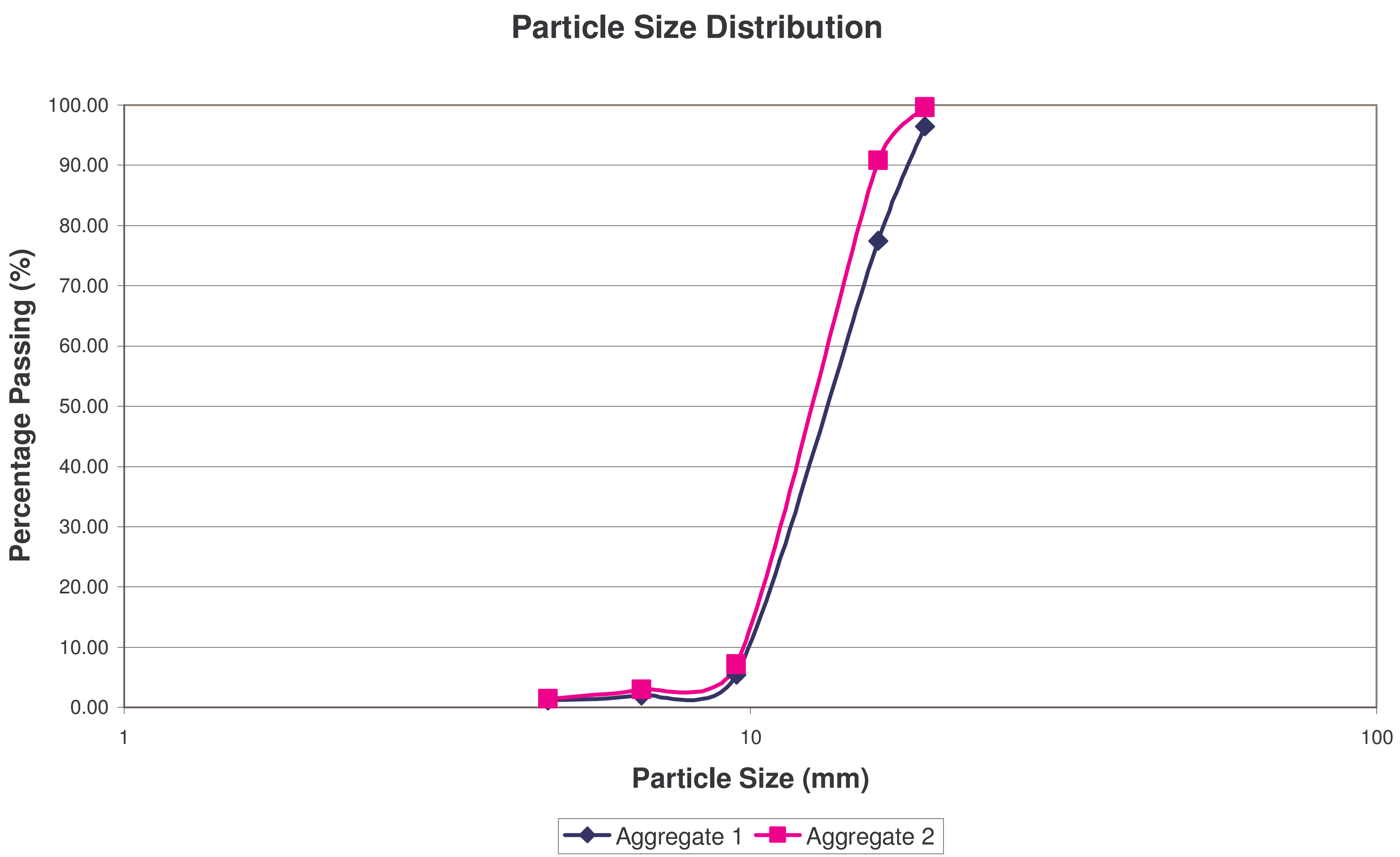
AGGREGATE TESTING

Sieve Analysis

Sieve Size (mm)	Mass Retained (g)	Total Mass (g)	Percentage Retained (%)	Percentage Passing (%)
19	21.09	21.09	0.42	99.58
16	445.09	466.18	9.23	90.77
9.5	4223.31	4689.49	92.86	7.14
6.7	206.62	4896.11	96.95	3.05
4.75	81	4977.11	98.56	1.44
< 4.75	72.89	5050	100.00	0.00
TOTAL	**5050**			

Flakiness Index

Aggregate Size (mm)	M_1 (g)	M_2 (g)	Flakiness Index
19	21.1	0.0	0.00
16	445.1	0.0	0.00
9.5	647.5	114.5	17.69
6.7	206.6	22.9	11.10
4.75	81.0	16.2	20.05
Σ	**1401.3**	**153.7**	**10.97**



Particle Size Distribution
Percentage Passing (%)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1
10
100
Particle Size (mm)
Aggregate 1
Aggregate 2

APPENDIX D

DATA COLLECTED

"TEST METHOD","BASIC COMPRESSION CYLINDER TEST.MSM"
"SAMPLE I. D.","PAULNFC1.MSS"
"SPECIMEN NUMBER","1"

"TIME (S)","EXTENSION (MM)","LOAD (KN)","STRESS (MPA)"

0.150,-0.296,0.168,0.021
0.200,-0.296,0.180,0.023
0.250,-0.296,0.185,0.024
0.300,-0.296,0.185,0.024
0.350,-0.296,0.188,0.024
0.400,-0.296,0.203,0.026
0.450,-0.296,0.218,0.028
0.500,-0.296,0.176,0.022
0.550,-0.296,0.185,0.024
0.600,-0.296,0.186,0.024
0.650,-0.296,0.235,0.030
0.700,-0.296,0.245,0.031
0.750,-0.296,0.260,0.033
0.800,-0.296,0.250,0.032
0.850,-0.296,0.300,0.038
0.900,-0.296,0.302,0.038
0.950,-0.296,0.284,0.036
1.000,-0.296,0.285,0.036
1.050,-0.296,0.297,0.038
1.100,-0.296,0.297,0.038
1.150,-0.296,0.302,0.038
1.200,-0.296,0.284,0.036
1.250,-0.296,0.285,0.036
1.300,-0.296,0.264,0.034
1.350,-0.296,0.280,0.036
1.400,-0.296,0.289,0.037
1.450,-0.296,0.262,0.033
1.500,-0.296,0.277,0.035
1.550,-0.296,0.349,0.044
1.600,-0.296,0.366,0.046
1.650,-0.296,0.425,0.054
1.700,-0.296,0.581,0.074
1.750,-0.296,0.764,0.097
1.800,-0.296,1.019,0.130
1.850,-0.296,1.309,0.167
1.900,-0.296,1.700,0.216
1.950,-0.296,2.175,0.277
2.000,-0.288,2.593,0.330
2.050,-0.280,2.585,0.329
2.100,-0.280,2.551,0.325
2.150,-0.280,2.566,0.327
2.200,-0.280,2.551,0.325
2.250,-0.280,2.543,0.324
2.300,-0.280,2.518,0.320
2.350,-0.280,2.519,0.321
2.400,-0.280,2.533,0.322
2.450,-0.280,2.558,0.326
2.500,-0.280,2.568,0.327
2.550,-0.280,2.640,0.336
2.600,-0.280,2.687,0.342
2.650,-0.280,2.702,0.344
2.700,-0.280,2.748,0.350
2.750,-0.276,2.837,0.361
2.800,-0.276,2.763,0.352
2.850,-0.276,2.754,0.351
2.900,-0.276,2.785,0.354
2.950,-0.276,2.810,0.358
3.000,-0.276,2.795,0.356
3.050,-0.276,2.842,0.362
3.100,-0.276,2.857,0.364
3.150,-0.276,2.949,0.375
3.200,-0.276,2.993,0.381
3.250,-0.276,3.122,0.398
3.300,-0.276,3.240,0.412
3.350,-0.272,3.172,0.404
3.400,-0.272,3.152,0.401
3.450,-0.272,3.167,0.403
3.500,-0.272,3.206,0.408
3.550,-0.272,3.206,0.408
3.600,-0.268,3.221,0.410
3.650,-0.268,3.157,0.402
3.700,-0.268,3.144,0.400
3.750,-0.268,3.114,0.396
3.800,-0.268,3.117,0.397
3.850,-0.268,3.120,0.397
3.900,-0.268,3.109,0.396
3.950,-0.268,3.194,0.407
4.000,-0.268,3.172,0.404
4.050,-0.268,3.223,0.410
4.100,-0.268,3.256,0.415
4.150,-0.268,3.340,0.425
4.200,-0.264,3.268,0.416
4.250,-0.264,3.223,0.410
4.300,-0.264,3.229,0.411
4.350,-0.264,3.243,0.413
4.400,-0.264,3.256,0.415
4.450,-0.264,3.255,0.414
4.500,-0.264,3.332,0.424
4.550,-0.260,3.302,0.420
4.600,-0.260,3.307,0.421
4.650,-0.260,3.275,0.417
4.700,-0.260,3.263,0.415
4.750,-0.260,3.282,0.418
4.800,-0.260,3.278,0.417
4.850,-0.260,3.292,0.419
4.900,-0.260,3.292,0.419
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5.050,-0.260,3.468,0.442
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5.150,-0.260,3.525,0.449
5.200,-0.256,3.503,0.446
5.250,-0.256,3.508,0.447
5.300,-0.256,3.496,0.445
5.350,-0.256,3.557,0.453
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5.450,-0.252,3.508,0.447
5.500,-0.252,3.516,0.448
5.550,-0.252,3.481,0.443
5.600,-0.252,3.505,0.446
5.650,-0.252,3.463,0.441
5.700,-0.252,3.458,0.440
5.750,-0.252,3.466,0.441
5.800,-0.252,3.498,0.445
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5.950,-0.252,3.587,0.457
6.000,-0.252,3.617,0.460
6.050,-0.252,3.637,0.463
6.100,-0.252,3.688,0.470
6.150,-0.248,3.609,0.459
6.200,-0.248,3.604,0.459
6.250,-0.244,3.474,0.442
6.300,-0.244,3.498,0.445
6.350,-0.244,3.443,0.438
6.400,-0.244,3.459,0.440
6.450,-0.244,3.412,0.434
6.500,-0.244,3.441,0.438
6.550,-0.244,3.434,0.437
6.600,-0.244,3.439,0.438
6.650,-0.244,3.426,0.436
6.700,-0.244,3.441,0.438
6.750,-0.244,3.449,0.439
6.800,-0.244,3.480,0.443
6.850,-0.244,3.538,0.450
6.900,-0.244,3.607,0.459
6.950,-0.244,3.620,0.461
7.000,-0.244,3.626,0.462
7.050,-0.244,3.681,0.469
7.100,-0.240,3.659,0.466
7.150,-0.240,3.642,0.464
7.200,-0.240,3.666,0.467
7.250,-0.240,3.668,0.467
7.300,-0.240,3.657,0.466
7.350,-0.236,3.726,0.474
7.400,-0.236,3.708,0.472
7.450,-0.236,3.693,0.470
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7.550,-0.236,3.681,0.469
7.600,-0.236,3.689,0.470
7.650,-0.236,3.676,0.468
7.700,-0.236,3.683,0.469
7.750,-0.236,3.701,0.471
7.800,-0.236,3.748,0.477
7.850,-0.236,3.775,0.481
7.900,-0.236,3.844,0.489
7.950,-0.236,3.894,0.496
8.000,-0.236,3.911,0.498
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8.100,-0.232,3.807,0.485
8.150,-0.232,3.777,0.481
8.200,-0.232,3.765,0.479
8.250,-0.228,3.726,0.474
8.300,-0.228,3.681,0.469
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8.450,-0.228,3.664,0.466
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8.550,-0.228,3.649,0.465
8.600,-0.228,3.639,0.463
8.650,-0.228,3.629,0.462
8.700,-0.228,3.652,0.465
8.750,-0.228,3.701,0.471
8.800,-0.228,3.720,0.474
8.850,-0.228,3.745,0.477
8.900,-0.228,3.763,0.479
8.950,-0.228,3.748,0.477
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9.200,-0.224,3.631,0.462
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9.350,-0.220,3.626,0.462
9.400,-0.220,3.637,0.463
9.450,-0.220,3.614,0.460
9.500,-0.220,3.626,0.462
9.550,-0.220,3.602,0.459
9.600,-0.220,3.657,0.466
9.650,-0.220,3.671,0.467
9.700,-0.220,3.666,0.467
9.750,-0.220,3.693,0.470
9.800,-0.220,3.686,0.469
9.850,-0.220,3.741,0.476
9.900,-0.216,3.708,0.472
9.950,-0.216,3.664,0.466
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10.100,-0.216,3.676,0.468
10.150,-0.216,3.678,0.468
10.200,-0.212,3.688,0.470

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10.450,-0.212,3.664,0.466
10.500,-0.212,3.642,0.464
10.550,-0.212,3.620,0.461
10.600,-0.212,3.622,0.461
10.650,-0.212,3.676,0.468
10.700,-0.212,3.698,0.471
10.750,-0.212,3.726,0.474
10.800,-0.212,3.738,0.476
10.850,-0.212,3.726,0.474
10.900,-0.212,3.730,0.475
10.950,-0.208,3.647,0.464
11.000,-0.208,3.642,0.464
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11.200,-0.204,3.503,0.446
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11.300,-0.204,3.508,0.447
11.350,-0.204,3.493,0.445
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11.500,-0.204,3.500,0.446
11.550,-0.204,3.508,0.447
11.600,-0.204,3.543,0.451
11.650,-0.204,3.594,0.458
11.700,-0.204,3.678,0.468
11.750,-0.204,3.693,0.470
11.800,-0.204,3.681,0.469
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11.950,-0.200,3.683,0.469
12.000,-0.200,3.676,0.468
12.050,-0.200,3.686,0.469
12.100,-0.200,3.694,0.470
12.150,-0.200,3.694,0.470
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12.300,-0.196,3.693,0.470
12.350,-0.196,3.694,0.470
12.400,-0.196,3.708,0.472
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12.500,-0.196,3.684,0.469
12.550,-0.196,3.704,0.472
12.600,-0.196,3.726,0.474
12.650,-0.196,3.730,0.475
12.700,-0.196,3.782,0.482
12.750,-0.196,3.785,0.482
12.800,-0.192,3.693,0.470
12.850,-0.192,3.706,0.472
12.900,-0.192,3.662,0.466
12.950,-0.192,3.674,0.468
13.000,-0.192,3.676,0.468
13.050,-0.192,3.716,0.473
13.100,-0.188,3.672,0.468
13.150,-0.188,3.659,0.466
13.200,-0.188,3.654,0.465
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13.400,-0.188,3.627,0.462
13.450,-0.188,3.602,0.459
13.500,-0.188,3.626,0.462
13.550,-0.188,3.664,0.466
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13.650,-0.188,3.694,0.470
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13.800,-0.188,3.783,0.482
13.850,-0.184,3.711,0.472
13.900,-0.180,3.676,0.468
13.950,-0.180,3.604,0.459
14.000,-0.180,3.575,0.455
14.050,-0.180,3.558,0.453
14.100,-0.180,3.594,0.458
14.150,-0.180,3.589,0.457
14.200,-0.180,3.580,0.456
14.250,-0.180,3.584,0.456
14.300,-0.180,3.584,0.456
14.350,-0.180,3.592,0.457
14.400,-0.180,3.577,0.455
14.450,-0.180,3.620,0.461
14.500,-0.180,3.642,0.464
14.550,-0.180,3.693,0.470
14.600,-0.176,3.738,0.476
14.650,-0.176,3.740,0.476
14.700,-0.176,3.703,0.471
14.750,-0.176,3.726,0.474
14.800,-0.176,3.708,0.472
14.850,-0.176,3.676,0.468
14.900,-0.176,3.678,0.468
14.950,-0.176,3.703,0.471
15.000,-0.176,3.760,0.479
15.050,-0.176,3.795,0.483
15.100,-0.176,3.840,0.489
15.150,-0.176,3.857,0.491
15.200,-0.176,3.904,0.497
15.250,-0.176,3.936,0.501
15.300,-0.172,3.817,0.486
15.350,-0.168,3.741,0.476
15.400,-0.168,3.647,0.464
15.450,-0.168,3.642,0.464
15.500,-0.168,3.642,0.464
15.550,-0.168,3.632,0.462
15.600,-0.168,3.622,0.461
15.650,-0.168,3.592,0.457
15.700,-0.168,3.595,0.458
15.750,-0.168,3.600,0.458
15.800,-0.168,3.575,0.455
15.850,-0.168,3.594,0.458
15.900,-0.168,3.626,0.462
15.950,-0.168,3.659,0.466
16.000,-0.168,3.693,0.470
16.050,-0.168,3.748,0.477
16.100,-0.164,3.762,0.479
16.150,-0.164,3.756,0.478
16.200,-0.164,3.748,0.477
16.250,-0.164,3.751,0.478
16.300,-0.164,3.726,0.474
16.350,-0.164,3.748,0.477
16.400,-0.164,3.773,0.480
16.450,-0.164,3.795,0.483
16.500,-0.164,3.835,0.488
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16.600,-0.164,3.892,0.496
16.650,-0.164,3.891,0.495
16.700,-0.160,3.850,0.490
16.750,-0.160,3.810,0.485
16.800,-0.156,3.755,0.478
16.850,-0.156,3.689,0.470
16.900,-0.156,3.661,0.466
16.950,-0.156,3.631,0.462
17.000,-0.156,3.634,0.463
17.050,-0.156,3.632,0.462
17.100,-0.156,3.641,0.464
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17.200,-0.152,3.463,0.441
17.250,-0.152,3.441,0.438
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17.350,-0.152,3.454,0.440
17.400,-0.152,3.424,0.436
17.450,-0.152,3.429,0.437
17.500,-0.152,3.449,0.439
17.550,-0.152,3.481,0.443
17.600,-0.152,3.469,0.442
17.650,-0.152,3.431,0.437
17.700,-0.152,3.436,0.437
17.750,-0.152,3.424,0.436
17.800,-0.152,3.429,0.437
17.850,-0.152,3.456,0.440
17.900,-0.152,3.444,0.438
17.950,-0.152,3.511,0.447
18.000,-0.152,3.600,0.458
18.050,-0.152,3.626,0.462
18.100,-0.152,3.676,0.468
18.150,-0.152,3.711,0.472
18.200,-0.152,3.782,0.482
18.250,-0.152,3.793,0.483
18.300,-0.152,3.834,0.488
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18.400,-0.144,3.710,0.472
18.450,-0.144,3.710,0.472
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18.550,-0.140,3.374,0.430
18.600,-0.140,3.344,0.426
18.650,-0.140,3.307,0.421
18.700,-0.140,3.375,0.430
18.750,-0.140,3.365,0.428
18.800,-0.140,3.391,0.432
18.850,-0.140,3.441,0.438
18.900,-0.140,3.441,0.438
18.950,-0.140,3.453,0.440
19.000,-0.140,3.474,0.442
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19.100,-0.140,3.490,0.444
19.150,-0.140,3.459,0.440
19.200,-0.140,3.476,0.443
19.250,-0.140,3.466,0.441
19.300,-0.140,3.486,0.444
19.350,-0.140,3.491,0.444
19.400,-0.140,3.558,0.453
19.450,-0.140,3.614,0.460
19.500,-0.140,3.659,0.466
19.550,-0.140,3.728,0.475
19.600,-0.140,3.743,0.476
19.650,-0.140,3.763,0.479
19.700,-0.140,3.798,0.484
19.750,-0.140,3.819,0.486
19.800,-0.140,3.889,0.495
19.850,-0.136,3.805,0.484
19.900,-0.132,3.812,0.485
19.950,-0.132,3.741,0.476
20.000,-0.128,3.668,0.467
20.050,-0.128,3.458,0.440
20.100,-0.128,3.391,0.432
20.150,-0.128,3.391,0.432
20.200,-0.128,3.362,0.428
20.250,-0.128,3.391,0.432
20.300,-0.128,3.391,0.432
20.350,-0.128,3.439,0.438
20.400,-0.128,3.412,0.434
20.450,-0.128,3.459,0.440
20.500,-0.128,3.441,0.438
20.550,-0.128,3.458,0.440
20.600,-0.128,3.448,0.439
20.650,-0.128,3.471,0.442
20.700,-0.128,3.464,0.441
20.750,-0.128,3.466,0.441
20.800,-0.128,3.537,0.450
20.850,-0.128,3.545,0.451

20.900,-0.128,3.641,0.464
20.950,-0.128,3.704,0.472
21.000,-0.128,3.777,0.481
21.050,-0.128,3.780,0.481
21.100,-0.128,3.804,0.484
21.150,-0.128,3.911,0.498
21.200,-0.128,3.950,0.503
21.250,-0.124,3.961,0.504
21.300,-0.120,3.904,0.497
21.350,-0.120,3.894,0.496
21.400,-0.120,3.908,0.498
21.450,-0.116,3.788,0.482
21.500,-0.116,3.575,0.455
21.550,-0.116,3.498,0.445
21.600,-0.116,3.491,0.444
21.650,-0.116,3.474,0.442
21.700,-0.116,3.474,0.442
21.750,-0.116,3.449,0.439
21.800,-0.116,3.458,0.440
21.850,-0.116,3.474,0.442
21.900,-0.116,3.476,0.443
21.950,-0.116,3.480,0.443
22.000,-0.116,3.458,0.440
22.050,-0.116,3.469,0.442
22.100,-0.116,3.443,0.438
22.150,-0.116,3.443,0.438
22.200,-0.116,3.469,0.442
22.250,-0.116,3.491,0.444
22.300,-0.116,3.542,0.451
22.350,-0.116,3.641,0.464
22.400,-0.116,3.694,0.470
22.450,-0.116,3.753,0.478
22.500,-0.116,3.793,0.483
22.550,-0.116,3.822,0.487
22.600,-0.116,3.896,0.496
22.650,-0.116,3.978,0.506
22.700,-0.112,3.978,0.506
22.750,-0.108,3.961,0.504
22.800,-0.108,3.954,0.504
22.850,-0.108,3.961,0.504
22.900,-0.108,3.933,0.501
22.950,-0.104,3.793,0.483
23.000,-0.104,3.592,0.457
23.050,-0.104,3.496,0.445
23.100,-0.104,3.496,0.445
23.150,-0.104,3.505,0.446
23.200,-0.104,3.525,0.449
23.250,-0.104,3.516,0.448
23.300,-0.104,3.553,0.452
23.350,-0.104,3.526,0.449
23.400,-0.104,3.557,0.453
23.450,-0.104,3.537,0.450
23.500,-0.104,3.542,0.451
23.550,-0.104,3.553,0.452
23.600,-0.104,3.542,0.451
23.650,-0.104,3.604,0.459
23.700,-0.104,3.597,0.458
23.750,-0.104,3.642,0.464
23.800,-0.104,3.726,0.474
23.850,-0.104,3.808,0.485
23.900,-0.104,3.847,0.490
23.950,-0.104,3.950,0.503
24.000,-0.104,4.054,0.516
24.050,-0.104,4.141,0.527
24.100,-0.100,4.193,0.534
24.150,-0.100,4.131,0.526
24.200,-0.096,4.106,0.523
24.250,-0.096,4.087,0.520
24.300,-0.096,4.072,0.518
24.350,-0.096,4.047,0.515
24.400,-0.096,4.045,0.515
24.450,-0.096,4.047,0.515
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24.550,-0.092,3.804,0.484
24.600,-0.092,3.745,0.477
24.650,-0.092,3.728,0.475
24.700,-0.092,3.762,0.479
24.750,-0.092,3.735,0.476
24.800,-0.092,3.731,0.475
24.850,-0.092,3.730,0.475
24.900,-0.092,3.745,0.477
24.950,-0.092,3.750,0.477
25.000,-0.092,3.751,0.478
25.050,-0.092,3.748,0.477
25.100,-0.092,3.748,0.477
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25.200,-0.092,3.849,0.490
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25.450,-0.092,4.438,0.565
25.500,-0.088,4.456,0.567
25.550,-0.088,4.430,0.564
25.600,-0.084,4.399,0.560
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25.750,-0.084,4.364,0.556
25.800,-0.084,4.381,0.558
25.850,-0.084,4.364,0.556
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26.100,-0.080,4.060,0.517
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26.200,-0.080,4.057,0.516
26.250,-0.080,4.045,0.515
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26.400,-0.080,4.015,0.511
26.450,-0.080,4.028,0.513
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26.550,-0.080,4.023,0.512
26.600,-0.080,4.060,0.517
26.650,-0.080,4.132,0.526
26.700,-0.080,4.213,0.536
26.750,-0.080,4.372,0.557
26.800,-0.080,4.520,0.576
26.850,-0.080,4.683,0.596
26.900,-0.080,4.804,0.612
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27.050,-0.072,4.779,0.608
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27.150,-0.072,4.752,0.605
27.200,-0.072,4.755,0.605
27.250,-0.072,4.775,0.608
27.300,-0.072,4.762,0.606
27.350,-0.072,4.765,0.607
27.400,-0.072,4.764,0.606
27.450,-0.072,4.733,0.603
27.500,-0.072,4.758,0.606
27.550,-0.068,4.777,0.608
27.600,-0.068,4.782,0.609
27.650,-0.068,4.733,0.603
27.700,-0.068,4.769,0.607
27.750,-0.068,4.733,0.603
27.800,-0.068,4.784,0.609
27.850,-0.068,4.748,0.605
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28.350,-0.064,5.470,0.696
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28.450,-0.064,5.398,0.687
28.500,-0.060,5.422,0.690
28.550,-0.060,5.383,0.685
28.600,-0.060,5.370,0.684
28.650,-0.060,5.370,0.684
28.700,-0.060,5.376,0.684
28.750,-0.060,5.329,0.678
28.800,-0.060,5.311,0.676
28.850,-0.060,5.302,0.675
28.900,-0.060,5.291,0.674
28.950,-0.060,5.333,0.679
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29.450,-0.056,5.729,0.729
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29.650,-0.052,5.776,0.735
29.700,-0.052,5.735,0.730
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29.800,-0.052,5.757,0.733
29.850,-0.052,5.744,0.731
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29.950,-0.052,5.809,0.740
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30.250,-0.048,6.043,0.769
30.300,-0.048,6.021,0.766
30.350,-0.048,6.039,0.769
30.400,-0.048,6.011,0.765
30.450,-0.048,6.083,0.774
30.500,-0.048,6.194,0.789
30.550,-0.048,6.311,0.804
30.600,-0.048,6.461,0.822
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30.700,-0.044,6.563,0.836
30.750,-0.044,6.529,0.831
30.800,-0.044,6.508,0.828
30.850,-0.044,6.496,0.827
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30.950,-0.040,6.472,0.824
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31.250,-0.040,6.336,0.807
31.300,-0.040,6.299,0.802
31.350,-0.040,6.311,0.804
31.400,-0.040,6.380,0.812
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31.500,-0.040,6.605,0.841

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31.650,-0.036,6.732,0.857
31.700,-0.036,6.714,0.855
31.750,-0.036,6.722,0.856
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31.850,-0.036,6.736,0.858
31.900,-0.036,6.830,0.870
31.950,-0.036,6.922,0.881
32.000,-0.036,7.075,0.901
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32.150,-0.032,7.150,0.910
32.200,-0.032,7.169,0.913
32.250,-0.032,7.142,0.909
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32.650,-0.028,7.399,0.942
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32.750,-0.028,7.369,0.938
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32.900,-0.028,7.572,0.964
32.950,-0.028,7.736,0.985
33.000,-0.024,7.839,0.998
33.050,-0.024,7.829,0.997
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33.150,-0.024,7.756,0.988
33.200,-0.024,7.748,0.986
33.250,-0.024,7.746,0.986
33.300,-0.024,7.817,0.995
33.350,-0.024,7.899,1.006
33.400,-0.024,8.027,1.022
33.450,-0.024,8.196,1.044
33.500,-0.020,8.174,1.041
33.550,-0.020,8.136,1.036
33.600,-0.020,8.154,1.038
33.650,-0.020,8.109,1.032
33.700,-0.020,8.090,1.030
33.750,-0.020,8.099,1.031
33.800,-0.020,8.169,1.040
33.850,-0.020,8.258,1.051
33.900,-0.016,8.376,1.066
33.950,-0.016,8.309,1.058
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34.100,-0.016,8.294,1.056
34.150,-0.016,8.275,1.054
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34.300,-0.016,8.424,1.073
34.350,-0.016,8.532,1.086
34.400,-0.016,8.730,1.112
34.450,-0.016,8.946,1.139
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34.550,-0.012,9.040,1.151
34.600,-0.012,9.015,1.148
34.650,-0.012,9.014,1.148
34.700,-0.012,9.047,1.152
34.750,-0.012,9.098,1.158
34.800,-0.008,9.103,1.159
34.850,-0.008,9.081,1.156
34.900,-0.008,9.079,1.156
34.950,-0.008,9.052,1.152
35.000,-0.008,9.064,1.154
35.050,-0.008,9.015,1.148
35.100,-0.008,9.046,1.152
35.150,-0.008,9.030,1.150
35.200,-0.008,9.076,1.156
35.250,-0.008,9.165,1.167
35.300,-0.008,9.287,1.182
35.350,-0.008,9.450,1.203
35.400,-0.008,9.687,1.233
35.450,-0.004,9.673,1.232
35.500,-0.004,9.660,1.230
35.550,-0.004,9.596,1.222
35.600,-0.004,9.584,1.220
35.650,-0.004,9.586,1.220
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36.050,0.000,9.786,1.246
36.100,0.000,9.786,1.246
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36.360,0.000,10.338,1.316
36.700,0.004,10.188,1.297
36.950,0.004,10.137,1.291
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37.350,0.008,8.029,1.022
37.550,0.008,8.023,1.022
37.750,0.008,8.057,1.026
37.950,0.008,8.412,1.071
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42.350,0.048,14.502,1.846
42.550,0.048,14.504,1.847
42.750,0.048,14.998,1.910
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43.550,0.056,15.634,1.991
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43.950,0.060,15.880,2.022
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44.550,0.064,16.668,2.122
44.750,0.068,17.138,2.182
44.950,0.068,17.120,2.180
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45.350,0.072,17.384,2.213
45.550,0.072,17.624,2.244
45.750,0.076,18.111,2.306
45.950,0.076,18.128,2.308
46.150,0.080,18.512,2.357
46.350,0.080,18.436,2.347
46.550,0.080,18.833,2.398
46.750,0.084,18.841,2.399
46.950,0.084,19.033,2.423
47.150,0.088,19.322,2.460
47.350,0.088,19.309,2.458
47.550,0.088,19.948,2.540
47.750,0.092,20.071,2.556
47.950,0.096,20.328,2.588
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51.350,0.120,24.047,3.062
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51.750,0.128,24.850,3.164
51.950,0.128,24.760,3.152
52.150,0.128,24.775,3.154
52.350,0.132,25.553,3.253
52.550,0.132,25.491,3.246
52.750,0.132,25.891,3.296
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53.150,0.136,26.437,3.366
53.350,0.140,26.928,3.428
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55.950,0.160,30.196,3.845
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59.350,0.188,34.667,4.414
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62.350,0.212,38.701,4.928
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62.750,0.216,38.908,4.954
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68.950,0.268,45.924,5.847
69.150,0.272,46.030,5.861
69.350,0.272,45.941,5.849
69.550,0.272,46.387,5.906
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69.950,0.276,46.712,5.948
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71.550,0.288,49.406,6.291
71.750,0.292,49.474,6.299
71.950,0.292,49.970,6.362
72.150,0.296,49.876,6.350
72.350,0.296,50.048,6.372
72.550,0.300,50.345,6.410
72.750,0.300,50.314,6.406
72.950,0.304,50.943,6.486
73.150,0.304,50.814,6.470
73.350,0.304,51.150,6.513
73.550,0.308,52.118,6.636
73.750,0.308,52.135,6.638
73.950,0.312,52.772,6.719
74.150,0.312,52.636,6.702
74.350,0.312,53.113,6.763
74.550,0.316,53.226,6.777
74.750,0.316,53.343,6.792
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75.350,0.320,54.328,6.917
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75.750,0.324,54.929,6.994
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76.150,0.328,56.015,7.132
76.350,0.332,56.158,7.150
76.550,0.332,56.096,7.142
76.750,0.336,55.853,7.111
76.950,0.336,55.760,7.100
77.150,0.336,55.942,7.123
77.350,0.336,57.114,7.272
77.550,0.340,57.379,7.306
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93.550,0.472,88.456,11.262
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93.950,0.476,89.230,11.361
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97.350,0.504,96.006,12.224
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163.350,1.056,134.461,17.120
163.550,1.060,131.495,16.742
163.750,1.060,131.117,16.694
163.950,1.060,130.875,16.664
164.150,1.060,130.994,16.679
164.350,1.060,132.362,16.853
164.550,1.060,134.785,17.161
164.750,1.068,134.487,17.123
164.950,1.072,131.561,16.751
165.150,1.072,130.917,16.669
165.350,1.072,130.622,16.631
165.550,1.072,130.622,16.631
165.750,1.072,131.701,16.769
165.950,1.076,133.207,16.960
166.150,1.080,132.953,16.928
166.350,1.084,132.396,16.857
166.550,1.084,131.260,16.712
166.750,1.084,130.899,16.667
166.950,1.084,130.640,16.634
167.150,1.088,131.167,16.701
167.350,1.088,130.751,16.648
167.550,1.092,130.160,16.572
167.750,1.096,129.061,16.432
167.950,1.096,127.435,16.225
168.150,1.096,127.220,16.198
168.350,1.096,127.075,16.180
168.550,1.096,127.610,16.248
168.750,1.100,128.868,16.408
168.950,1.104,128.188,16.321
169.150,1.108,121.918,15.523
169.350,1.108,119.612,15.229
169.550,1.108,119.468,15.211
169.750,1.108,119.372,15.199
169.950,1.108,119.664,15.236
170.150,1.108,121.218,15.434
170.350,1.108,123.942,15.781
170.550,1.108,127.728,16.263
170.750,1.124,121.092,15.418
170.950,1.124,112.073,14.270
171.150,1.124,107.574,13.697
171.350,1.124,106.709,13.587
171.550,1.124,106.677,13.582
171.750,1.124,106.657,13.580
171.950,1.124,107.557,13.694
172.150,1.124,109.672,13.964
172.350,1.124,112.980,14.385
172.550,1.124,117.612,14.975
172.750,1.124,123.287,15.697
172.950,1.148,115.324,14.684
173.150,1.148,92.574,11.787
173.350,1.148,77.230,9.833
173.550,1.148,66.715,8.494
173.750,1.148,59.759,7.609
173.950,1.148,55.542,7.072
174.150,1.148,53.945,6.868
174.350,1.148,54.004,6.876
174.550,1.148,54.100,6.888
174.750,1.148,54.468,6.935
174.950,1.148,55.845,7.110
175.150,1.148,58.348,7.429
175.350,1.148,62.038,7.899
175.550,1.148,67.012,8.532
175.750,1.148,73.393,9.345
175.950,1.148,81.093,10.325
176.150,1.148,89.916,11.448
176.350,1.148,99.659,12.689
176.550,1.148,109.729,13.971
176.750,1.176,113.124,14.403
176.950,1.176,102.254,13.019
177.150,1.176,96.059,12.231
177.350,1.176,93.812,11.944
177.550,1.176,93.713,11.932
177.750,1.176,93.666,11.926
177.950,1.176,93.962,11.964
178.150,1.176,95.409,12.148
178.350,1.176,97.997,12.477
178.550,1.176,101.784,12.959
178.750,1.176,106.808,13.599
178.950,1.184,110.697,14.094
179.150,1.192,107.416,13.677
179.350,1.196,105.496,13.432
179.550,1.196,99.051,12.612
179.750,1.196,96.821,12.328
179.950,1.196,96.616,12.302
180.150,1.196,96.498,12.286
180.350,1.196,96.873,12.334
180.550,1.196,98.303,12.516
180.750,1.196,100.837,12.839
180.950,1.196,103.934,13.233
181.150,1.216,96.088,12.234
181.350,1.216,78.975,10.055
181.550,1.216,67.460,8.589
181.750,1.216,59.848,7.620
181.950,1.216,55.072,7.012
182.150,1.216,52.929,6.739
182.350,1.216,52.817,6.725
182.550,1.216,52.916,6.737
182.750,1.216,53.146,6.767
182.950,1.216,54.201,6.901
183.150,1.216,56.256,7.163
183.350,1.216,59.386,7.561
183.550,1.216,63.782,8.121
183.750,1.216,69.558,8.856
183.950,1.216,76.625,9.756
184.150,1.216,84.681,10.782
184.350,1.216,93.325,11.882
184.550,1.256,77.338,9.847
184.750,1.256,46.612,5.935
184.950,1.256,27.557,3.509
185.150,1.236,20.250,2.578
185.350,1.232,23.426,2.983
185.550,1.232,27.638,3.519
185.750,1.232,32.756,4.171
185.950,1.232,38.926,4.956
186.150,1.232,46.104,5.870
186.350,1.232,54.227,6.904
186.550,1.232,63.118,8.036
186.750,1.232,71.794,9.141
186.950,1.704,-0.215,-0.027
187.150,1.560,-0.199,-0.025
187.350,1.248,-0.185,-0.024