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The Effect of Low-Grade Aggregates on the Abrasion Resistance of Concrete

Martyn Webb

Doctor of Philosophy

The University of Aston in Birmingham

January 1996

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Summary

This thesis describes a project which has examined the effect of low-grade aggregates on the abrasion resistance of concrete. A literature review is included which highlights previous research relevant to the fields of both abrasion resistance and the use of low-grade aggregates in concrete.

Three types of crushed rock aggregate were appraised, these being Carboniferous Sandstone, Magnesian Limestone and Jurassic Limestone. A comprehensive aggregate testing programme assessed the properties of these materials.

Two series of specimen slabs were cast and power finished using recognised site procedures to assess firstly the influence of these aggregates as the coarse fraction, and secondly as the fine fraction. Each specimen slab was tested at 28 days under three regimes to simulate 2-body abrasion, 3-body abrasion and the effect of water on the abrasion of concrete. The abrasion resistance was measured using a recognised accelerated abrasion testing apparatus employing rotating steel wheels.

Relationships between the aggregate and concrete properties and the abrasion resistance have been developed, with the following properties being particularly important - Los Angeles Abrasion and grading of the coarse aggregate, hardness of the fine aggregate and water-cement ratio of the concrete. The sole use of cube strength as a measure of abrasion resistance has been shown to be unreliable by this work. A graphical method for predicting the potential abrasion resistance of concrete using various aggregate and concrete properties has been proposed. The effect of varying the proportion of low-grade aggregate in the mix has also been investigated. Possible mechanisms involved during abrasion have been discussed, including localised crushing and failure of the aggregate/paste bond.

Aggregates from each of the groups were found to satisfy current specifications for direct finished concrete floors. This work strengthens the case for the increased use of low-grade aggregates in the future.

Keywords:- Abrasion resistance, low-grade aggregates, OPC concrete, floor slabs.

To Helen

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Chapter 1 Introduction

1.1 Background to the Project

The rationale behind the current research project was to bring together two separate fields of research that have been carried out over the last ten years, the first being the investigation of abrasion resistance at Aston University, and the second being an on-going project at the Building Research Establishment (BRE) examining the utilisation of lower-grade materials in concrete. Summaries of these research projects are given below.

1.1.1 Abrasion Resistance

The abrasion resistance of concrete has been examined by many different research workers using a wide variety of test methods, which has conspired to make comparison of data difficult. This problem was overcome, to a certain extent, by a comprehensive research programme carried out at Aston University. The primary aims of this work were to develop a standardised test apparatus and test method and to determine the principal factors affecting abrasion resistance. Rather than adopt yet another new test and procedure, an existing apparatus was chosen for subsequent use that met all the performance criteria required for the project (Sadegzadeh, 1985). The apparatus was based on a design that had been developed by the Cement and Concrete Association (C. & C.A., 1980) and initial work conducted between the two laboratories confirmed that the results obtained would be both repeatable and reproducible. An extensive laboratory test programme followed which explored, on a macroscopic scale, the influence of mix design, finishing techniques, curing regimes and surface treatments on the abrasion resistance of concrete. A microstructural study, using techniques such as mercury intrusion porosimetry, microhardness and scanning electron microscopy, showed the quality of the surface layer to be of primary importance when an abrasion resistant finish was required. Non-destructive tests such as ultrasonic pulse velocity, Schmidt rebound number and initial surface absorption were undertaken, to see if there was a non-destructive way of accurately assessing abrasion resistance. Only the initial surface absorption test (ISAT) proved to be sensitive to the factors shown to influence abrasion resistance. Comparisons were also made between the results from laboratory prepared specimens and those from warehouse floors currently in use, which led to the development of abrasion criteria for concrete slabs in a medium industrial environment. Parallel work by Chaplin (1987) at the C. & C.A. (now the British Cement Association) produced similar criteria for floor performance, and these values have been related to floor classifications in BS 8204: 1987 in The Concrete Society Technical Report 34 - Concrete Industrial Ground Floors (The Concrete Society, 1994). All subsequent work has utilised the basic apparatus and test procedure developed during this research programme.

More recent work (Phitides, 1991) has investigated the effect of cement replacement materials on the abrasion resistance of concrete. This showed that positive curing was critical for mixes containing these materials, particularly those containing ground granulated blast-furnace slag (ggbfs). It was also demonstrated that for concretes containing pulverised fuel ash (pfa) up to levels of 40 per cent, the level of cement replacement was not critical providing the mix designs were adjusted to achieve a constant strength level. There was also evidence that the 3 and 6 month abrasion depths were less than those obtained at 28 days, implying that cement replacement materials in concrete could lead to better long term performance in floor slabs.

1.1.2 Low-Grade Aggregates

The use of crushed rock aggregates in concrete has long been the subject of research at the BRE, Watford. The first major work from this research programme investigated the characteristics of concrete made with coarse and fine crushed rock aggregates from 24 quarries in the United Kingdom representing many types of rock. The report (Teychenné, 1978) concluded that good quality concrete could be made with all the aggregates, and that materials often considered to be of too poor quality for use in concrete may in fact be quite suitable for that purpose. Subsequent work (Collins, 1986, 1989, 1991) has looked specifically at three types of crushed rock aggregate, Carboniferous Sandstone, Magnesian Limestone and Jurassic Limestone. None of these aggregates have been used extensively in concrete, but it has been shown that they can be successfully used to make satisfactory concrete. With environmental pressures increasing, both in terms of reducing quarry expansion and for the increased use of marginal materials, these aggregates could provide a significant contribution to aggregate supply particularly for less demanding applications. On-going research is investigating further uses for these and other low-grade materials so that all aggregate resources can be used in the most efficient way possible.

A combination of these two fields of research should not only investigate the potential use of these aggregates in ground floor slabs, it would give the opportunity to explore the effects of the different aggregates and their properties on the abrasion resistance of concrete.

1.2 Aims of the Project

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

- To determine the effect of low-grade coarse aggregate properties on the abrasion resistance of concrete, and the role of the coarse aggregates in the wear process.
- To determine the effect of low-grade fine aggregate properties on the abrasion resistance of concrete, and the role of the fine aggregates in the wear process.
- To investigate the effect of moisture on the abrasion resistance of concrete.
- To investigate the difference between two-body and three-body wear of concrete.

Additional aims were to examine the effects of varying the low-grade aggregate content, for both coarse and fine fractions, and to examine the mechanisms involved during the abrasion of concrete.

1.3 Thesis Outline

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

1.3.1 Literature Review

This presents a review of available research literature concerning factors considered relevant to the current project. Subjects covered include different types of wear and wear mechanisms, factors which affect the abrasion resistance of concrete and the different test methods for assessing the abrasion resistance of concrete. An assessment is also included of the properties of low-grade crushed rock aggregates and their influence on concrete, and the environmental factors which are beginning to significantly affect current sources of aggregate supply, and which will affect aggregate supply in the future.

1.3.2 Test Methods and Procedures

Methods or standards are given for all the aggregate and concrete tests, including the microscopic tests. The accelerated abrasion test apparatus, the method of specimen fabrication and the methods of testing 2-body, 3-body and wet abrasion resistance are described in detail.

1.3.3 Material Characteristics

The geological history of each aggregate group is discussed, together with the geological descriptions for each individual aggregate source. The results of the tests described in

Chapter 3 are presented and discussed, and any interrelationships shown. The grading characteristics of aggregate groups are compared with current standards.

1.3.4 Test Results

Details of all the trial mixes are given, together with the final mix design for coarse and fine aggregate mixes. Results of the tests for cube strength and abrasion resistance for all coarse and fine aggregate mixes are presented, together with a preliminary discussion which compares the results of each aggregate group with each other and with current standards. The results of the microscopic analyses are presented and discussed.

1.3.5 Discussion

Initially, relationships between the properties of all aggregate types and abrasion resistance are discussed, for both coarse and fine aggregate mixes. Relationships between parameters are presented with a correlation coefficient and a significance level pertaining to the number of points on the graph. This is followed by the effect of individual aggregates, and the effect of varying the low-grade aggregate content on the abrasion resistance of concrete. Possible wear mechanisms are discussed.

1.3.6 Conclusions and Recommendations for Further Research

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

1.3.7 Appendices

The appendices contain information which is deemed non-essential to the main part of the thesis. Included here are the original data from the abrasion resistance testing programme and details of quarry location and ownership.

Chapter 2 Literature Review

2.1 Introduction

This chapter provides a review of the available literature concerning subjects allied to the current project. Initially wear and wear mechanisms are examined, with an emphasis on brittle materials such as concrete. Factors affecting the abrasion of concrete are explored, and the different test methods are described. The latter part of the review summarises the properties of low-grade crushed rock aggregates, and their uses in concrete. A possible future strategy for the use of these materials is discussed.

2.2 Wear

Lansdown and Price (1986) have defined wear as the progressive loss of material from the operating surface of a body occurring as a result of relative motion at the surface, whereas Scott (1983) simply described wear as the undesired displacement or removal of surface material. Burwell (1957) has described four major types of wear and three minor types of wear, and these still provide the basic classification for wear processes.

2.3 Major Types of Wear

2.3.1 Adhesive Wear

Based upon theories by Bowden and Tabor (1954) and Archard (1953) adhesive wear principally affects ductile materials. Macroscopically smooth surfaces tend to be rough on a microscopic scale. When these 'smooth' surfaces are brought into contact, the contact will only be made in a few places. Consequently the applied load will produce very high localised pressure and, if the yield stress is exceeded, plastic deformation will occur until the contact area is large enough to support the applied load. If lubricants or surface films are absent the two surfaces may bond together. Continued sliding will cause this bond to shear, leading to the transferral of the resultant particle. Although this constitutes a wear process in itself, more severe wear under these conditions is caused by the transferred particles becoming loose particles, and hence having an abrasive effect. It is thought that the production of these loose particles is due to the repeated compression and tension of an asperity tip. Eventually it becomes sufficiently weakened to be dislodged (Lansdown and Price, 1986).

2.3.2 Abrasive Wear

Abrasive wear has been described as probably the most serious single cause of wear in engineering practice (Scott, 1983). The general concept of abrasive wear is the ploughing or gouging of softer material by a harder surface, and it can happen in one of two situations:-

- A hard rough surface slides against a smoother, softer surface resulting in scratching and indentation.

- Abrasion is caused by loose hard particles sliding between rubbing surfaces.

These two modes of wear have been described as 2-body and 3-body abrasive wear respectively by Burwell (1957).

Rabinowicz (1965) has illustrated that even an apparently smooth surface will contain troughs and peaks on a microscopic scale. The troughs on this microscopic 'rough' surface have been described as Abbot's Volumes by Godet (1984). The initial phases of wear would be 2-body wear as the surfaces rub together. Debris produced from this action would collect in the Abbot's Volumes, which eventually fill and overspill, thus allowing 3-body wear conditions to prevail. It is possible that both 2-body and 3-body wear mechanisms may co-exist in one contact. It has also been noted by several workers (Rabinowicz, 1961; Godet, 1984; Misra and Finnie, 1981) that 2-body abrasion often causes more severe wear than 3-body abrasion. This is attributed, in the case of metals, to the third body particles rolling and recirculating for much of the time rather than abrading.

Most work in this field has used rough surfaces and/or abrasive particles that are harder than the surface whose wear is being studied. If the wearing surface is harder than the abrading material, abrasive wear still occurs, but at a greatly reduced rate (Misra and Finnie, 1980). Further to this, Moore (1974) stated that soft angular abrasive particles produced more wear than hard rounded particles, implying that particle shape is of more significance than the hardness of the particles.

Abrasive wear theory can be applied to brittle solids such as concrete as well as metals, although the subject has not been researched as thoroughly as the wear of metals. The fracture mechanisms that occur in brittle materials during abrasion may cause the rate of material removal to be about 10 times that for ductile solids (Moore and King, 1980). They have also stated that the effects on wear of both the size and of the type of the abrasive particles are very much greater for brittle solids than for ductile materials. Deterioration of the third body is also an important factor in determining wear rates of brittle materials.

2.3.3 Corrosive Wear

Corrosive wear occurs as a result of sliding in a corrosive environment, either gaseous or liquid. Chemical reactions take place which may result in reaction products forming on one or both surfaces. As the reaction products are often loosely bonded to these surfaces further sliding may cause their removal, enabling the removed particles to act as an abrasive. Corrosive wear therefore has an element of both adhesive and abrasive wear within a chemically active environment. As the wear rate of a corroded surface will often be higher than that of an uncorroded surface, and the corrosion of a worn surface will often be higher than that of an unworn surface, the total rate of material loss can become very high very quickly. This form of wear applies almost exclusively to metals.

2.3.4 Fracture Wear

Two types of fracture wear have been described. The first, rolling contact fatigue, occurs principally in cyclical situations, and the second, brittle fracture wear, occurs in brittle materials under either sliding or rolling conditions.

2.3.4.1 Rolling Contact Fatigue

Rolling contact fatigue is characterised by the sudden removal of surface material or fracture due to the repeated application of stress cycles, where stresses are individually within the elastic limit of the material (Arnell *et al.*, 1991). This form of wear generally initiates with the formation of surface or near-surface cracks. These cracks are associated with the zone of maximum stress in the material due to the applied load, *Figure 2.1.* Surface cracks tend to form transverse to the direction of rolling, propagate down into the material and subsequently run parallel to the surface as they become influenced by the zone of high stress. As these cracks join up surface material may become detached and form a pit on the surface, *Figure 2.2a.* Sub-surface cracks initiate at depths associated with the zone of maximum stress, and propagate parallel to the surface, again leading to the removal of material, *Figure 2.2b.*

2.3.4.2 Brittle Fracture

Most studies of fracture wear, such as Rabinowicz (1965) and Grover (1961), have been concerned with metals, but the basic principles have been extended to brittle solids such as concrete.

Avram (1980) undertook an extensive study of the failure of concrete due to cyclic loading and concluded that the behaviour of concrete, under loading, represents the complex inner response of the material to an external action. This response was attributed to the combined action of the following factors quoted from Avram (1980):-

- The specific behaviour of the concrete to different kinds of stresses.

- The multi-phase, heterogeneous and varied structure of the material.

- The intricate structure of the binder, which includes many mineralogical compounds whose hardening conditions are interacting upon one another.

- The complexity of phenomena taking place at the matrix-aggregate interface, which causes concrete cohesion.

- The effects of concrete preparation and casting conditions.

- The temperature and environmental curing conditions during concrete maturation.

- The loading conditions, including the shape and rate of the loading cycles.

- The time kept under the maximum load.

As part of the same study, he postulated the forces exerted on an idealised aggregate particle in concrete during a loading cycle, and the locations of possible aggregate/paste bond failure due to the compressional and tensional forces. These features are shown in *Figure 2.3.*

Mindess and Young (1981) found the aggregate/paste bond to be equally important during the cyclic loading of concrete, and have attributed fatigue failure of concrete to its composite nature. The modulus of elasticity for the aggregate, paste and concrete are all quite different. Consequently, their differential response in concrete to an applied stress leads to inelastic behaviour, and a highly non-linear stress-strain curve. The inelastic behaviour was not only due to the composite nature of the concrete, but also to the quality of the aggregate/paste bond.

Microcracks are inevitably present in concrete, both within the body of the paste and at the interface with aggregate particles. These cracks may be due to bleeding and segregation, and/or changes within the paste during hydration. When the concrete is loaded, the stresses at the tips of these microcracks can become very large, exceeding the cohesive strength of the paste (or aggregate/paste bond). Under repeated cycles of loading these cracks will tend to grow. The energy supplied by repeated loading will eventually make the damage at the crack tips worse, and the crack may propagate sufficiently to cause failure (Griffith, 1924).

2.4 Minor Types of Wear

The following have been described as minor types of wear by both Burwell (1957) and Arnell *et al.* (1991). They can be the main form of wear in certain situations, but are generally additional to the modes of wear outlined in Section 2.3.

2.4.1 Fretting

This is the result of small reciprocating movements between the two moving surfaces. This movement usually exacerbates wear caused by adhesion, abrasion, corrosion or a combination of the three.

2.4.2 Erosive Wear

This can occur when sharp particles impact a surface and remove material, producing a surface roughness. The difference from abrasive wear is that the impacting particles may remove material from low points as well as from the high points. With ductile materials low angles of impact cause maximum damage, whereas impacts normal to the surface cause maximum damage in brittle materials.

2.4.3 Cavitation Erosion

Cavitation erosion occurs when a solid and fluid are in relative motion and bubbles, formed in the fluid, become unstable and implode against the surface of the solid. Repetition of this process may lead to crack formation and eventually to the removal of particles, and is a common form of wear in closed conduits.

2.5 Factors affecting wear

Although there are many types of wear mechanisms, and combinations thereof, there are some factors which are important in determining the nature of wear in general. These are briefly described.

2.5.1 Load and Speed

The applied load and speed are two factors which can be considered together, and whose effects have been comprehensively described by Burwell (1950). Relative rubbing speed is the speed at which two surfaces traverse each other whilst in contact. The relative rubbing speed under pure (theoretical) rolling is zero, but it is high if a large amount of slip is present. Rolling speed is described as the speed at which the applied load passes over the surface being worn, and it regulates the frequency with which surface to surface contact is made. Under impact loading there is also a speed component of the two surfaces normal to each other. Rolling speed, together with the velocity of surface movement normal to each other, and the frequency and magnitude of load, all determine the speed and frequency with which a compressive stress is applied to a point on the surface. In hard materials this loading may lead to fatigue failure (Buckingham and Talbourdet, 1950).

2.5.2 Lubrication

Rabinowicz (1965) has defined a lubricant as a substance which is capable of altering the nature of the surface interaction between contacting solids. He sub-divided lubrication into two types, fluid lubrication and boundary lubrication. Fluid lubrication occurs when a thick film of liquid or gas completely separates two solids, whereas boundary lubrication is the situation that occurs when a lubricant layer is present but is of insufficient thickness to prevent the occasional asperity contact through the film. Lubricants are generally introduced into a system to reduce the interaction between contacting surfaces, and may be used to reduce the amount of wear by reducing frictional forces by primarily reducing surface adhesion. There are, however, certain situations when lubricants can increase wear. It is possible that lubricants may trap loose abrasive particles, thus preventing them from being removed from the contact area as wear continues. The abrasive particles are then subjected to repeated loading, and may fracture to produce sharper particles and so a form of grinding paste.

2.5.3 Temperature

Temperature has its greatest effect on the wear of metals (Halling, 1983). In general, the hardness of metals is temperature dependent, the higher the temperature the lower the hardness. Thus there is a tendency for asperities to adhere and the wear rate to increase with increasing temperature. Higher temperatures can also reduce the viscosity of lubricants leading to poorer lubrication and a possible increase in wear, although the use of lubricants can also lower the surface temperature and so lower the rate of wear.

2.5.4 Hardness

Holm (1950) has stated that wear increases if the hardness values for the contacting surfaces approach each other, and will become excessive when both elements are of the same material. The reason for this being that the elements have the same tendency to deform, so that the degree of deformation readily increases. Halling (1983) has shown that many metals start to show severe wear when the nominal contact pressure, that is the applied load divided by the apparent area of contact, becomes greater than one third of the hardness value. This is attributed to gross plastic deformation beneath the contact zones. It has been shown by Lansdown and Price (1986), that hardness is of significance during abrasive wear. Not only does it affect the softer of the two contacting surfaces, it determines the behaviour of loose abrasive particles. If these particles are harder than one of the contacting surfaces they could become embedded in this softer surface rather than remaining loose, thus changing the mode of wear from 3-body abrasive wear to 2-body abrasive wear.

2.5.5 Surface Films

The presence of surface films are particularly beneficial in reducing adhesive wear (Lipson, 1967). These surface films typically consist of chemical reaction products such as oxides, chlorides and sulphides, that possess low shear strength and bond well to the harder base material. The low shear strength of the surface film enables shearing damage to be localised to the film itself, thus reducing the effect upon the base material.

2.5.6 Presence of Abrasive Materials

The presence of abrasive particles leads to the 3-body abrasive wear condition. The abrasive particle, or third body, adheres temporarily or becomes embedded in one of the sliding surfaces. When the abrasive particles are very small, or of softer material than the sliding surfaces, 3-body abrasion will not occur (Rabinowicz, 1965). Mulhearn and Samuels (1962) have shown that when the size of the abrasive particles is varied, there is a critical abrasive particle size such that the wear rate is independent of abrasive particle size when it is above the critical size, but there is a strong dependence of abrasion rate on particle size below this critical size. Many different wear mechanisms can produce loose abrasive particles, which results in 3-body abrasion becoming a secondary form of wear additional to the primary cause.

2.6 Abrasion Resistance of Concrete

The abrasion resistance of concrete can be defined as the ability of a concrete surface to resist being worn away by rubbing, rolling, sliding, cutting and impact forces (Sadegzadeh, 1985): Depending upon the environment in which the wear occurs, the wear of concrete can include any or all of the wear mechanisms described in Sections 2.3 and 2.4. It should be noted that the term 'abrasion resistance' in this context is a general one, and does not imply resistance solely to abrasive wear mechanisms.

The definition of wear given by Sadegzadeh can be applied to wear in a number of different situations, many of which have been listed in Taylor (1977):-

- Concrete floors and footways - wear is caused by rubbing action of foot traffic, light trucks and the skidding or sliding of objects over abrasive particles.
- Concrete roads - rubbing and impact cutting by vehicles, which may be accelerated by abrasive particles.
- Airport runways - impact and abrasion by high pressure tyres.
- Jet engine warm-up aprons and rocket launch platforms - disintegration due to blast and heat.
- Hydraulic structures - impact abrasion due to cavitation.
- Underwater constructions and pipework - abrasive materials carried in the water.

- Concrete bunkers in industry - grinding, shearing and impact due to the movement of raw materials.

- Lining of kilns - rubbing and impact at elevated temperatures.

2.6.1 Test Methods for Abrasion Resistance of Concrete

Out of necessity, due to the wide range of wear situations on concrete surfaces, numerous test methods have evolved over the years to replicate these situations. It is this variability in both the test apparatus and procedure that makes comparison between results obtained from different research programmes difficult. The more frequently used test methods are described in the following sections, although many of these have only been employed for limited experimental investigations.

2.6.1.1 Rattler Test

This test was favoured by early workers (Abrams, 1921 and Schofield, 1925) and utilised equipment generally used for aggregate testing, typically the Los Angeles Abrasion testing machine. Cubes or cylinders of the concrete under review are tumbled with steel balls for a specified number of revolutions. Abrasion resistance is determined from weight loss. This test method, which mainly involves erosive wear, has recently been re-employed in a slightly modified form as a test for impact resistance of concrete (Senbetta, 1992).

2.6.1.2 Reciprocating Test

This test was devised by A'Court (1949) to investigate the dust nuisance associated with concrete floors. The apparatus consisted of a frame into which specimens, each measuring 150 mm x 100 mm x 25 mm, were fitted. The frame was given a reciprocating motion by gearing driven by an electric motor. In a separate frame, but resting on the sample, was a deep cast-iron pan containing sand, which could pass through the base of the pan by means of a narrow slot. The sand acted as an abrasive medium between the sample and the base of the pan. Abrasion was measured in terms of the weight loss of the sample after testing, and was designed to simulate 3-body abrasive wear.

2.6.1.3 Cavitation Apparatus

Bubbles created in water flowing through a venturi are carried downstream to impact on the test specimen. The test employs the principle of cavitation erosion. By adjusting the pressures, both upstream and downstream, the bubbles collapse against an exposed concrete test specimen measuring 270 mm x 75 mm. The velocity within the venturi is 30 ms^{-1} with the period of exposure being 3 hours. The erosion resistance is expressed as the number of hours required to erode 2.5 cm^3cm^{-2} of exposed surface (Price and Wallace, 1950 and ACI Comm. 210, 1955).

2.6.1.4 Ball Bearing Test

Although slightly modified by various workers (Smith, 1958; Sawyer, 1957; Liu, 1981) the basic principle of the test ensures that abrasion is achieved by ball bearings under load being rotated against the test surface, thus causing wear by rolling contact fatigue and abrasive wear. The test is designed to simulate the rolling, sliding and impact forces imparted by steel-wheeled trollies. In this " Davis " type apparatus a load of 5 kN is applied to a test head resting on 41 steel balls of diameter 25 mm. The test head rotates at 60 rpm for 5 minutes, with loss of weight of the test specimen being recorded after this time. A slightly modified form of this test is specified as one of the test methods in ASTM Standard C-779 (1982) for assessing the abrasion resistance of concrete.

2.6.1.5 Shot-Blast Test

This test method was used by Smith (1958) to replicate the effect of water-borne abrasive particles on concrete, with erosion being the principal cause of wear. The test takes place in a " Ruemelin " apparatus, which essentially consists of a fixed diameter nozzle connected to an abrasive feed located a set distance from the specimen. All the components are enclosed within a sealed compartment. Steel shot or zirconium oxide is ejected by compressed air at a pressure of 0.62 MPa from a 6.5 mm diameter nozzle. The shot is directed against the surface of a specimen measuring 300 mm x 300 mm x 50 mm, located 100 mm from the nozzle end. The shot is discharged at 500 g per minute, and 8 tests are carried out per specimen. The specimen is weighed before and after the test, with the abrasion resistance being expressed in terms of the weight loss.

2.6.1.6 Rotating Disc Test

Three steel discs of 60 mm diameter, rotating at 200 rpm, rub against a concrete surface whilst abrasive grit is continuously fed between the two. Wear, which involves 3-body abrasion, is measured using a depth micrometer after a fixed period of time, typically 30 and 60 minutes. The method has been used by several workers (Schuman and Tucker, 1939; Kessler, 1928; Scripture, 1953) and is currently one of the test methods specified in ASTM C-779 (1982).

2.6.1.7 Reamer

Described by Taylor (1977), this test has been designed to simulate the mode of wear which occurs in ore chutes and bunkers. As with the shot-blast test the main wear mechanism is erosion. A reamer of 40 mm diameter is ground to a chisel edge and cross-fluted with 4 mm indentations. The tool is loaded to 1.35 kN and rotated anticlockwise in a modified drill press at 134 rpm. The test specimen measures 150 mm x 150 mm x 60 mm and rotates at 23 rpm in a clockwise direction with an eccentricity of 40 mm to the reamer. The debris is removed by compressed air and the depth of the groove produced during successive runs of one minute is measured with a depth micrometer. The rate of wear is represented by the average increase in depth per minute taken over the three runs following the first, so that this test assesses the abrasion resistance of the concrete beneath the surface layer.

2.6.1.8 Dressing Wheels Test

This test employs a modified drill press to exert a load of 0.08 kN to 32 dressing (toothed) wheels which are in contact with the concrete test specimen. The test head rotates at 200 rpm for a total of 5000 revolutions whilst silicon carbide is fed at a rate of 3 g per minute to the specimen's surface. The loss in weight per unit area of abraded surface is determined upon completion. The test simulates heavy wheeled traffic, and is the second test method specified in ASTM C-779 (1982). Erosive wear and a gouging form of abrasive wear are examined in this test.

2.6.1.9 Rolling Wheel Test

This test has proved popular with research workers over the years, and in common with other test methods has numerous variations. Essentially, though, they all use the same principle which incorporates a framework supporting a motor which drives a test head containing a number of wheels. The unit as a whole is loaded, and acts upon a prepared concrete surface. Some machines use rubber wheels (Wastlund and Erikson, 1946), whereas most use steel wheels (Sadegzadeh and Kettle, 1988a and Chaplin, 1987). Abrasion resistance is determined by depth of wear in the wheels' path after a set period of exposure to the rotating wheels. This test method has several different wear mechanisms interacting together. Rolling contact fatigue and brittle fracture are occurring together with a small amount of abrasive wear.

It is interesting to note that of all the wear tests described, only the cavitation test investigates the role of water on the abrasion resistance of concrete. Considering the important effect that moisture has on many other concrete properties, such as compressive strength, tensile strength and coefficient of thermal expansion, very little research has been applied to investigating its effect on concrete wear mechanisms.

2.7 Factors Affecting the Abrasion Resistance of Concrete

It has been stated by Lane (1978) that the factors which influence the general properties of concrete will also affect its abrasion resistance. These factors include compressive strength, aggregate properties and curing. Other factors such as surface finishing and treatments and the microstructure of the surface matrix are more specifically related to the characteristics of the surface which is to withstand abrasion (Sadegzadeh, 1985).

2.7.1 Compressive Strength of Concrete

It is generally accepted that an increase in compressive strength produces an increase in the abrasion resistance, this relationship being shown by several workers including Taylor (1977) and Naik, Singh and Hossain (1994). It has also been noted by Neville (1981) that factors which are important in determining the compressive strength also influence the abrasion resistance. Smith (1958) and Sadegzadeh (1985) have demonstrated a reduction in abrasion resistance with increasing water-cement ratio, while Witte and Backstrom (1951) demonstrated the influence of porosity and Sawyer (1957) that of cement content. Troxell, Davis and Kelly (1968) concluded that lowering the water-cement ratio by improving the aggregate grading and employing the lowest practicable slump was more effective in improving wear resistance than when the same reduction in water-cement ratio was achieved by increasing the cement content.

Some workers, however, have reported results contrary to the general trend. For example A'Court (1954) could not establish a clear relationship between abrasion resistance and crushing strength and Langan, Joshi and Ward (1990) stated that the compressive strength did not seem to have a significant effect on abrasion resistance. Dhir, Hewlett and Chan (1991) have shown that concrete slabs of equal strength, but having undergone different curing regimes, could possess very different abrasion resistances, so it is evident that factors other than compressive strength can have major effects on the abrasion resistance of concrete. Indeed, compressive strength has often been used as a convenient factor to rank concrete performance even though the link with other specific properties may not have been clearly established.

2.7.2 Aggregates

Much of the research in this field has examined the role played by the aggregate, both coarse and fine, on abrasion resistance. The reported effects of the coarse and fine fractions are considered separately in the following sections.

2.7.2.1 Coarse Aggregate

It is evident from a review of the literature that the role of the coarse aggregate has been highly dependent upon the test method and specimen preparation. Smith (1958) used cast specimens in his testing programme, and employed three different testing techniques - steel ball abrasion, shot blasting and dressing wheel. He concluded that the compressive strength, cement content and water-cement ratio affected the abrasion resistance regardless of aggregate quality. Limestone proved more susceptible to crushing and pulverisation, as opposed to granite and quartz which had a tendency to chip and spall. Although the breakdown characteristics of the aggregates were found to influence the abrasion resistance of the concrete, when the compressive strength approached 55 MPa their influence became very small. No significant correlation was found between the quality of the coarse aggregate as determined by the Sodium Sulphate Soundness Test or the Los Angeles Abrasion Test, and the abrasion resistance of concrete containing them. Jackson and Pauls (1924) and Pogany (1935) concluded that the rate of wear of concrete was generally not affected by the coarse aggregate, providing that it was equal or superior to the mortar matrix in terms of resistance to wear. Omeregie, Gutschow and Russell (1994) have stated that the abrasion-erosion resistance of cement-hardened materials is primarily a function of the aggregate hardness, and only secondarily a function of the strength of the cement paste.

It is perhaps not surprising that these conclusions have been reached when normal practice is considered. Following placing and compaction, the concrete is subjected to surface finishing such as floating and trowelling either by hand or machine. This process creates a surface layer which is intrinsically quite different to the main body of concrete and, generally, contains little or no coarse aggregate. When this surface is tested, the coarse aggregate only becomes involved when wear is of sufficient depth to expose them to the test regime.

More recently, assessment of abrasion resistance of concrete has entailed the testing of surfaces from sawn specimens (Laplante, Aïtchin and Vézina, 1991; Liu, 1981; Ozturan and Kocataskin, 1987). This presents a surface to the test head which contains both coarse and fine aggregates and cement matrix. Perhaps not surprisingly, workers using this method have found the coarse aggregate to be an important factor, with Laplante, Aïtchin and Vézina (1991) stating the coarse aggregate to be the most important factor affecting concrete abrasion resistance as measured by ASTM C-779 (1982).

In a comparative study by Witte and Backstrom (1951) they found that for a mix of given compressive strength, the maximum aggregate size did not affect abrasion resistance. Contrary to this Dhir, Hewlett and Chan (1991) have demonstrated that concretes having a maximum aggregate size of 5 mm and 40 mm had an inferior abrasion resistance as compared to concretes having a maximum aggregate size of 10 mm and 20 mm.

2.7.2.2 Fine Aggregate

An examination of the influence of fine aggregate on the abrasion resistance of concrete has been approached in several ways by different researchers (Smith, 1958; Chaplin, 1987; Ozturan and Kocataskin, 1987; Laplante, Aïtchin and Vézina, 1991), but they all came to very similar conclusions:-

- Concrete floors containing crushed rock fines are likely to have a reduced abrasion resistance compared to those containing natural sands.

- In general, an increase in the percentage of sand in a mix results in a decrease in abrasion resistance.

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

Chaplin (1987) has suggested, with crushed rock fines, that it may be particle shape rather than grading which governs its performance with regard to abrasion resistance. Similarly, Meininger (1978) stated that the influence of the fine aggregate on concrete strength is almost exclusively through its shape, texture and grading.

2.7.3 Cement Replacement Materials

The effect of cement replacement materials on the durability of concrete is generally well known (Taylor, 1977 and Neville, 1981) whereas only a limited amount of research has examined the effect of these materials on the abrasion resistance of concrete. Chaplin (1987) found that concrete containing ground granulated blast-furnace slag (ggbfs) and pulverised fuel ash (pfa) at 50 per cent and 35 per cent replacements respectively, gave no reduction in abrasion resistance compared with Ordinary Portland cement (OPC) concrete of the same cement content, providing efficient curing was employed. However, Fernandez and Malhotra (1990) found the abrasion resistance of concrete containing slag to be inferior to that of the concrete made with OPC alone. Dhir, Hewlett and Chan (1991) showed concrete containing pfa and microsilica exhibited comparable abrasion resistance to OPC concrete. Naik, Singh and Hossain (1994) examined the abrasion resistance of high-volume pfa concrete (50 to 70 per cent replacement). They showed that these concretes had lower abrasion resistance over a long testing period (60 minutes) when compared with OPC concrete of the same water-cementitious material ratio, but they passed the abrasion resistance requirements of ASTM C-779, Procedure B. Phitides (1991) reported 3 and 6 month abrasion depths less than those obtained at 28 days for concretes containing cement replacements, and suggested that these materials may produce better long term performance in floor slabs.

2.7.4 Curing

Efficient curing, i.e. the maintenance of a moist environment conducive to continued cement hydration, is accepted as being beneficial to concrete. Not only will it be stronger, it is likely to be more resistant to traffic wear, more watertight and less likely to be harmed by chemical attack (Murdock and Brook, 1979).

It has been reported by several workers that efficient curing is reflected in increased abrasion resistance, with Sadegzadeh, Kettle and Page (1989) stating that proper curing was particularly important for mixes with higher water-cement ratios. It was noted during this study that of all the curing methods used routinely on site, plastic sheeting was the most reliable and easy to perform. An even more efficient method of curing is to use curing compounds. These generally improve abrasion resistance further, with resin based types resulting in the best abrasion resistance (Chaplin, 1987). The efficiency of curing compounds depends upon the roughness of the surface to which they applied.

Sadegzadeh, Kettle and Page (1989) concluded that adequate curing can increase the abrasion resistance by allowing the retained moisture to hydrate the cement more fully. This in turn reduces the surface porosity and so creates a denser surface layer.

2.7.5 Surface Finishing

As abrasion is concentrated on the outermost layer of concrete, it is natural that several workers have directed their research towards the characteristics of this layer.

When concrete is placed and compacted excess water rises to the surface through the bleeding phenomenon. If this water is allowed to evaporate and the surface to harden, a weak zone is created due to the locally high water-cement ratio. This in turn results in poor abrasion resistance. Similarly, overworking wet concrete by premature finishing can lead to decreased abrasion resistance, and possible scaling of the surface (Bury, Bury and Martin, 1994).

Some workers in this field have produced specimens which have been finished using a wooden float followed by a steel trowel (Sawyer, 1957; Liu, 1981; Dhir, Hewlett and Chan, 1991). Although this method of finishing improves abrasion resistance compared to no finishing at all, it can still be improved further by employing powered plant for the floating and trowelling processes. This is currently the standard practice in industry today (Perkins, 1993 and The Concrete Society, 1994).

Power finishing has been examined by several workers. Fentress (1973) found improvements in abrasion resistance following delayed trowelling and repeated trowelling. Power trowelling recompacts the surface of the concrete, bringing water, cement and fine aggregate to the surface. After excess water has evaporated the surface layer has an increased density. Repeated power trowelling increases the density of the surface layer by repeating the process after a period of time has elapsed. Baxter (1975) and Pickard (1981) demonstrated further improvements to abrasion resistance after combining the vacuum dewatering process with power finishing. Vacuum dewatering enables the bleed water to be removed from the concrete surface before finishing. This has the effect of decreasing the water-cement ratio at the surface.

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

2.7.6 Surface Treatments

Surface treatments that are designed to improve the abrasion resistance generally take the form of dry shakes which are applied to the concrete whilst it is still in a plastic state, or chemical treatments which are applied after the concrete has hardened.

Dry shakes consist of a pre-mixed combination of cement and either a mineral or a metallic aggregate. This mixture is applied to the plastic surface of the concrete and finished with a steel trowel. The application of a dry shake gives improved abrasion resistance due to a high concentration of hard aggregate at the surface and the local lowering of the water-cement ratio (Tyo, 1991). Workers in this field have found concrete treated with metallic aggregate dry shakes to give the best abrasion resistance (Scripture, 1936; Sadegzadeh, 1985; Tyo, 1991). However, Tyo (1991) stated that, as they are only present to a shallow depth, dry shakes may only have a limited effect in heavily trafficked areas.

Surface treatments applied to a hardened concrete surface usually consist of either zinc or magnesium fluorosilicates or sodium silicate. Such chemical treatments react with the free lime to produce calcium fluoride and calcium silicate respectively. These reaction products are not only harder in themselves they block pores at the surface, and generally improve abrasion resistance (Schuman and Tucker, 1939). Sadegzadeh and Kettle (1988b) found that liquid hardeners were more effective in improving the abrasion resistance of mixes with low water-cement ratio rather than those with higher water-cement ratios. Penetrating sealing and hardening treatments significantly improved the abrasion resistance of all types of concrete mix, and the application of these treatments reduced the influence of the concrete mix design on the abrasion resistance of the slab.

2.8 The Use of Non-Standard Crushed Rock Aggregates.

Crushed rocks have always been used as aggregates, but not perhaps as extensively as natural sands and gravels (Teychenné, 1978). The reason for this could be two-fold, firstly the location of source rock may be too distant for the market, and secondly the source rock may exhibit undesirable properties when crushed for aggregate. There are many properties which can render a source rock unsuitable, or at best marginal, for use in concrete, and these are briefly described.

2.8.1 Aggregate Properties

2.8.1.1 Grading

The grading of an aggregate is closely associated with its surface area, surface texture and shape in that they can all affect the water requirement of a given mix. Orchard (1979) stated that the degree of compaction possible is controlled by the grading and shape of the aggregate, and that the ease of compaction for a given water content is controlled by the surface area of the aggregate. Grading and surface area are particularly important with fine aggregates, as their total surface area is greater than that of coarse aggregates. If a fine aggregate is too coarse, harshness, bleeding and segregation may result and if it is too fine the water requirement may become excessive.

The most common reason for an aggregate to fail grading specifications is to have an excess of fines, i.e. too much material passing the 150 μm sieve. However, in a comprehensive examination of crushed rock aggregates, Teychenné (1978) found only a 7 per cent decrease in compressive strength when the material finer than 150 μm was increased from 10 to 25 per cent. He also found that, by examining and modifying mix designs for concrete containing aggregates with atypical gradings, satisfactory compressive strengths could be obtained in every case.

2.8.1.2 Shape

Mather (1966) stated that particle shape was a function of sphericity and roundness, with roundness being a function of particle strength and abrasion resistance and the amount of wear to which the particle has been subjected. He added that equidimensional aggregate particles were superior to flat or elongated particles because they present less surface area per unit volume and generally produce denser packing when compacted. Blanks (1950) showed that flat or elongate particles decrease the workability, tend to reduce the bulk density and decrease the compressive strength. Kaplan (1959) demonstrated that approximately 25 per cent of variation in concrete strength could be related to differences in aggregate shape, and that workability was reduced by 10 per cent in changing from a rounded to an angular particle (Kaplan, 1958).

2.8.1.3 Surface Texture

The surface texture of an aggregate particle is a direct result of its petrological nature and the forces to which it has been subjected. The surface texture of aggregates, particularly fine aggregates, is an important factor which can affect workability, with workability generally decreasing with an increase in particle angularity and roughness (Neville and Brooks, 1987).

Shape and surface texture can also influence both the flexural and compressive strengths. Rougher, more angular particles possess a larger surface area and hence a greater contact area with the surrounding paste. This leads to a better bond between aggregate and paste as the paste can key into the aggregate more readily than with a smooth particle, and so lead to higher tensile strength (Neville and Brooks, 1987).

2.8.1.4 Density

As aggregates can comprise up to 70 per cent of the volume of concrete, it is not surprising that the density of the aggregates significantly affects the density of the concrete in which they are placed (Teychenné, 1978). Aggregates that have low densities are generally of lower strength, and may also have high absorption and porosity values. Such aggregates can be used to make lightweight concrete, whereas aggregates with particularly high densities can be used in specialist applications such as radiation shielding

2.8.1.5 Porosity

Lewis, Dolch and Woods (1953) stated that the amount of water that an aggregate can absorb is determined by the type and size of pores, their continuity within the aggregate and the degree to which access is provided to the surface of the aggregate. In Dolch (1966), it is stated that porosity can affect concrete behaviour in three possible ways:-

- The influence of the total porosity on density is significant in the matter of mix proportions.

- Other things being equal the strength and abrasion resistance of the aggregate are inversely related to the total porosity.

- Sometimes the size and nature of the pores can control the ingress of aggressive solutions, thereby determining the durability with regard to freezing and thawing and chemical attack.

Aggregates having high absorption and high permeability values such as many limestones, dolomites and sandstones often have a coarse pore structure and so do not develop very high internal hydraulic pressures during freezing. However, they can still cause freezing failure in concrete because water forced from the aggregate pores exerts high external pressure on the surrounding paste (Verbeck and Landgren, 1960).

2.8.1.6 Absorption and Free Moisture

The water absorption values for typical UK aggregates generally lie in the range 1 to 5 per cent (Newman, 1959) although for lightweight aggregates they can be as high as 20 per cent. Aggregates with lower absorption values are usually more resistant to mechanical breakdown as the absorption characteristics are indirectly related to properties such as strength and density.

The absorption and moisture content are important properties when considering water-cement ratio. The moisture contained within the aggregates should be included in calculations for total water-cement ratio, whilst absorption needs to be taken into account when determining the effective or free water-cement ratio.

2.8.1.7 Aggregate Coatings

Coatings can be a fraction of a millimetre to several millimetres in thickness. They can vary from dense and hard to soft and porous, and may be loosely or firmly bonded to aggregate particles (Mielenz, 1966). These usually consist of fine material such as clay, silt or crusher dust. Coatings which adhere to aggregate surfaces, even after mixing and placing, may have an adverse effect on the aggregate/paste bond, although some may only have the effect of altering the grading by adding the coating material to the mix. This latter situation may increase the water requirement of the mix (Mather, 1966).

2.8.1.8 Strength

According to Phemister *et al.* (1946) the compressive strength of concrete aggregates is usually within the range 70 to 350 MPa. Popovics (1979) stated that aggregates at the lower end of this range may be weak because they contain inherently weak substances, or because the constituent grains are poorly cemented together. He continues that even with a high strength aggregate such as granite, which consists primarily of hard crystals of quartz and feldspar, they may have lower overall strengths than gabbro and dolerite because the bond between crystals is poor. The strength of a particle therefore, does not depend primarily upon the hardness of the constituents, but on the way in which the particles are cemented or bonded together. He concludes that a hard stone is not necessarily a strong stone.

Within the normal range of particle strengths, there seems to be little reported correlation with the compressive strength of concrete in which they are used (Rhoades and Mielenz, 1948 and Popovics, 1979). However, Senbetta (1992) found a good correlation between aggregate toughness and the impact resistance of concrete containing the same aggregates, and Davis (1975) reported a close correlation between aggregate crushing strength and attrition value as determined by the Los Angeles test. Rhoades and Mielenz (1948) also commented that, although high strength aggregates are beneficial in ballast and road metal, the use of moderate or low strength aggregate particles in concrete may decrease distress of the cement paste during wetting and drying, heating and cooling and freezing and thawing by decreasing the stress concentrations in the paste for unit volume change, thus leading to reduced cracking of the paste.

2.8.1.9 Soundness

Soundness is a general term which gives some indication of an aggregate's durability, particularly its ability to withstand excessive volume changes due to freezing and thawing, wetting and drying and temperature changes (Bloem, 1966). Powers (1955) suggested that frost action was due to water freezing within aggregate pores, thus relating soundness to porosity. The resultant expansion can lead to volume changes of up to 9 per cent, leaving quite significant damage to the concrete. Other workers (Dolch, 1966; Roeder, 1977; Sweet, 1948) have noted that aggregates of higher porosity but low permeability, such as cherts, can also cause freezing failure. This is due to a large number of micron sized pores becoming saturated and then freezing, thus exerting high internal hydraulic pressures.

The following list includes the most common impurities which may render a rock unsound:-

- The presence of organic matter, chlorides, shell fragments, sulphates, alkalis, pyrites and mica.
- Excess of clay, silt and dust, i.e. material passing the 75 μm sieve.
- Presence of chemically reactive particles.

Although the above mentioned materials are undesirable it does not mean aggregates containing them are necessarily unusable. With adequate examination of the materials prior to designing concrete mixes, many undesirable properties can be accounted for in the design process (Teychenné, 1978; Fookes and Revie, 1982; ASTM STP 597, 1976).

2.8.1.10 Elastic Modulus

The modulus of elasticity of aggregates can vary from 50 to 100 GPa for good igneous rocks, and from 25 to 75 GPa for good sedimentary rocks. The modulus of elasticity of siliceous gravel is around 60 GPa. The absolute value of the modulus of elasticity of the aggregate does not generally cause a problem, it is the differences in moduli values between aggregate, paste and concrete that can cause problems (Mindess and Young, 1981). They found that a differential response from the aggregate and paste within the concrete to an applied stress can lead to inelastic behaviour. This can severely weaken the aggregate/paste bond, extend existing cracks and possibly create further cracking.

2.8.1.11 Shrinkage

Aggregates which exhibit higher than normal volume changes on wetting and drying can adversely affect the drying shrinkage and wetting expansion characteristics of the concrete containing them (Smith and Collis, 1994). Rock types exhibiting excessive shrinkage usually contain clay or mica minerals, so it is possible that altered basalts and dolerites, greywackes, mudstones, shales and mica-schists can potentially cause drying shrinkage problems in concrete. Snowdon and Edwards (1962) found a good relationship between the water absorption of the aggregate and aggregate drying shrinkage, and Weinert (1968) found a good relationship between secondary mineral content and drying shrinkage potential. Drying shrinkage of an aggregate in concrete, particularly the coarse aggregate, can lead to cracking of the concrete making it susceptible to attack and facilitating the corrosion of reinforcement.

2.8.1.12 Thermal Properties

The most important thermal property of an aggregate is the coefficient of expansion. This characterises length and volume changes in response to temperature changes. The coefficient of expansion is largely dependent on the internal structure of the material, particularly the absorption. This is due to the fact that even relatively small amounts of water within the aggregates can dramatically change the thermal properties as there is a large difference between the thermal response of water and dry aggregates (Lewis, 1966). Thermal properties do not normally cause a problem, but they can contribute to large temperature and stress/strain differences between surface and interior in mass concrete structures.

2.9 The Future for Non-Standard Crushed Rock Aggregates

2.9.1 Potential Aggregate Sources

Teychenné (1978) used various igneous, metamorphic and sedimentary rocks of varying quality to examine their influence on the production of concrete. This followed previous work concentrating on sands and crushed rock fines (Newman and Teychenné, 1954 and Teychenné, 1967). He concluded that all of the aggregates produced concrete of satisfactory, but different, qualities. Unsatisfactory workability was common to some mixes but, with slight modifications to mix design and cement content, normal-strength concrete with adequate workability could be readily produced. No relationship was found between the characteristics of the aggregates as measured by standard tests, and their performance in concrete. Collins (1986, 1989, 1991) has examined the potential use in concrete of three specific rock types - Carboniferous Sandstone, Magnesian Limestone and Jurassic Limestone. None of these aggregates are widely used in the production of concrete at the present time, even though they are found in, or close to, regions with limited high quality aggregate supplies.

Of the three rocks studied, the Carboniferous Sandstone proved to be the most variable in quality, even within samples from the same quarry. These aggregates typically have relative density values in the range 2.3 to 2.5, and 24 hour water absorptions in the range 2 to 5 per cent. In concrete, some aggregates exhibited compressive strengths comparable to normal concrete aggregates, whereas others produced only half the strength for the same cement content. Concrete strength correlated well with strength of the aggregates measured by the ten per cent fines test (BS 812: Part 111: 1990). The drying shrinkage of these aggregates was generally high, which produced drying shrinkage of the concrete in the range 0.046 to 0.085 per cent (BRE, 1991) which is sufficient to restrict the use of these aggregates in certain applications. The aggregates affected carbonation depth in that their porosity demanded a higher water content, with a resultant higher water-cement ratio. This could be overcome by increasing cement content, using admixtures or providing extra cover over steel reinforcement.

The properties of the Jurassic Limestone aggregates varied widely, examples being relative densities within the range 2.06 to 2.45, and 24 hour water absorptions within the range 3 to 9 per cent. At low cement contents the difference in aggregate properties had little effect on concrete properties, but at higher cement contents the weaker aggregates produced lower compressive strengths than normal aggregates. The crushed fines from these limestones were generally dusty, but removal of some of this material slightly improved the strength of the resulting concrete. Initial drying shrinkage and wetting expansion values for concretes made with both coarse and fine aggregates were within limits set for structural concrete, and the levels of carbonation were low. The frost resistance of concretes made with these coarse aggregates was good, but the crushed fines performed less well in this respect.

Like the Jurassic Limestones, the properties of the Magnesian Limestones were very variable, with relative densities within the range 2.10 to 2.65 and 24 hour absorption values within the range 1.3 to 10.3 per cent. Variation in the material within individual quarries can be significant, but it is usually in the form of vertical bed variation rather than lateral variation within the same horizon. In some instances this has been overcome by producing two or three different outputs from one quarry. Differences in the ten per cent fines values of these aggregates had a negligible effect on concrete strength, with the Magnesian

Limestone coarse aggregates producing concrete with compressive strengths generally within the range 40 to 50 MPa. Crushed fines from the same material, which often had a high proportion passing 150 μm, in combination with coarse aggregate from the same source, gave compressive strengths within the range 25 to 45 MPa. Magnesian Limestones have been used more extensively in concrete than both Carboniferous Sandstone and Jurassic Limestones, and they have generally performed well. Frost resistance after 20 years has been shown to be as good as standard concrete aggregates (Collins, 1991).

Although perhaps not suitable for unrestricted use, it is possible that the above-mentioned rock types can make a significant contribution to aggregate supply for concrete in less demanding applications such as floor slabs and foundations, which it is estimated account for 40 per cent of concrete usage in new buildings.

2.9.2 Future Aggregate Specifications

Since 1976 (Advisory Committee on Aggregates, 1976) it has been recognised that high quality aggregates should be conserved for the more demanding applications and that the use of low grade and secondary materials should be maximised. In 1993, an efficiency report published by the Building Research Establishment (BRE, 1993) highlighted several important factors concerning low grade aggregates:-

- Overspecification frequently precludes aggregates which could be used quite satisfactorily.
- There is currently little or no incentive to use lower grade or secondary materials.
- The 'risk factor' restricts the use of innovative materials. An increased degree of risk sharing may be required.
- Consideration should be given to setting up an 'Aggregate Efficiency Agency' to promote the use of lower grade and secondary aggregates.
- The Government could lead by example by using such aggregates in public works contracts.

Although it is important that specifications allow an adequate safety margin, to ensure unsuitable materials are not used and that a structure is fit for use, these margins are often excessive. As there are often no appropriate specifications governing the use of low-grade aggregates, these aggregates are frequently overlooked and are not used in situations for which they may be suitable. Overspecification is a problem which tends to occur at the design stage, and may partly be due to the fact that the designer often becomes liable when disputes arise. Specifications are only one of many obstacles to using low-grade aggregates in concrete, and there is currently very little incentive for using them, with contractors and suppliers only likely to use these materials if there is some form of financial incentive. At the present time, any cost advantage of using low-grade aggregates could be offset by extra storage costs, increased cement contents to achieve specified strengths or increased testing costs to demonstrate that they satisfy a particular specification. In fact, the use of these aggregates in concrete is further restricted by the specification of concrete solely in terms of compressive strength rather than a performance specification, which would confirm the suitability of a particular concrete for a specific application.

The establishment of an agency to supervise the efficient use of aggregates, the reduction of waste on sites and the increased use of low-grade and secondary materials is of great environmental as well as economic importance. Not only could it publicise the availability of these materials, it would provide information on possible applications of the materials. For an agency of this sort to be effective, and for the use of low-grade materials to become more widespread, legally enforceable targets would probably be needed, as well as financial arrangements to make these materials competitive with higher quality ones. Associated with this, initially, an element of risk sharing would have to be adopted. This could be demonstrated by the Government's encouragement of the use of these materials for their use in public works contracts.

A significant step has been taken to address some of the above factors with the publication of the revised Minerals Planning Guidance document (Department of the Environment, 1994) which encourages the use of alternative, secondary and recycled aggregates. This has been reflected in the Minerals Local Plans of the County Councils. Similarly, the problem of overspecification is being addressed by the Comité Européen de Normalisation (CEN) in its preparation of many Europe-wide aggregate tests and standards (Collins, 1994).

2.10 Overview

From the literature review presented in this chapter, it is evident that there are several areas which require further investigation. Although wear and wear mechanisms have been extensively researched, the work has predominantly involved the study of metals. The examination of wear in brittle materials has been less extensive, especially the aspects of fatigue and cyclic loading. In particular, the microscopic effects of rolling contacts and fatigue in concrete are little understood, as is the effect of moisture in many different wear situations. Section 2.9 has highlighted the need to explore alternative aggregate sources, and to establish their effects on concrete properties. A thorough examination of possible applications for these aggregates is required before performance specifications can be proposed.

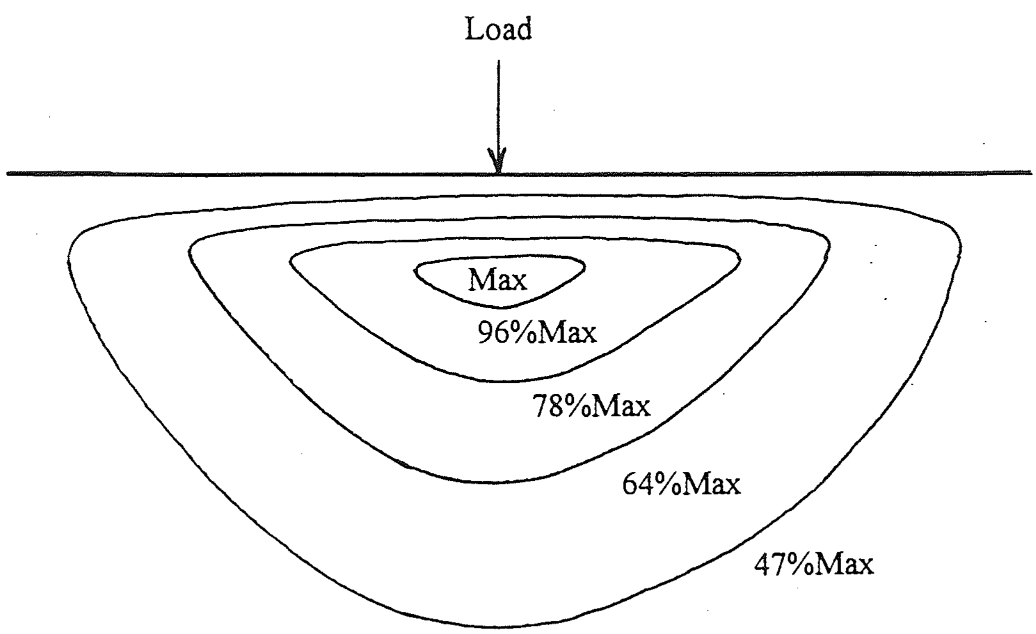

Figure 2.1. Zone of maximum stress during rolling contact fatigue (Davies, 1949).

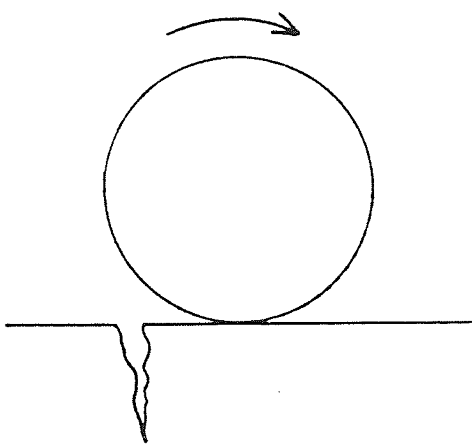

Figure 2.2a.

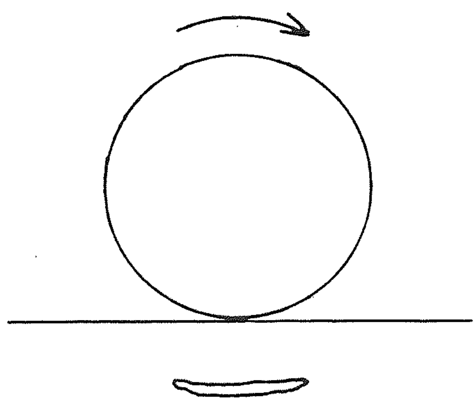

Figure 2.2b.

Diagrams showing the two types of crack formation associated with rolling contact fatigue.

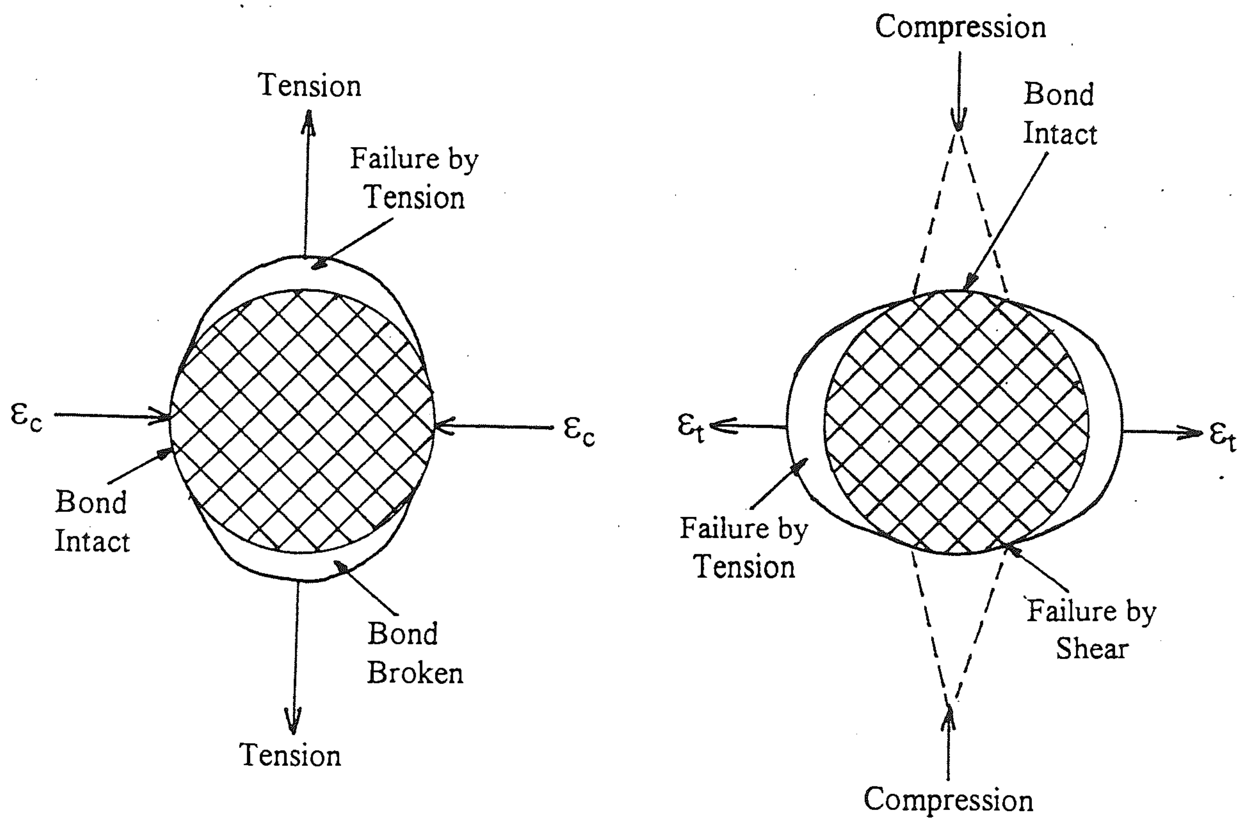

Figure 2.3. Stress and strain states around an idealised aggregate particle during a loading cycle (Avram, 1980).

Chapter 3 Test Methods and Procedures

3.1 Introduction

As the main aim of this project was to examine the effect of low-grade aggregates on the properties of concrete, in particular abrasion resistance, it was important to subject the selected aggregates to a wide range of tests to clearly establish their characteristics. This was considered essential so that possible links could subsequently be explored between these characteristics and the properties of the concretes containing these materials. Having established the aggregate characteristics, and casting a series of trial mixes to determine a mix design for the test programme, mixes were cast which included the low-grade coarse aggregates in combination with a control fine aggregate, and low-grade fine aggregates in combination with a control coarse aggregate, hereafter referred to as coarse aggregate mixes and fine aggregate mixes respectively. Although standard concrete tests such as cube strength and workability were performed on these mixes, the main concrete testing programme involved determining the abrasion resistance of test slabs under three different modes of wear. Certain microscopic tests were carried out to determine the hardness and microporosity of the aggregates, and to try to identify the mechanisms of breakdown which occur within the concrete and aggregates during abrasion. It was intended from the outset that the abrasion resistance specimens would be power finished using current site practices where possible, so that the potential use of these aggregates by the industry could be assessed more accurately. The test results are presented in Chapters 4 and 5.

3.2 Aggregate Tests

3.2.1 Sampling

All the aggregate samples were taken from quarry stockpiles according to BS 812: Part 102: 1989: Methods for sampling aggregate. The samples were bagged for removal to the laboratory, with each sample consisting of between 500 and 750 kg of aggregate.

3.2.2 Petrographic Description

Petrographic descriptions of the aggregates were carried out following the guidelines given in the Geological Society Engineering Geology Special Publication No.9 (Smith and Collis, 1994).

3.2.3 Moisture Content

The moisture content determinations for all the aggregate samples, both fine and coarse, were carried out in accordance with BS 812: Part 109:1990: Methods for determination of moisture content. The moisture content of the samples was measured on the day of mixing, so that the total water content of the mix could be determined.

3.2.4 24 Hour Absorption

The 24 hour water absorptions of all the aggregates were determined in accordance with BS 812: Part 2: 1975: Methods for determination of physical properties.

3.2.5 Relative Density

The relative density of all the aggregates was determined in accordance with BS 812: Part 2: 1975: Methods for determination of physical properties. The values reported are based on the oven-dried condition.

3.2.6 Grading

Grading tests on all the aggregate samples were carried out according to BS 812: Part 103: Section 103.1: 1985: Sieve tests.

3.2.7 Los Angeles Abrasion Loss

This test was carried out to ASTM C131 (1989): Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine. It was performed on all the coarse aggregate samples.

3.2.8 Mohs' Hardness

The Mohs' Hardness is a comparative scratch hardness test, and is performed using a set of 'standard' minerals which range in hardness from 1 (softest) to 10 (hardest) (Tabor, 1954). The material under examination is used to scratch the standard minerals in ascending order of hardness until the material only slides over the surface of a particular standard mineral. The test specimen will have the same hardness as this mineral. This is confirmed if the test specimen can itself be scratched by the next hardest mineral on the scale. It is usually possible to be more accurate by using 'half' values if the hardness of a test specimen falls between those of two standard minerals. The test was performed on ten particles from each sample. The tabulated results in Chapter 4, *Table 4.1*, give the range of values obtained. The full list of Mohs' Hardness minerals is given in Appendix G.

3.3 Concrete Tests

3.3.1 Mixing and Sampling

All mixing and sampling carried out during the research programme followed the procedures given in BS 1881: Part 125: 1986: Methods for mixing and sampling fresh concrete in the laboratory.

3.3.2 Slump

The slump test was carried out according to BS 1881: Part 102: 1983: Method for determination of slump.

3.3.3 Cube Strength

Concrete cubes (100 mm) were cast, cured and tested according to the following British Standards. BS 1881: Part: 108: 1983: Method for making test cubes from fresh concrete, BS 1881: Part 111: 1983: Method of normal curing of test specimens (20 °C method) and BS 1881: Part 116: 1983: Method for determination of cube strength of concrete cubes.

3.4 Abrasion Testing

3.4.1 Specimen Fabrication

3.4.1.1 Preparation

To allow for the preparation of three test specimens measuring 1.0 m x 0.5 m x 0.1 m and six 100 mm cubes, the volume of concrete prepared was 0.18 m^3. This equates to a total mass of approximately 380 kg. To facilitate handling of the materials and casting, the mixes were batched and mixed in three equal parts. The constituent materials were batched by weight the day prior to casting, and stored in steel bins. All the weighing was carried out using scales accurate to 0.1 kg, and all the experimental aggregates were used in the 'as received' condition, with the standard laboratory aggregates being used in an air-dried condition. The overall size of the mould in which the specimens were to be cast was 2.0 m x 1.5 m x 0.1 m, this was sub-divided into six separate sections each measuring 1.0 m x 0.5 m x 0.1 m. This mould had been used during previous research (Sadegzadeh, 1985 and Phitides, 1991) when all six sections had been used. For the current work only three of the sections were to be used, one specimen slab for each of the three testing conditions to be investigated. The mould is illustrated in *Plate 3.1.*

3.4.1.2 Casting

On the morning of casting a sample of aggregate was taken for the determination of the moisture content to establish the water in the aggregate. This quantity, together with 24 hour water absorption, is essential in determining both the total and the free water-cement ratios of the mix. Prior to mixing the mould was coated with release oil to ease subsequent specimen removal.

Mixing was carried out following the practice recommended in BS 1881: Part 125: 1986, using a pan mixer. After an initial period of dry mixing, water was added, mixed thoroughly and then left for 15 minutes, after which a slump test was undertaken. The 15 minute period was deemed necessary to allow for the absorption of water by the aggregates (Orchard, 1979). For the second batch, the quantity of added water was adjusted until a slump within the range 10 to 30 mm was achieved. The total water content required to achieve this slump value was noted, and used for the third and final batch. The water-cement ratios described in subsequent chapters, and tabulated in Chapter 5, *Tables 5.2* and *5.3*, all refer to the values obtained from the third batch of each mix. Previous research (Sadegzadeh, 1985 and Phitides, 1991) has shown this part of a mix to be the most influential on abrasion resistance. Overall water-cement ratios representing all three batches of each mix are given in Appendix A, *Tables A.1* and *A.2*. Each of the three batches was placed in the mould by shovel and compacted using a 50 mm diameter vibrating poker, five passes of the poker being applied to each specimen. After placing the first batch, two lengths of 10 mm diameter steel reinforcement were placed in each specimen. These were included to prevent damage during demoulding with the fork lift. From the third batch, six 100 mm cubes were taken for 7-day and 28-day cube strength tests. When the mould was full and compaction completed, the concrete was tamped and levelled by hand using a wooden beam across the three sections of the mould that were being used. The specimens were then left until the conditions for finishing were met.

3.4.1.3 Finishing

Before the power finishing procedure could commence it was important that two main conditions were met. Firstly, all the bleed water should have evaporated and secondly the concrete should be stiff enough to allow the power float to move easily over the surface, while still being sufficiently workable to respond to power finishing. An estimate of when these conditions were met was obtained when a footprint made a negligible impression upon the surface of the concrete. Specimens were generally ready for finishing 2 to 4 hours after casting and the finishing times for each mix are shown in *Tables 3.1* and *3.2*.

The first stage of power finishing was power floating, which utilised a Fyne Model RT9002 power float driven by a 3.7 kW motor fitted with a steel float of 920 mm diameter and a stabilising bar, as shown in *Plate 3.2*. As the power float was designed for use on much larger areas, the addition of the stabilising bar was found necessary for use on these relatively small specimens. The floating operation brings moisture and the mortar fraction of the mix to the surface, and evens out any irregularities on the surface. This operation was carried out by two people and lasted 10 minutes and, subsequently, the specimens were left for this surface moisture to evaporate. The final stage of the process was power trowelling. This used the same equipment as floating, except it was fitted with four trowel blades each measuring 340 mm x 160 mm. The pitch of the blades could be adjusted. The aim of the trowelling procedure was to produce a dense, smooth surface comparable to that obtained on site for a typical warehouse floor. The operation was carried out for 10 minutes, with the blades becoming progressively more tilted throughout the 10 minute period. Upon completion the specimens were covered with heavy duty polythene for 24 hours.

3.4.1.4 Curing

After 24 hours the specimens were removed from the mould using a fork lift, and completely wrapped and sealed in heavy duty polythene. The specimens were stored in the laboratory and left undisturbed for 21 days when they were unwrapped so that they would acclimatise to laboratory conditions before testing at 28 days. This was the standard procedure followed in previous studies of abrasion resistance (Sadegzadeh, 1985 and Phitides, 1991).

3.4.2 Abrasion Test Apparatus

The test apparatus consisted of a 0.25 kW motor mounted vertically on a steel framework, and is shown in *Plate 3.3*. The motor powered, by means of a shaft, a circular steel plate to which were attached the three test wheels. The wheels of the test head, shown in *Plate 3.4*, were made of case hardened steel, measured 80 mm in diameter and 20 mm in width, and were free to move on their individual axles. The mode of operation of the apparatus ensures that the test head rotates at 180 ± 5 rpm. In order to accelerate the effect of the machine, a dead load of 40 kg in the form of a lead collar was placed over the motor. To prevent lateral movement of the apparatus during testing, the outer framework was located into two pre-drilled holes with bolts. Although restricting sideways movement this practice did not inhibit the ability of the test head to move vertically over any surface irregularities. During testing the three wheels abraded a 20 mm wide circular path on the surface of the concrete and it was the depth of this groove which was used to determine the abrasion resistance of the concrete. The depth of the abrasion path was measured at 5, 10 and 15 minute intervals, with selected specimens also being measured after 30 minutes.

3.4.3 Specimen Testing

3.4.3.1 Preparation

Before testing it was necessary to mark out three test areas on each specimen using a wooden template whose outer perimeter coincided with the abrasion path of the machine. The three test areas were equally spaced across the specimen and marked accordingly. Utilising the same template eight measurement points were marked around the circumference of each test area, again these were equally spaced, as shown in *Plate 3.5*. An initial dial gauge reading was taken at each of these measurement points, to which all subsequent measurements could be related. The dial gauge readings were taken from the centre of the abrasion path and to an accuracy of 0.01 mm.

3.4.3.2 3-Body Abrasion Test Method

The 3-body abrasion test method entailed running the test machine for 15 minutes, with intermediate measurements being made after 5 and 10 minutes. For certain specimens the test period was extended to 30 minutes. At the end of each 5 minute period the apparatus was moved aside, the loose debris removed with a brush, and the depth measurements retaken. The apparatus was then replaced and testing continued.

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3.4.3.3 2-Body Abrasion Test Method

This test method was very similar to the 3-body test method, except that any debris produced during testing was immediately removed using a standard vacuum cleaner. For each 5 minute test period the cleaner nozzle was continuously moved around the periphery of the abrasion path, allowing 30 seconds for one complete traverse around the abrasion path. Abrasion depths were measured as described in Section 3.4.3.2.

3.4.3.4 Wet Abrasion Test Method

This method was conducted in a similar way to the normal test except that water from a hosepipe was allowed to flow across the test surface at a rate of 1.0 litre per minute. The remainder of the test was identical to the 3-body test described previously in Section 3.4.3.2.

3.4.3.5 Investigation of Variable Low-Grade Aggregate Content

The specimens cast to investigate the effects on abrasion of variations in the content of low-grade aggregate were prepared and cast using the procedure detailed in Section 3.4.1. The specimens were tested using the 3-body and wet test methods.

3.5 Microscopic Tests

Sub-samples, in the form of 100 mm diameter cores were cut from selected specimen slabs. Each core sample was cut to include a section of the abrasion path, and was taken through the complete depth of the slab. The top 40 mm of the sub-sample was separated from the remainder using a concrete saw, and two 70 mm x 40 mm x 10 mm slices were cut from it as shown in *Plate 3.6*. The two slices were vacuum impregnated with an epoxy resin containing fluorescent dye. One slice was to be used for a microscopic examination, and the other for the determination of the aggregate microhardness.

3.5.1 Microscopic Examination

One face of the concrete slice to be examined microscopically was initially ground flat using a 15 μm aluminium oxide abrasive and then a 9 μm abrasive on a Logitech PM2A lapping machine. The slice was then bonded to a ground glass slide using epoxy resin. When the resin had hardened the slice was sawn to approximately 250 μm in thickness, ground to 30 μm thickness and covered with a glass cover slip for protection.

The thin sections of concrete were examined using an Olympus BH2 polarising microscope following guidelines given in ASTM C-856 (1983).

3.5.3 Microhardness

One face of the second concrete slice, taken from selected core samples of coarse aggregate mixes, was ground flat using a 9 μm aluminium oxide abrasive, and bonded to a ground glass slide using epoxy resin. The upper face of the slice was ground to 1 μm using diamond cutting pastes on a lapping plate. Each slice was subsequently examined using a Bueler Micromet 4 to determine the Vickers Hardness Number (VHN) for the coarse aggregate particles under examination. Five separate particles of the selected aggregate were tested, 20 readings being taken from each. The readings were taken along a traverse at 0.2 mm intervals. The mean VHN number was calculated from the values of the five particles.

3.5.2 Mercury Intrusion Porosimetry

This test was carried out on each of the aggregates used in the testing programme to determine the characteristics of their microporosity. A 0.2 kg sub-sample was taken from the bulk aggregate sample and crushed in a pestle and mortar to produce equidimensional fragments of 2 to 5 mm. Approximately 0.006 kg of the material was oven-dried for 24 hours, and cooled in a desiccator. The samples were tested using a Micromeretics Mercury Penetration Porosimeter Model 910. The test technique relies on the principle that mercury, a non-wetting liquid, will only penetrate the pores of a solid material under sufficient pressure, and was first used extensively by Washburn (1921). During the test, as the applied pressure increases, mercury is forced into progressively smaller and smaller pores until the maximum pressure is attained. Data obtained from the test included a plot of applied pressure against pore size, which not only shows at what pressure certain pores are filled with mercury, it also indicates the volume of mercury that has entered pores of a given size. With this information the microporosity of different materials can be readily compared. Other data from the test gave total pore area, total pore volume and mean pore diameter. The experimental procedure is described fully in the manufacturer's manual (Micromeretics Corporation, 1988).

Specimen	Time elapsed before power floating (Mins)	Time elapsed before power trowelling (Mins)
Control (CS2)	210	135
C1S1	210	130
C2S1	150	45
C3S1	155	180
C4S1	250	40
M5S1	165	150
M6aS1	165	90
M6bS1	240	120
M8S1	Not Recorded	Not Recorded
J9S1	Not Recorded	Not Recorded
J10S1	220	135
J11S1	210	120
J12S1	120	105

Table 3.1 Time elapsed before power finishing of specimens containing low-grade coarse aggregates.

Specimen	Time elapsed before power floating (Mins)	Time elapsed before power trowelling (Mins)
Control (CSF1)	190	160
C1FS1	Not Recorded	Not Recorded
C2FS1	225	75
C3FS1	185	130
C4FS1	135	180
M5FS1	165	120
M6FS1	180	150
M8FS1	150	260
J9FS1	120	180
J10FS1	115	125
J11FS1	Not Recorded	Not Recorded
J12FS1	120	105

Table 3.2. Time elapsed before power finishing of specimens containing low-grade fine aggregates.

Plate 3.1 The mould used for casting the three test specimens.

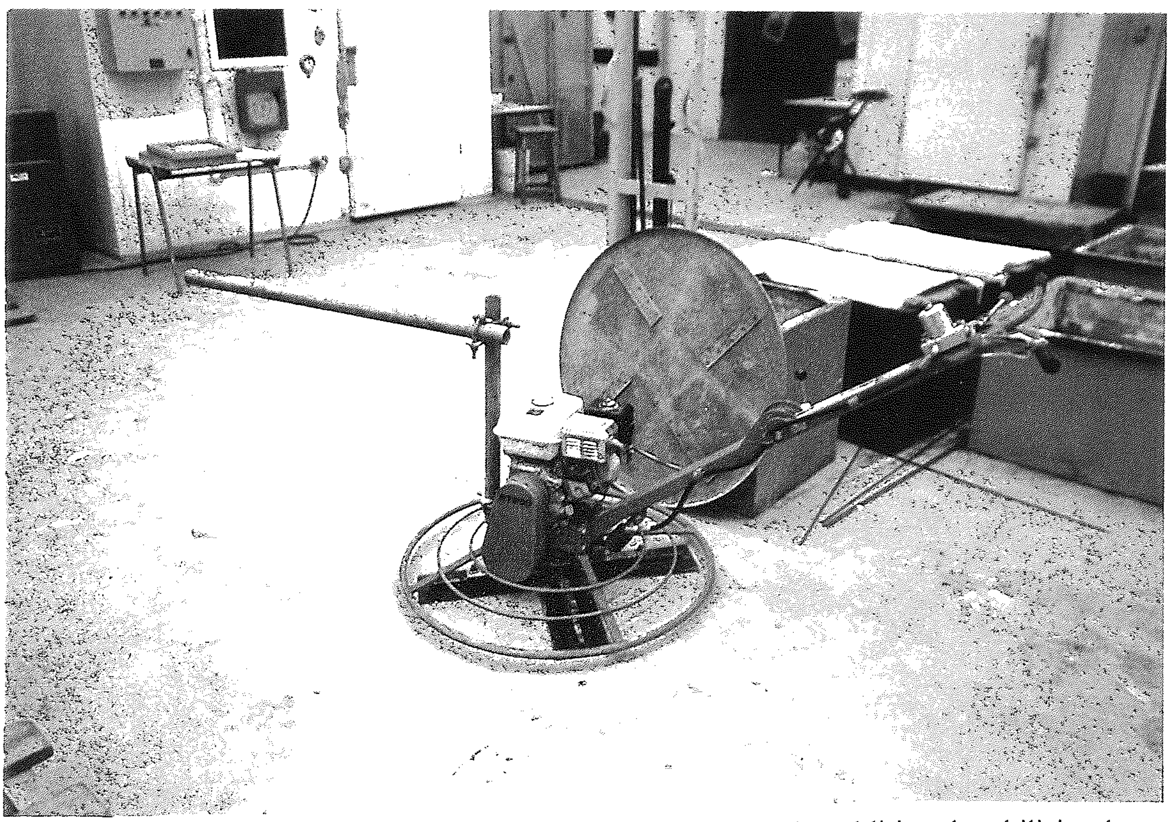

Plate 3.2 The apparatus used for power finishing, showing the additional stabilising bar.

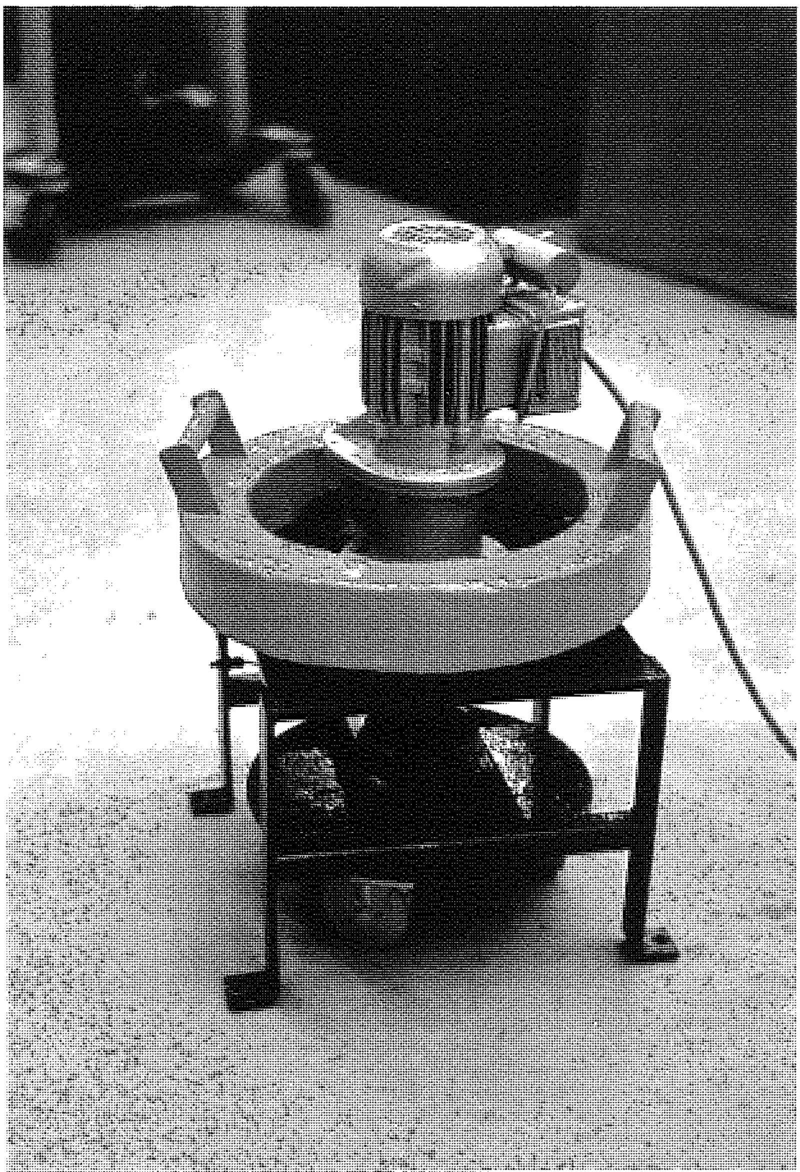

Plate 3.3. The accelerated abrasion test apparatus.

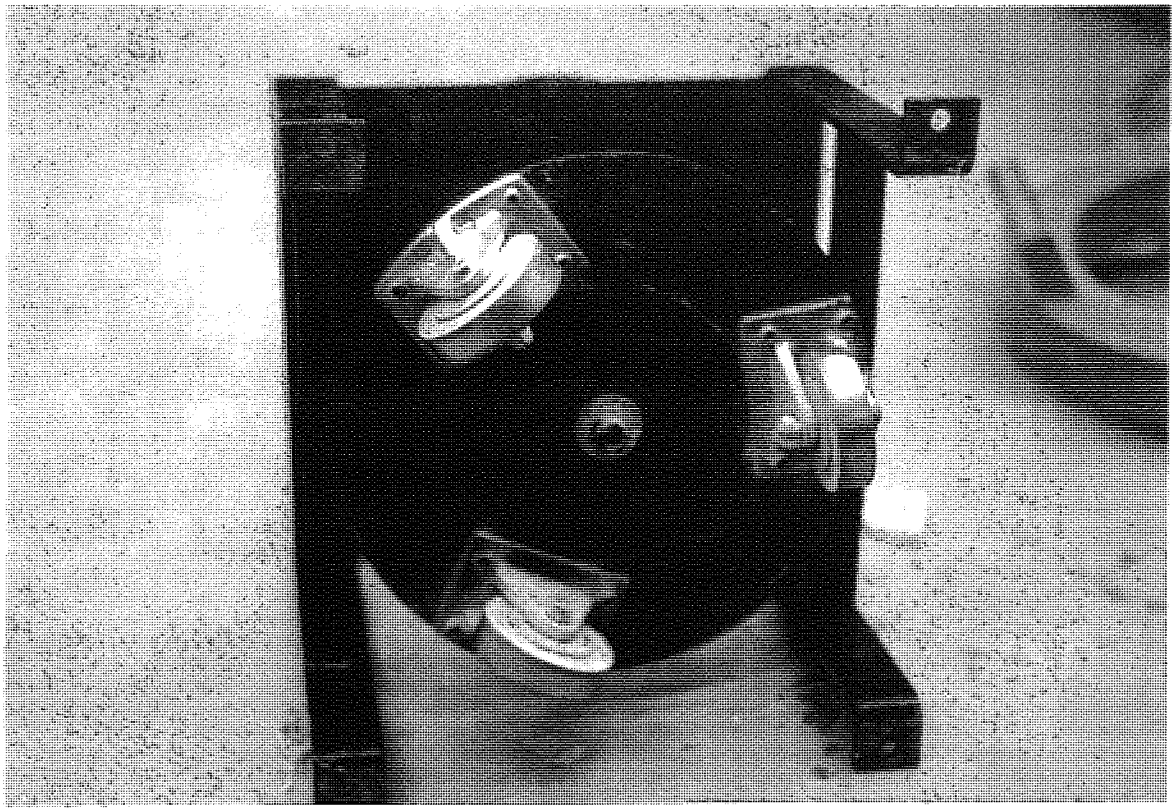

Plate 3.4. Detail of the test head from the abrasion apparatus.

Plate 3.5. Layout of test areas and measurement locations on a specimen slab.

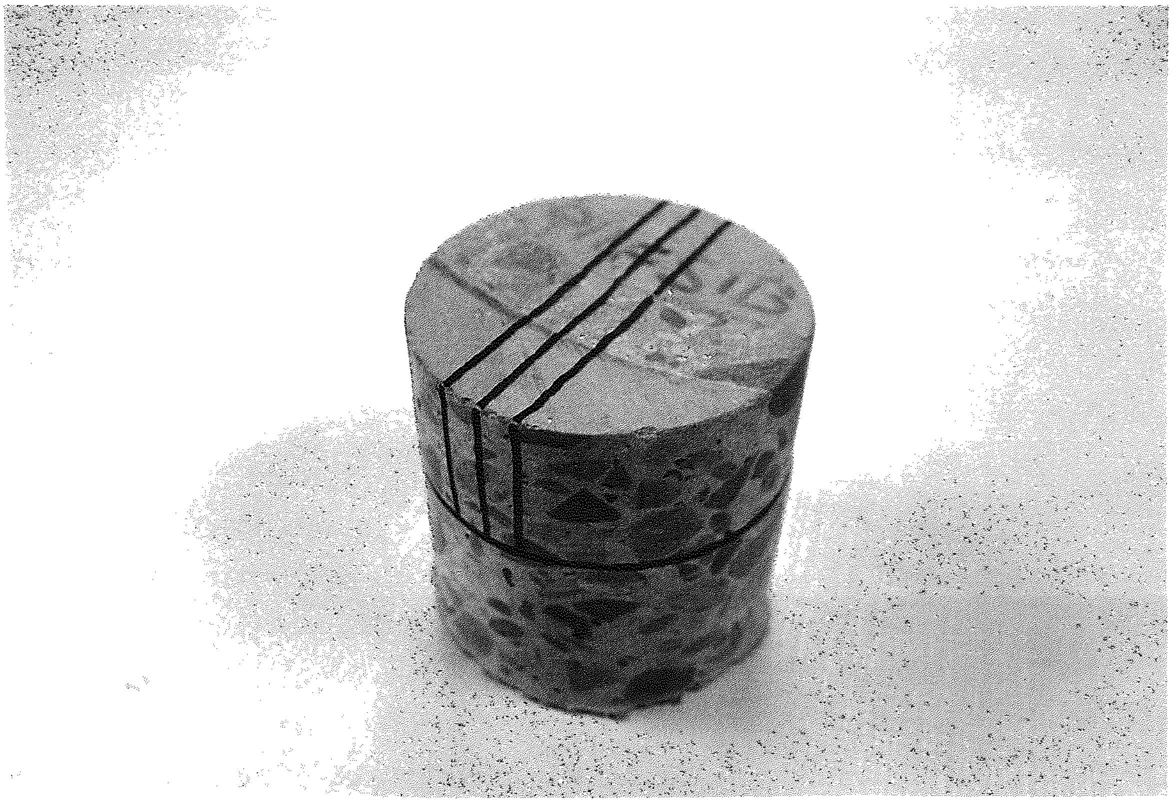

Plate 3.6. Core sample showing the location of the slices for microscopic testing.

Chapter 4 Material Characteristics

4.1 Introduction

As discussed in Chapter 1 the aggregates used were, where possible, from the same sources as those used in the previous BRE research programmes conducted by Collins (1986, 1989, 1991). Four sources of Carboniferous Sandstone were selected from Lancashire (prefix C), three sources of Magnesian Limestone from Yorkshire/Nottinghamshire (prefix M) and four sources of Jurassic Limestone from Oxfordshire/Gloucestershire (prefix J). The quarry details are given in Appendix B together with photographs showing the typical appearance of each of the aggregates used. Crushed rock fines are denoted by the suffix 'F', no suffix indicates a coarse aggregate. The control aggregates (prefix CS), both fine and coarse, were a quartzite-rich gravel and a similar sand. Initially this chapter describes the rock types from which the samples were taken, and then each aggregate source individually. The aggregate properties are discussed collectively and individually, and are compared with current specifications where applicable. Other materials used to produce the test specimens are briefly described.

4.2 Aggregate Descriptions

4.2.1 Carboniferous Sandstone

The geological system known as the Carboniferous period extends from 360 million years ago (mya) to 280 mya. The system is broadly divided into two stages, the earliest being the Dinantian (Lower Carboniferous) and the other being the Silesian (Upper Carboniferous). The Dinantian period is characterised by sedimentary rocks of marine origin, particularly detrital organic limestones containing corals and numerous other fossils. Limestones of this period are widely recognised as capable of yielding good quality aggregates and outcrop extensively in Lancashire, the Peak District, South Wales and the Mendips. The lower part of the Silesian period is characterised by large areas of fluvial and near-coast marine deposits, principally consisting of coarse grained sandstones. These deposits are known as the Namurian or Millstone Grit Series, and outcrop in the Pennines, Lancashire and North Yorkshire. The remaining part of the Silesian period comprises the Lower and Upper Coal Measures, and consists of cycles of deposition, including alternating deposits of sandstone, shale and coal, the latter being the source of the United Kingdom's extensive coal deposits. The extent of the Carboniferous deposits in the Lancashire area is illustrated in *Figure 4.1*.

Historically, Carboniferous Sandstones have been quarried extensively for use as building stone, but only very rarely have they been used as aggregate for concrete (Collins, 1989). Although a few quarries currently supply sandstone crushed for use as a concrete sand, the principal use for this material at the present time is for fill or hardcore. The aggregates used for the current research are from the Millstone Grit Series and the Lower Coal Measures of North-West England, with the locations of the quarries shown in *Figure 4.1*, and their ownership details presented in Appendix B. The following sections describe the main characteristics of the Carboniferous Sandstones used in the project.

4.2.1.1 Sample C1

This sample was taken from a formation known as Ousel Nest Grit, part of the Lower Coal Measures, at Montcliffe Quarry near Horwich, Lancashire. The material consists of a buff-coloured, medium to coarse grained, quartz-rich sandstone with a rough surface texture. In thin section, the quartz grains are angular to sub-rounded in shape, in combination with lesser quantities of feldspar, mica and iron minerals. The sandstone is mainly grain supported, but a patchy matrix is evident which consists of microcrystalline quartz and occasionally clay minerals. Pore spaces are visible, but they are not generally interconnected.

4.2.1.2 Sample C2

This sample was taken from a formation known as Revidge Grit, part of the Millstone Grit Series, at Little Quarry, Whittle-Le-Woods, Lancashire. The material consists of a coarse grained, pale-brown, quartz-rich sandstone. The aggregate particles are angular in shape and have a rough, friable texture. In thin section, the dominant mineral is quartz, with feldspar, mica and iron oxide minerals also present. There is a wide range of grain sizes, with the shape being angular to sub-rounded. A finely crystallised quartz matrix is visible in some particles, and the pore space content is high.

4.2.1.3 Sample C3

This sample was taken from a formation known as Warley Wise Grit, part of the Millstone Grit Series, at Waddington Fell Quarry, Waddington, Lancashire. The material consists of a coarse grained, orange-brown, quartz-rich sandstone. The particles have a highly variable fabric, but are generally angular in shape and have a rough surface texture. In thin section, quartz is the dominant mineral present, with the grain size variable from coarse to very fine. The grains are rounded to sub-rounded in shape, with feldspars, iron minerals and mica evident. A number of pores are visible, many of which interconnect, and there is a patchy matrix consisting of finely crystallised quartz and clay minerals.

4.2.1.4 Sample C4

This sample was taken from a formation known as the Upper Haslingden Flags, part of the Millstone Grit Series, at Whitworth Quarry, near Rochdale, Lancashire. The material is somewhat different to the other Carboniferous Sandstone samples, and consists of a fine grained, smooth textured, quartz-rich sandstone. The particles are elongate and angular, with some showing evidence of small-scale bedding. In thin section, this rock is composed of fine, angular quartz grains with some feldspars, iron minerals and mica. A patchy matrix consisting of finely crystallised quartz and clay minerals is present in some particles, and the void content is noticeably lower than samples C1, C2 and C3.

Plate 4.1 shows the microscopic texture of sample C4 and *Plate 4.2* shows that of sample C1, which is typical of the coarse-grained sandstones C1, C2 and C3.

4.2.2 Magnesian Limestone

The term Magnesian Limestone is a general one which describes two separate geological horizons within the Permian System (280-225 mya), the Upper Magnesian Limestone and the Lower Magnesian Limestone. Both horizons are within the Upper Permian system. Rocks of the Lower Permian are characterised by continental 'red-bed' deposits of coarse sandstones, marls and mudstones, all exhibiting a distinctive red colour which is indicative of desert conditions during deposition. A series of marine transgressions began during the Upper Permian, resulting in cyclical deposits of dolomitic limestones and evaporites. The Upper and Lower Magnesian Limestones represent two of these dolomitic limestone deposits. Although Permian 'red-bed' deposits are found in SW England, the Welsh Borders and the Lake District, the Magnesian Limestones are only found in Northern England and Ireland. The extent of the Magnesian Limestones in England is shown in *Figure 4.2.*

The Magnesian Limestones as a group are widely variable in both chemistry and durability. Pure Magnesian Limestones (low quartz and clay content) have been used for the production of lime and in other chemical applications. Others have been used in building, York Minster being an example of the use of Magnesian Limestone as a building stone. Some of the more durable types have been used as concrete aggregates. The aggregates used for the current research programme are from both the Upper and Lower Magnesian Limestones, with the quarry locations being shown in *Figure 4.3,* and ownership details given in Appendix B.

4.2.2.1 Sample M5

This sample was from the Lower Magnesian Limestone horizon, at Whitwell Quarry, near Worksop, Nottinghamshire. The aggregate particles are generally soft and dusty, angular in shape, and light grey in colour. In thin section, the sample consisted of a sparry dolomitic limestone, with a few voids visible and a uniform texture throughout the sample.

4.2.2.2 Samples M6a and M6b

Both samples were taken from the Lower Magnesian Limestone horizon at Cadeby Quarry, near Doncaster, South Yorkshire. Sample M6b is essentially similar to M6a except that it has been through the crushing process twice to remove weak or potentially deleterious particles. Both samples consist of a buff-yellow limestone, with sample M6a containing numerous brown clay lumps (up to 10 mm across) and particles with a visibly high void content. In thin section, the mineralogy of sample M6a is dolomitic, with some oomicritic particles, which have a high porosity. Oomicrite is a fine-grained limestone composed of spheroidal pellets (ooliths). Other particles consist of finely crystallised dolomite. The oomicritic particles are less frequently seen in sample M6b, and the majority of particles in this sample consist of finely crystallised dolomite.

4.2.2.3 Sample M8

This sample is from the Upper Magnesian Limestone horizon at Spring Lodge Quarry, near Doncaster, South Yorkshire. The material is a white-grey limestone, the particles being sub-angular in shape, soft and dusty. In thin section, the sample is seen to consist almost entirely of finely crystallised calcite, with very occasional small quartz grains within the fabric.

Plate 4.3 shows the microscopic appearance of oolitic particles seen in sample M6a and to a lesser extent in M6b, with voids showing as dark areas in the photograph. *Plate 4.4* shows the finely crystalline nature exhibited by both samples M5 and M8.

4.2.3 Jurassic Limestone

The Jurassic System (195-135 mya) is divided into three stages, the Lower, Middle and Upper, all of which outcrop in a band from Dorset to Yorkshire, see *Figure 4.4*. Rocks of the Lower Jurassic are generally marine deposits, consisting of limestones and mudstones.

The Middle Jurassic period saw shallower marine conditions, and is characterised by marginal marine and lagoonal deposits, typically oolitic limestone. Sea levels again rose during the Upper Jurassic period, which resulted in the deposition of thick clay beds.

Jurassic limestones have been used extensively as a building stone, with Portland stone originating from Dorset, and stone for the Palace of Westminster coming from deposits in Lincolnshire. Numerous villages in the Cotswolds are built from locally derived supplies of oolitic limestone, these aggregates having a distinctive honey-brown colour. Gravels containing rocks of the Jurassic age have been used extensively in concrete (Cullimore, Pike and Jordan, 1976) but its use in concrete as a crushed rock aggregate is minimal. The aggregates used for the current research programme are of Middle Jurassic age, from locations in the Gloucestershire/Oxfordshire area, these being shown in *Figure 4.5.*

4.2.3.1 Sample J9

This sample was taken from the Clypeus Grit formation of the Inferior Oolite at Town Quarry, Charlbury, Oxfordshire. It is a buff-brown coloured, fossiliferous limestone, the fossils being mainly echinoids and bivalves, with a rough friable texture and an appreciable clay content. The larger aggregate particles are sub-rounded in shape and show significant iron staining, whereas the smaller particles tend to consist of shell fragments. In thin section, the particles consist principally of calcitic shell fragments, many of which exhibit a high void content. Although supplied as a 20 to 5 mm graded aggregate the aggregate had the grading characteristics of 20 mm to dust aggregate, but was used with the grading with which it was supplied.

4.2.3.2 Sample J10

This sample was taken from an horizon known as the Chipping Norton Limestone, a formation that occurs between the Inferior Oolite and the Great Oolite, at Swellwold Quarry, near Naunton, Gloucestershire. The material consists of a medium to coarse grained limestone containing numerous shell fragments and ooliths. The aggregate particles are buff-yellow in colour and are relatively soft. In thin section, the limestone is composed of micritic calcite, with numerous ooliths and bivalve fragments. Within the fabric of many particles fine quartz grains and voids are also visible.

4.2.3.3 Sample J11

This sample was taken from the Stonesfield Slate horizon within the Great Oolite, at Huntsman Quarry, Naunton, Gloucestershire. This limestone is buff-grey in colour, with the particles being sub-rounded, soft and having a friable texture. In thin section, the limestone consisted of bivalve fragments and ooliths within a sparitic calcite cement with some voids also visible.

4.2.3.4 Sample J12

This sample was taken from the White Limestone horizon within the Great Oolite, at Daglingworth Quarry, near Cirencester, Gloucestershire. This dusty limestone is buff-yellow in colour and contains numerous shell fragments, including bivalves and ooliths. The aggregate particles are sub-angular in shape and soft. In thin section, the sample is a calcitic oomicrite, with some sparite cement visible. This composition is uniform throughout the sample, with very few voids evident.

The typical appearance of ooliths and shell fragments, typically seen in each of the Jurassic Limestones, is shown in *Plate 4.5* which shows the microscopic nature of sample J10.

4.2.4 Control Aggregate

The aggregate used as a control throughout the testing programme was supplied from Weeford Quarry, near Sutton Coldfield, Staffordshire, from the Bunter Pebble Beds of the Permo-Trias period (280-195 mya), which are thought to be derived from an ancient river system. The material consists of a coarse well-rounded gravel, with the main constituents being grey to brown quartzite and white to grey vein quartz. The finer size fractions (10 to 5 mm) of the coarse aggregate include some material produced from crushing the primary aggregate source. The fine aggregate (5 mm down) has the same principal constituents as the coarse aggregate and was supplied from the same source.

4.3 Aggregate Properties

This section presents and discusses the results of tests that were carried out on all of the aggregates prior to casting the specimen slabs. The results of relative density, 24 hour absorption, Los Angeles Abrasion and Mohs' Hardness tests are given in *Tables 4.1* and *4.2*. Subsequent sections discuss these results for both the coarse and fine aggregates. Grading data for the aggregate groups are presented in *Figures 4.6* to *4.13*, with the current British Standard grading limits (BS 882: 1992) being given for comparison. The grading data for the specific aggregates are presented in Appendix B. The results of the microscopic tests such as microhardness and pore size distribution are reported and discussed in Chapter 5, Section 5.5.

4.3.1 Relative Density

The relative density, commonly referred to as specific gravity, is the ratio of the mass of aggregate dried in an oven for 24 hours, to the mass of water occupying a volume equal to that of the solid including the impermeable pores (Neville and Brooks, 1987). The majority of natural aggregates used in concrete have relative densities in the range 2.6 to 2.7, with some lightweight aggregates such as sintered fly ash being as low as 1.4 (Neville, 1981). Relative density is not generally considered to be a measure of aggregate quality, and is not often quoted in contract specifications unless a minimum concrete density is specified, as is often the case with gravity dams and radiation shielding.

4.3.1.1 Relative Density of the Coarse Aggregates

The relative densities of the coarse aggregates reported in *Table 4.1* show a variation from 2.37 to 2.74. These values show a good relationship with the 24 hour absorption values, with trends for each rock type shown graphically in *Figure 4.14*, and can be related to the void content of the rock. The Carboniferous Sandstone coarse aggregates displayed this relation clearly, with C2 and C3 having the values of 2.39 and 2.37 respectively, compared to C4 which had a higher value of 2.6. In thin section, both C2 and C3 had an extensive void network, whereas there were negligible voids visible in aggregate C4. The Magnesian Limestone coarse aggregates also exhibited a range in values, with the lowest being 2.39 obtained from M6a, the aggregate containing numerous clay lumps and porous particles. Aggregates M5 and M8, which both had a well crystallised fabric, had values of 2.74 and

2.63 respectively. The relative densities of the Jurassic Limestone aggregates were more consistent with one another, with J10, J11 and J12 within the narrow range of 2.50 to 2.56. This was due to the similar nature of these aggregates, each was fossiliferous, consisting mainly of calcite and with a broadly similar void content. Sample J9 had a lower value of 2.45, which again can be attributed to an increased void content. Although some of the aggregates exhibited relative densities lower than those of aggregates normally used in concrete, previous research has shown that coarse aggregates with relative densities as low as 2.0 to 2.3 can be successfully used in concrete (Collins, 1986).

4.3.1.2 Relative Density of Fine Aggregates

The relative densities reported in *Table 4.2* show a variation from 2.23 to 2.58. As with the coarse aggregates, there is a correlation with 24 hour absorption, although it is not significant to the same level and trends for each rock type are not discernible. This correlation is shown in *Figure 4.15*. The relative density values of the crushed Carboniferous Sandstones were more consistent with each other than those of the coarse aggregates. This was probably due to the crushing process removing many of the inter-granular voids, particularly evident in C2 and C3. The resultant crushed fines from the sandstones were effectively quartz sands with broadly similar relative densities, namely 2.38 to 2.49. The fine aggregates from the Magnesian Limestone sources still exhibited variations in relative density, even after the crushing process. Aggregate M6F still had a value appreciably lower than the other aggregates in this group, and this was probably due to the presence of clays and porous particles that were visible in the coarse aggregate. The difference in values between M5F and M8F may be due to the fact that M8F was composed principally of calcite, which has a lower value of relative density of 2.7, whereas M5F was composed mainly of dolomite, which has a relative density of 2.8 to 2.9 (Read, 1970). The Jurassic Limestone crushed fines still exhibited results consistent with one another, although J9F had a slightly lower value, possibly due to its higher void content. No correlation was found between relative densities of the coarse aggregates and relative densities of the fine aggregates.

4.3.2 24 Hour Absorption

Water absorption is a good measure of the porosity and permeability of an aggregate and relationships between absorption and certain pore-space characteristics are explored in Chapter 5, Section 5.5.3. As discussed in Chapter 2, Section 2.9.1.6, typical UK aggregates have absorption values in the range 1 to 5 per cent (Newman, 1959) and a value below 1 per cent is considered to be low (Smith and Collis, 1994). Work at the Building Research Establishment (Collins, 1986) has demonstrated that satisfactory concrete can be made with aggregates having absorption values as high as 9.7 per cent. Contract specifications do not normally specify a maximum limit on the water absorption of aggregates, although BS 8007: 1987: Code of practice for design of concrete structures for retaining aqueous liquids, states that absorption should not normally be above 3 per cent.

The coarse aggregates used throughout the project had absorption values in the range 0.8 to 9.3 per cent whilst the fine aggregates had values in the range 1.2 to 8.9 per cent. The control aggregate exhibited the lowest absorption values for both the coarse and fine aggregates. The crushed fines generally exhibited values slightly lower than their corresponding coarse aggregates, as discussed in Section 4.3.1.2, and this is again probably due to the removal of the inter-granular voids during the crushing process. A significant correlation exists between 24 hour absorption of the coarse aggregates and 24 hour absorption of the fine aggregates, and is shown in *Figure 4.16*.

4.3.3 Los Angeles Abrasion Value

The Los Angeles Abrasion test can be considered a measure of toughness and the aggregates used in the current project exhibited a wide variation in results, from a minimum value of 20 per cent obtained from the control to a maximum of 95 per cent obtained from the Carboniferous Sandstone aggregate C3. A full list of Los Angeles Abrasion values is presented in *Table 4.1*. The three highest losses were obtained by the Carboniferous Sandstone aggregates C1, C2 and C3; these all had a granular texture with little or no matrix between constituent grains, enabling them to break up readily under impact loads. The three lowest losses, excluding the control, were obtained by the Carboniferous Sandstone C4, and the Magnesian Limestones M5 and M8. These rocks all possessed a well-crystallised fabric with no obvious planes of weakness, which enabled them to withstand impact loads to a greater degree. The Los Angeles Abrasion value for the sample J9 has not been included in correlation calculations in subsequent chapters, as it was deemed to be unrepresentative of the sample used in the mixes. The size fraction required for the test consisted entirely of relatively hard limestone fragments, and did not include the sizeable proportion of softer shell fragments of 10 mm and smaller.

4.3.4 Mohs' Hardness

The Mohs' Hardness of a mineral or rock is a comparative measure, and ranks a material on a scale from 1 to 10, 1 being the softest and 10 being the hardest. Although a relatively crude test, it is a widely used and recognised test in the geological field for ascertaining the hardness of a mineral. The full list of standard Mohs' Hardness minerals is given in Appendix G, with the results of the tests on the aggregates being given in *Table 4.1.* Subsequent relationships plotted using Mohs' Hardness values use the median value of those presented in *Table 4.1,* and these median values are given in Chapter 5, *Table 5.12.* The Carboniferous Sandstone aggregates were the hardest of those tested, with C1, C2 and C3 all measuring 6 to 6.5 and C4 measuring 5 to 5.5. The Magnesian Limestones were variable in hardness, particularly M6a and M6b which had values in the range 2 to 3.5 and 2 to 4.5 respectively. Aggregate M5 was the hardest at 4 to 4.5, with M8 measuring 3 to 3.5. The Jurassic Limestone aggregates were generally the softest with J9, J10 and J11 all having values within the range 2.5 to 3. Aggregate J12 was slightly harder, and had a value of 3 to 3.5. The control aggregate had a hardness in the range 6.5 to 7.

When these values of hardness are compared with those obtained from the Los Angeles Abrasion test, it is interesting to note that the hardest aggregates, the Carboniferous Sandstones, have the highest Los Angeles Abrasion losses, and that aggregates of different hardnesses, C4, M5 and M8, have similar Los Angeles Abrasion losses. It is important, therefore, to distinguish clearly between hardness and toughness, as a hard aggregate may clearly not be a tough aggregate. The difference between hardness and toughness is explored in more detail in Chapter 5, Section 5.5.2.

4.3.5 Grading

The overall grading of the combined coarse and fine aggregates should lead to the lowest possible water and cement contents necessary to achieve, principally, the desired workability and strength. By using appropriate proportions of aggregates within the limits in BS 882: 1992 it should be possible to produce concrete with satisfactory properties in both the fresh and hardened states. An excess of coarse material leads to harshness, and the concrete will be difficult to finish. An excess of fines leads to an increased water content to achieve the necessary workability and so a less durable concrete.

Grading envelopes for each of the aggregate groups, both coarse and fine, are presented in *Figures 4.6* to *4.13*, with the grading curves for individual aggregates being presented in Appendix B, *Figures B.1* to *B.25*. The grading characteristics of the coarse and fine aggregates are discussed in Sections 4.3.5.1 and 4.3.5.2 respectively.

4.3.5.1 Coarse Aggregate Grading Characteristics

The coarse aggregates were supplied from the quarries as nominally 20 to 5 mm graded aggregates, and it was the limits for this grading category with which the test aggregates are compared in the grading curves, *Figures 4.6, 4.8, 4.10* and *4.12*. The overall grading limits for 20 to 5 mm graded coarse aggregates are given in *Table 4.3,* and the grading curves for individual aggregates are presented in Appendix B. The Carboniferous Sandstone coarse aggregates were generally within the grading limits in BS 882: 1992, *Figure 4.6,* with three exceptions. Aggregate C4 had an excess of material in the 14 to 10 mm size range, *Figure B.7,* and both C1 and C2 were deficient in material of the 10 to 5 mm size range, *Figures B.1* and *B.3* respectively. The Magnesian Limestone aggregates were within the specified grading limits, *Figure 4.8,* with the exception of M6a which was deficient in material in the 10 to 5 mm range, *Figure B.11.* The presence of clay lumps tended to make the mix containing M6a rather cohesive. The Jurassic Limestones J10 and J12 were both deficient in material of the 10 to 5 mm range, whilst J9 had an excess of material passing the 5 mm sieve, *Figures B.18, B.22* and *B.16* respectively.

Overall, the gradings of the coarse aggregates, with the exception of J9, were generally within or close to the limits set in BS 882: 1992 for 20 to 5 mm graded aggregate.

4.3.5.2 Fine Aggregate Grading Characteristics

The fine aggregate grading curves presented in *Figures 4.7, 4.9, 4.11 and 4.13* show the grading envelopes for each aggregate type in relation to the overall grading limits set in BS

882: 1992 for crushed rock fines. The overall grading limits and the additional limits for coarse, medium and fine sands are given in *Table 4.4*. Detailed grading curves for individual aggregates are given in Appendix B. All of the Carboniferous Sandstone crushed fines satisfied the overall grading limits, *Figure 4.7*, with aggregates C1F, C2F and C3F also satisfying the additional limits for coarse sands (C) and medium sands (M), *Figures B.2, B.4* and *B.6* respectively. Aggregate C4F satisfied the limits for C class sands, *Figure B.8*. The grading characteristics of the Magnesian Limestone crushed fines were more variable, *Figure 4.9*, although M5F satisfied the overall and C class grading requirements, neither M6F or M8F satisfied the overall grading requirements, *Figures B.10, B.13* and *B.15* respectively. Aggregate M6F had an excess of material finer than 150 μm, whilst M8F was deficient in material finer than 2.36 mm. The coarseness of M8F was reflected in a harsh mix, although a satisfactory finish was still achieved after power finishing. The Jurassic Limestone crushed fines J10F and J11F both satisfied the overall grading limits, *Figures B.19* and *B.21*, with J10F also satisfying the additional limits for fine sands (F), and J11F the C and M limits. Aggregate J9F, *Figure B.17*, did not comply with the overall limits because it was deficient in material of the 10 to 2.36 mm range. Aggregate J12F, *Figure B.23*, did not comply because it had an excess of material finer than 150 μm. A significant correlation (for all aggregates) was found between the percentage of material finer than 150 μm and the 24 hour absorption value, and this is illustrated in *Figure 4.17*.

In broad terms, the crushed fines had grading characteristics within or close to the overall limits set in BS 882: 1992, with only the coarseness of M8F being subsequently reflected in the properties of the resultant concrete. It should be noted that BS 882: 1992 permits the use of sands which do not comply with the grading requirements provided that " the supplier can satisfy the purchaser that such materials can produce concrete of the required quality ". It is, however, possible to overcome certain grading deficiencies. Air entrainment may be employed to improve concrete containing sand that is too coarse, and water-reducing additives may be used in mixes where the sand is too fine.

4.4 Cement

Ordinary Portland Cement supplied by Blue Circle was used throughout the test programme. All cement used was from a single batch acquired at the beginning of the project and stored in double-sealed containers until required for casting. A detailed chemical analysis is given in Appendix F.

4.5 Mixing Water

All concrete specimens were prepared using tap water.

4.6 Steel

Mild steel reinforcement (10 mm diameter) was used in all specimens.

Agg. Ref.	Rel. Density (Oven Dry)	24 Hour Abs. (%)	LA Abrasion (% Loss)	Mohs' Hardness
C1	2.47	3.1	66	6 to 6.5
C2	2.39	4.4	87	6 to 6.5
C3	2.37	5.2	95	6 to 6.5
C4	2.60	2.5	22	4.5 to 5
M5	2.74	2.0	28	4 to 4.5
M6a	2.39	9.3	59	2 to 3.5
M6b	2.57	5.4	36	2 to 4.5
M8	2.63	2.6	27	3 to 3.5
J9	2.45	7.1	42	2.5 to 3
J10	2.56	3.9	44	2.5 to 3
J11	2.50	4.7	42	2.5 to 3
J12	2.50	5.3	42	3 to 3.5
Control (CS)	2.61	0.8	20	6.5 to 7

Table 4.1. Summary of relative density, absorption, Los Angeles Abrasion and Mohs' Hardness data for the coarse aggregates.

Agg. Ref.	Relative Density (Oven Dry)	24 Hour Absorption (%)
C1F	2.38	1.6
C2F	2.49	1.4
C3F	2.49	2.1
C4F	2.43	4.7
M5F	2.58	2.0
M6F	2.29	8.9
M8F	2.33	2.1
J9F	2.23	4.9
J10F	2.33	3.5
J11F	2.43	2.7
J12F	2.48	4.1
Control (CSF)	2.47	1.2

Table 4.2. Summary of relative density and absorption data for the fine aggregates.

Sieve Size (mm)	Grading Limits (% Passing)
50.0	-
37.5	100
20.0	90-100
14.0	40-80
10.0	30-60
5.0	0-10
2.36	-

Table 4.3. BS 882: 1992 limits for 20 to 5 mm graded aggregate.

Sieve Size (mm)	Overall Limits (% Passing)	Additional Grading Limits		
		C	M	F
10.0	100	-	-	-
5.00	89-100	-	-	-
2.36	60-100	60-100	65-100	80-100
1.18	30-100	30-90	45-100	70-100
0.60	15-100	15-54	25-80	55-100
0.30	5-70	5-40	5-48	5-70
0.15	0-15*	-	-	-

* Increased to 20 % for crushed rock sand, except when used for heavy duty floors.

Table 4.4. BS 882: 1992 grading limits for sand.

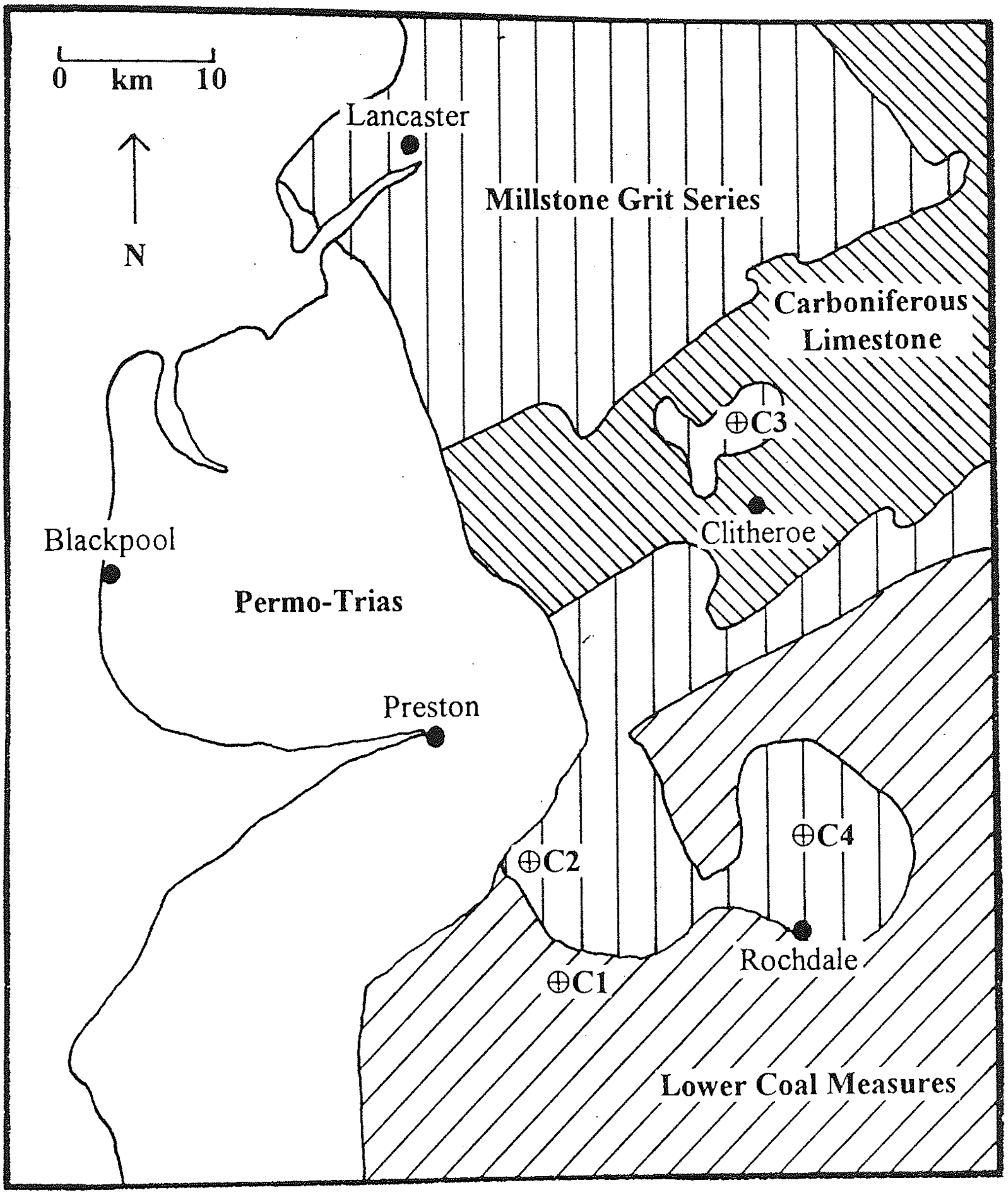

Figure 4.1. Schematic map of the geology of Lancashire, showing the sources of the Carboniferous Sandstone aggregates.

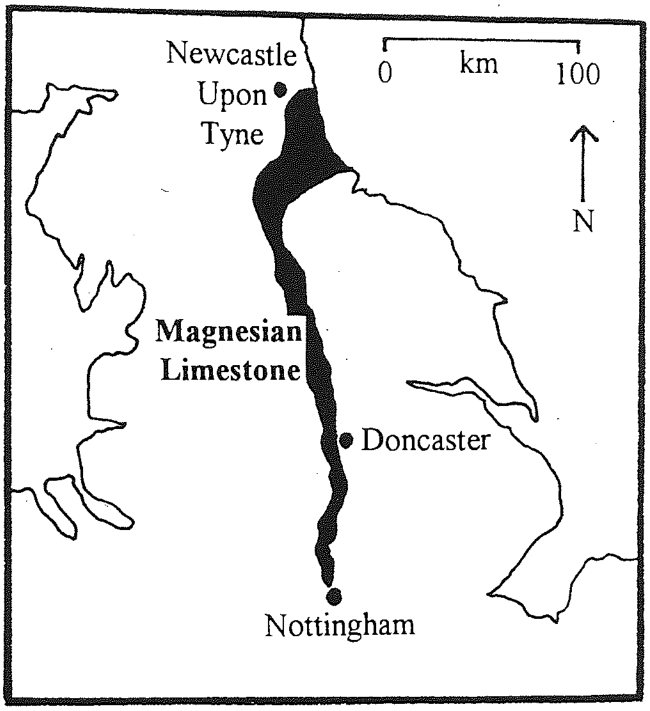

Figure 4.2. Map showing the extent of the Magnesian Limestone outcrop in England.

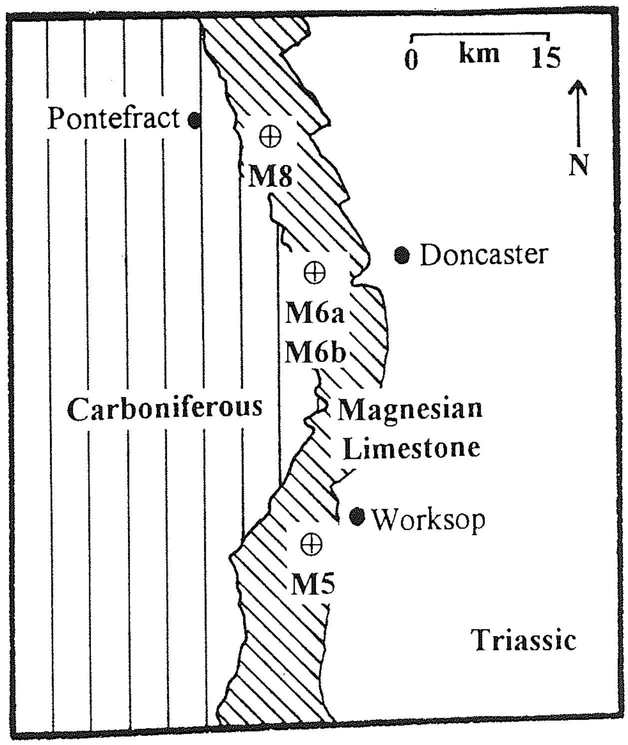

Figure 4.3. Location of the Magnesian Limestone aggregate sources.

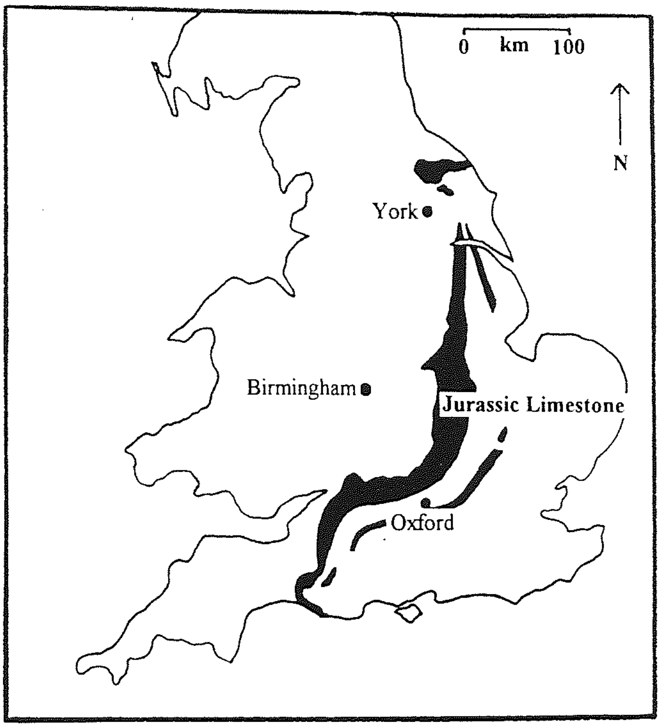

Figure 4.4. Map showing the extent of the Jurassic Limestone outcrop in England.

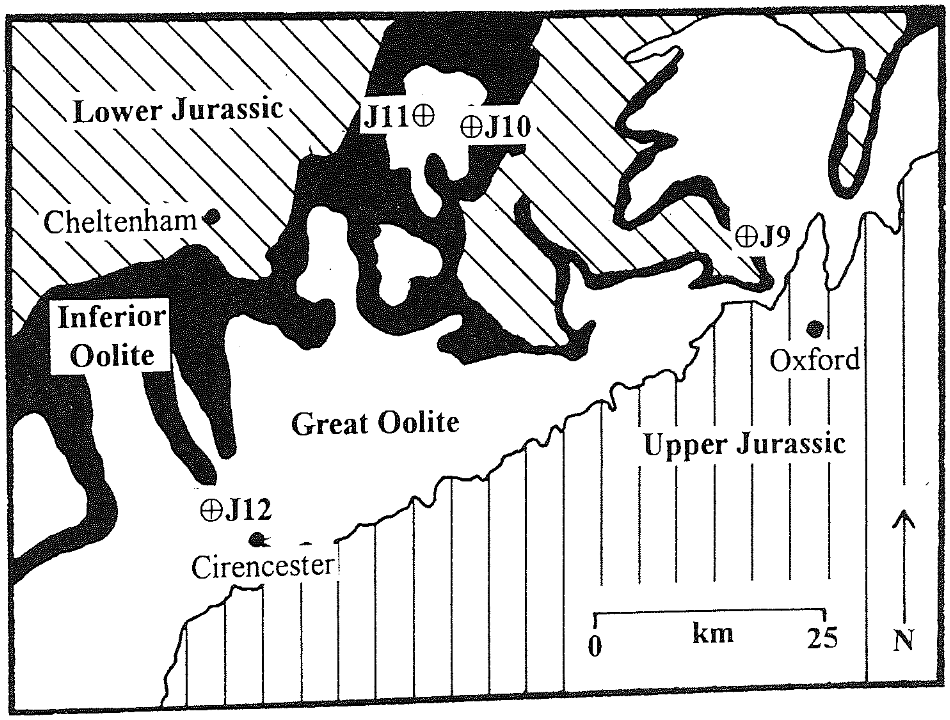

Figure 4.5. Location of the Jurassic Limestone aggregate sources.

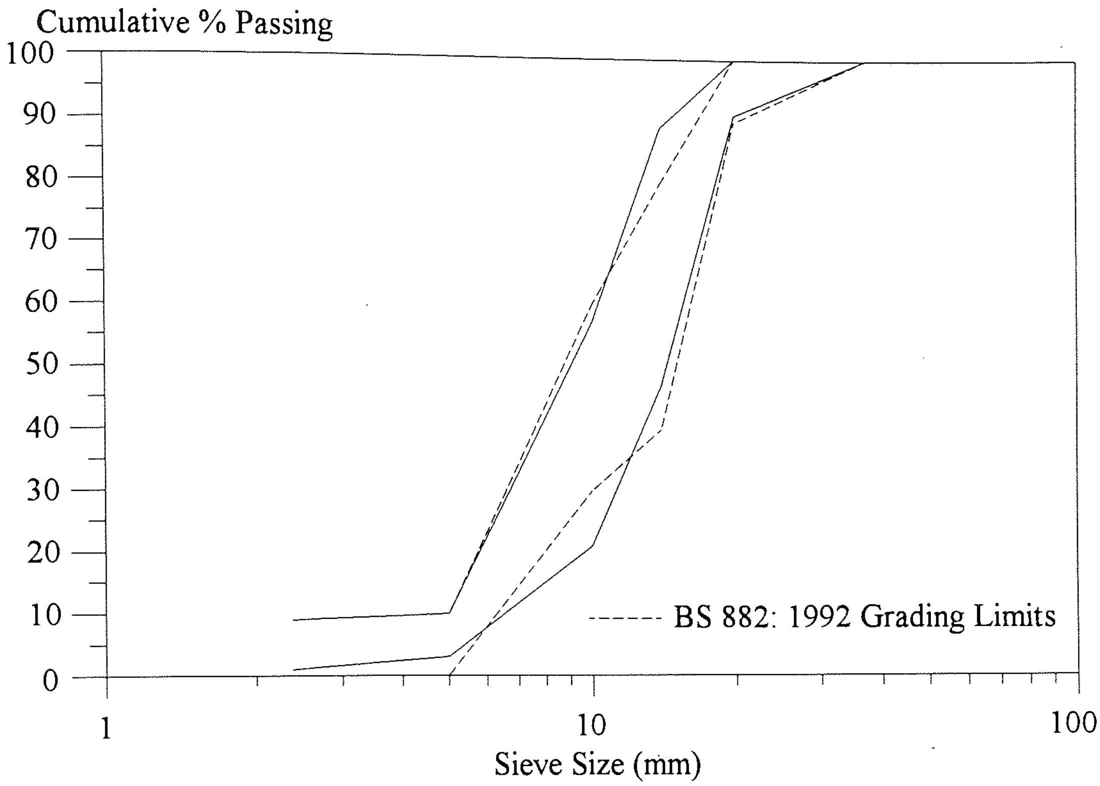

Figure 4.6 Grading envelope for Carboniferous Sandstone coarse aggregates.

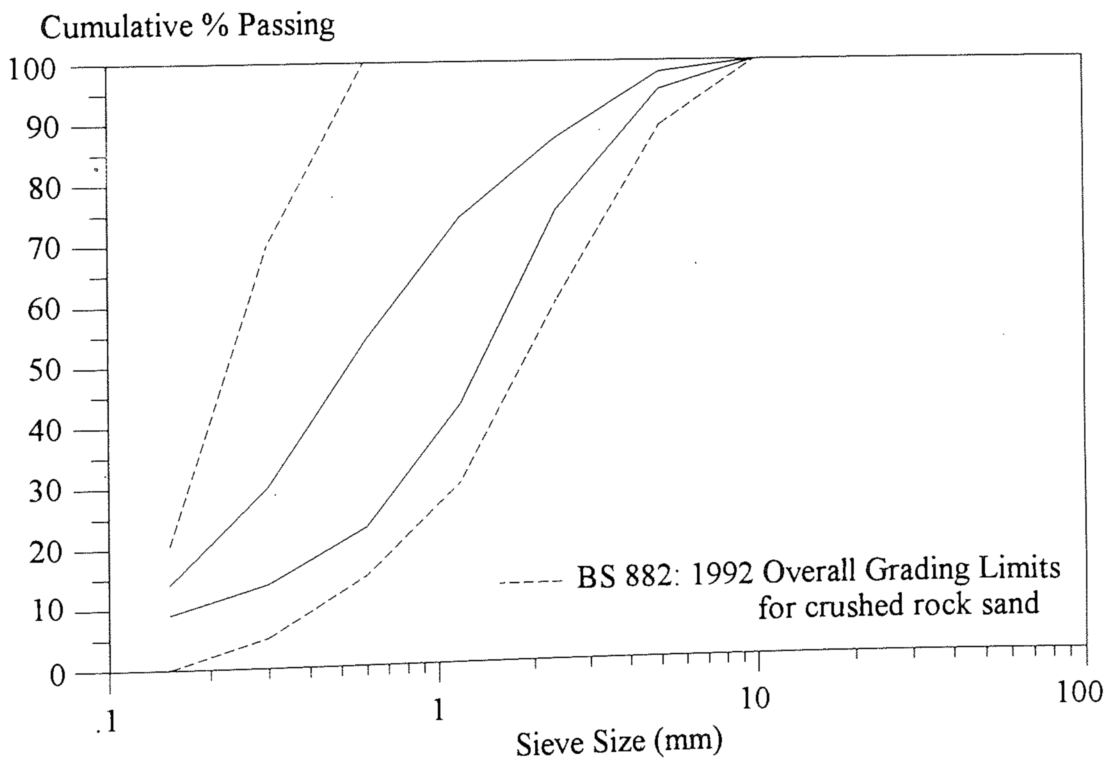

Figure 4.7 Grading envelope for Carboniferous Sandstone crushed rock fines.

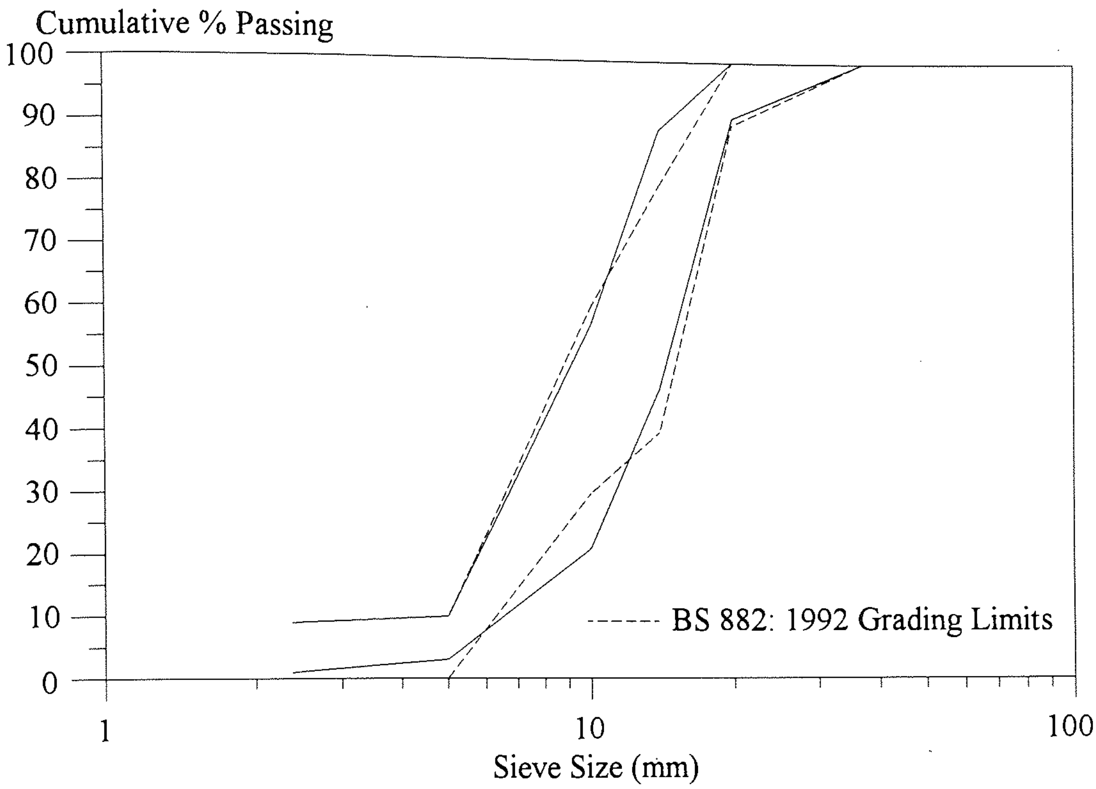

Figure 4.6 Grading envelope for Carboniferous Sandstone coarse aggregates.

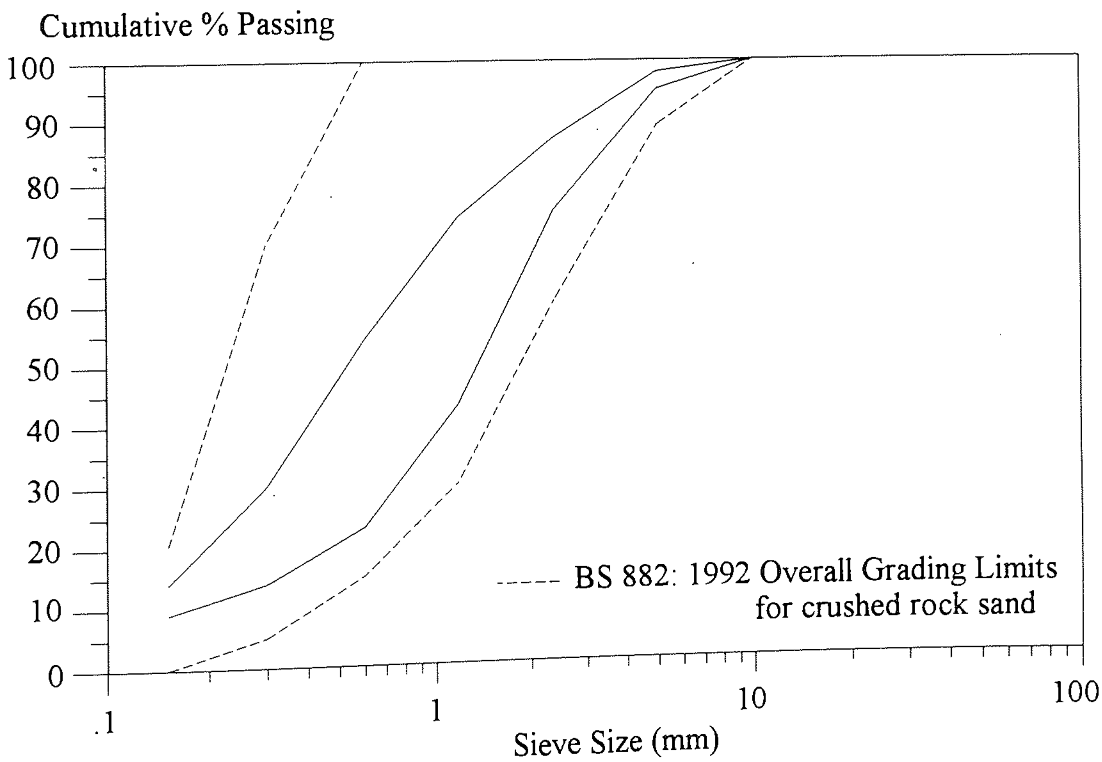

Figure 4.7 Grading envelope for Carboniferous Sandstone crushed rock fines.

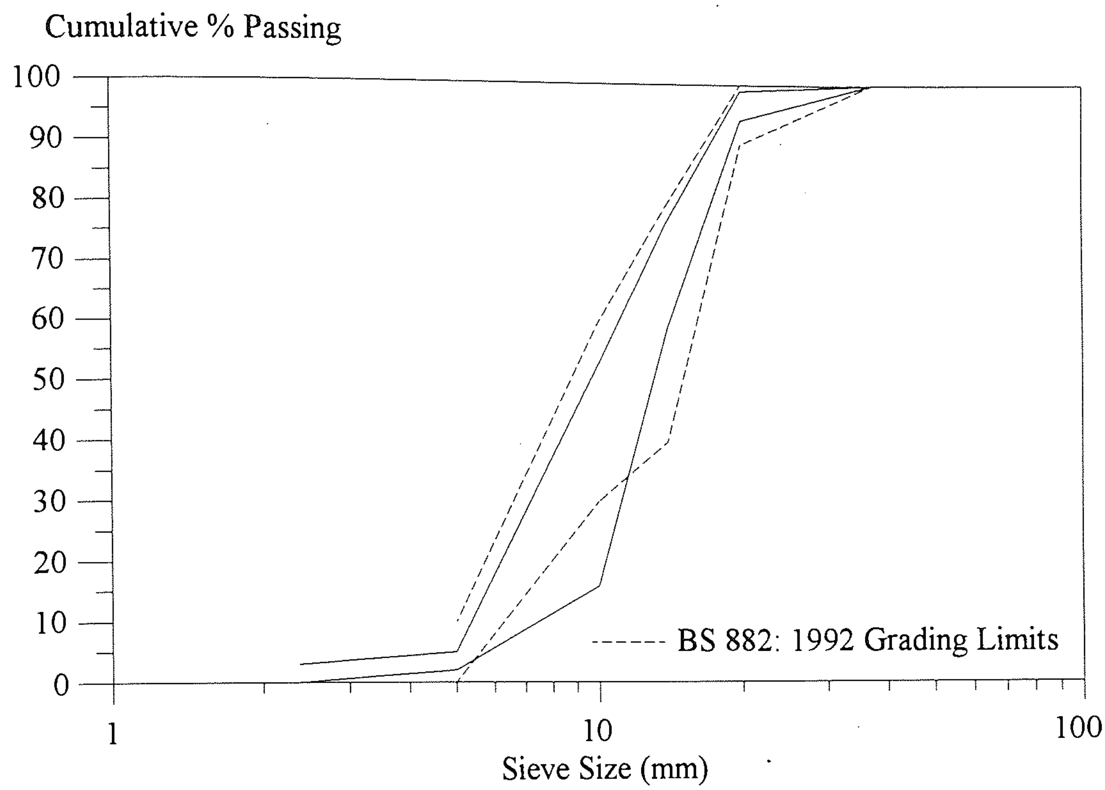

Figure 4.8 Grading envelope for Magnesian Limestone coarse aggregates.

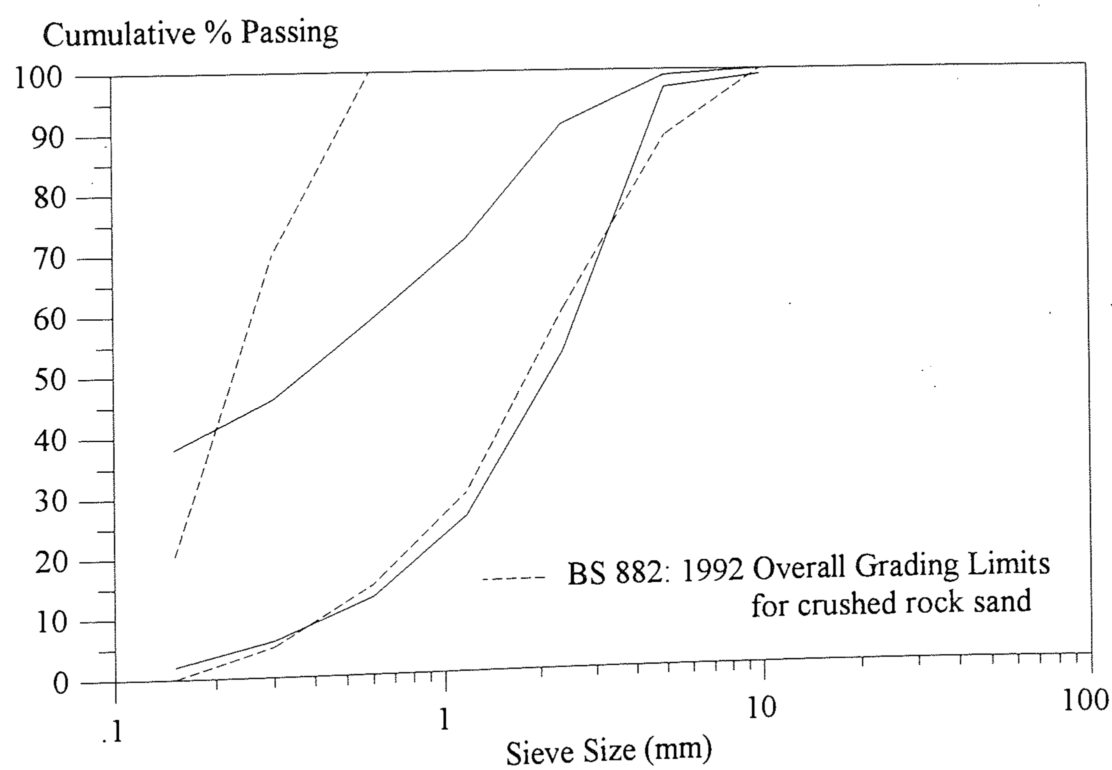

Figure 4.9 Grading envelope for Magnesian Limestone crushed rock fines.

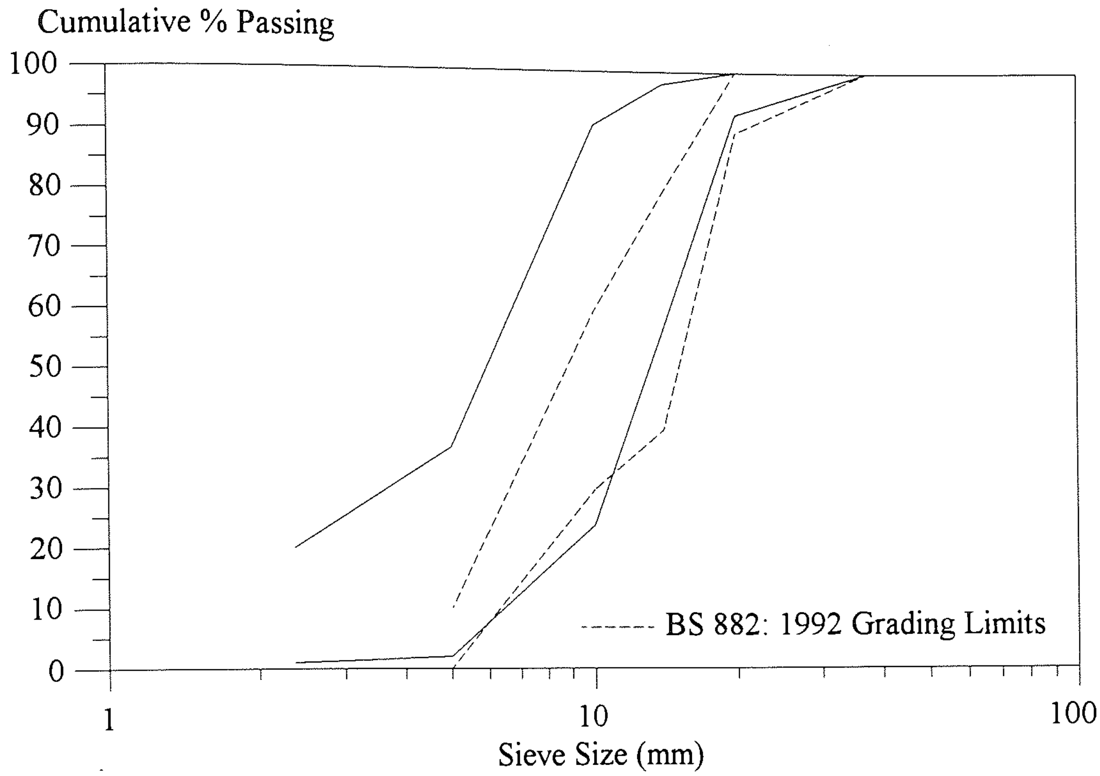

Figure 4.10 Grading envelope for Jurassic Limestone coarse aggregates.

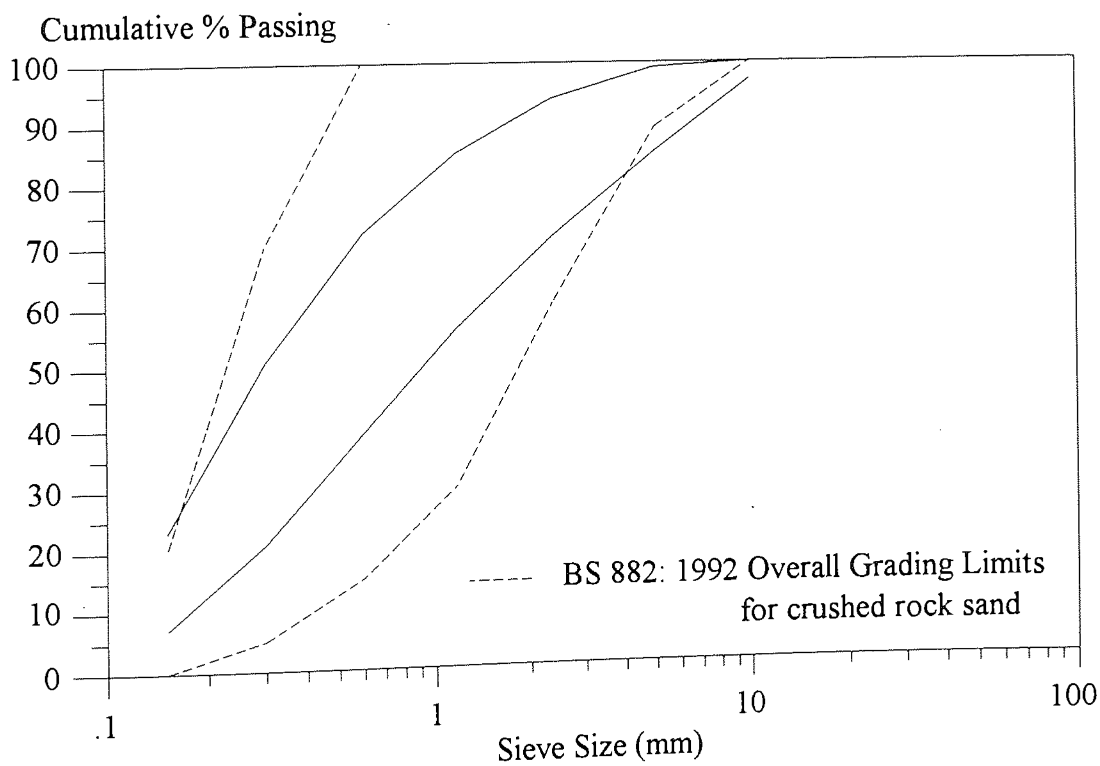

Figure 4.11 Grading envelope for Jurassic Limestone crushed rock fines.

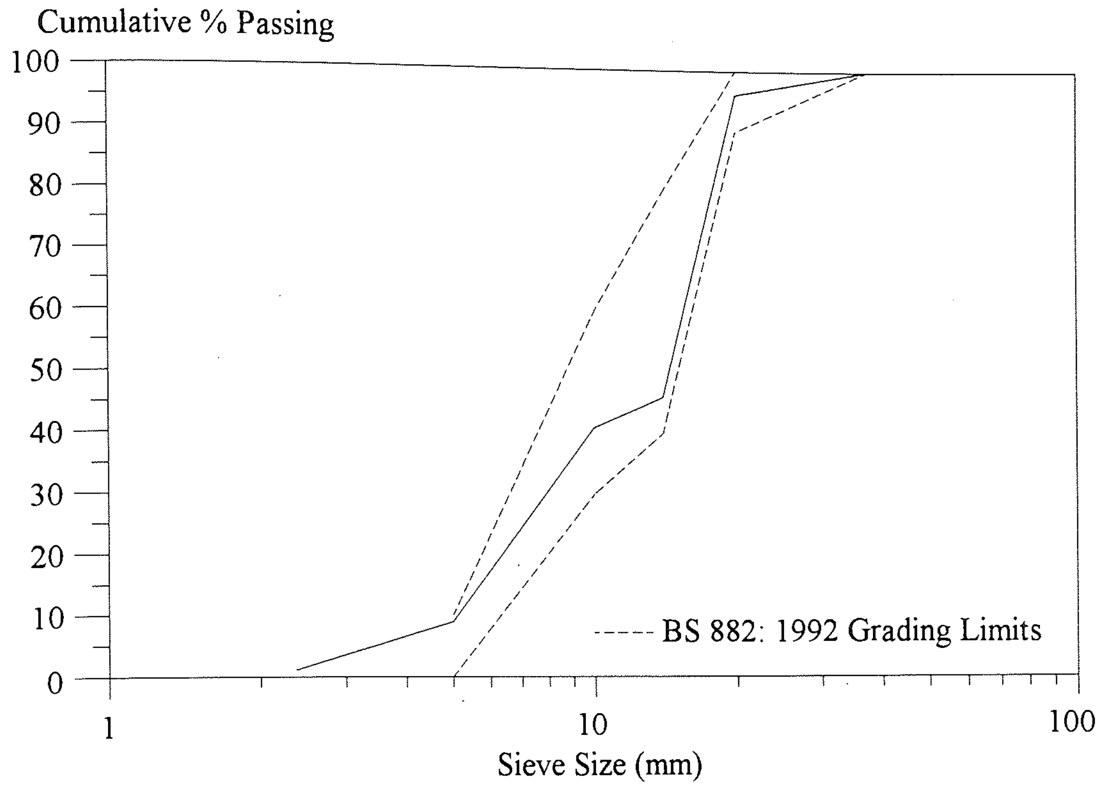

Figure 4.12 Grading curve for the coarse aggregate control.

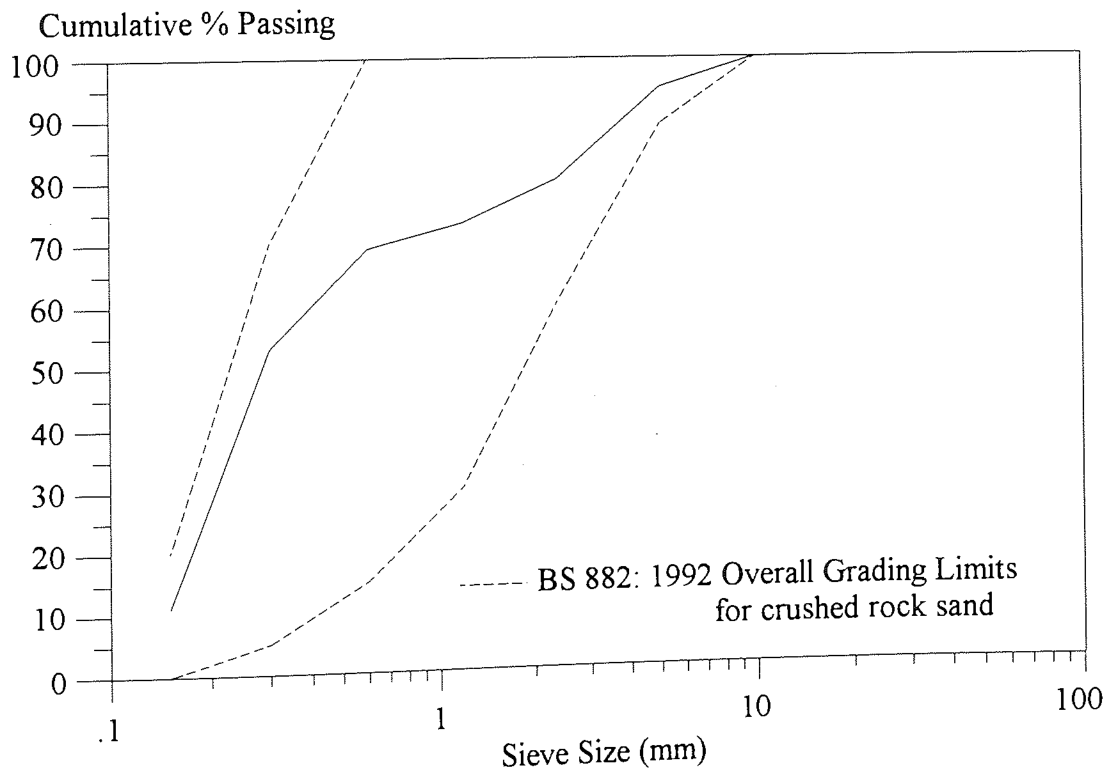

Figure 4.13 Grading curve for the fine aggregate control. For natural sands the upper limit on material passing 150 μm is reduced to 15 % from 20 %.

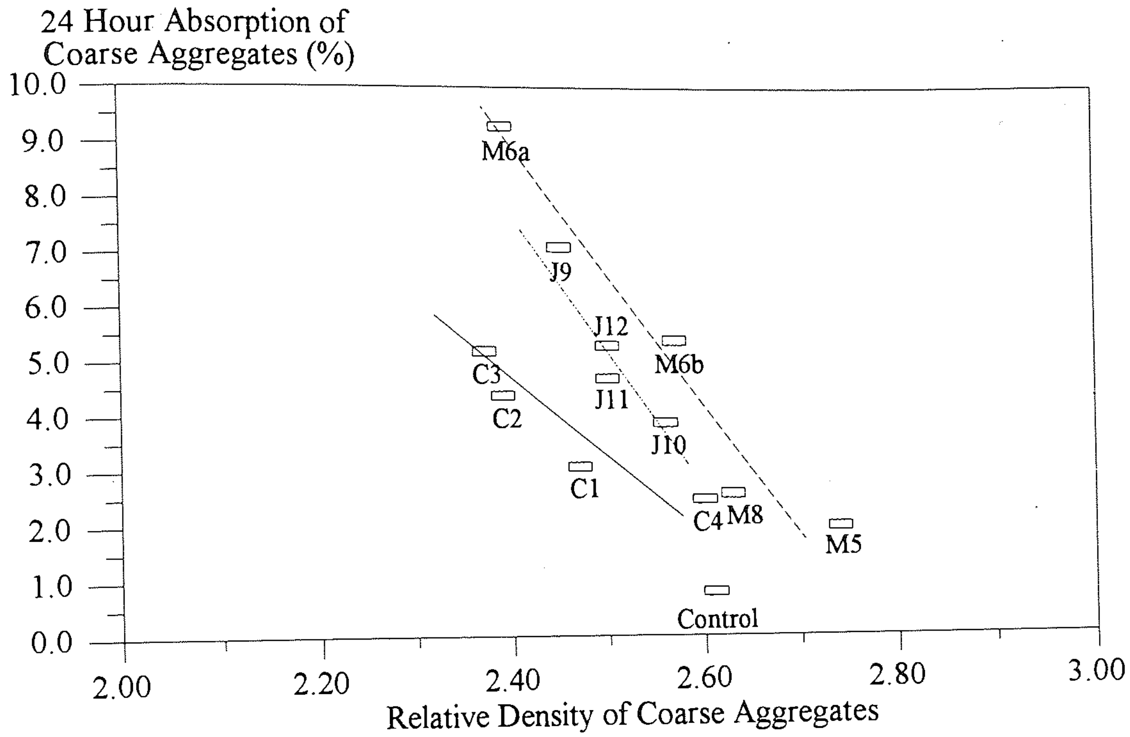

Figure 4.14. Relationship between relative density and absorption of the coarse aggregates.

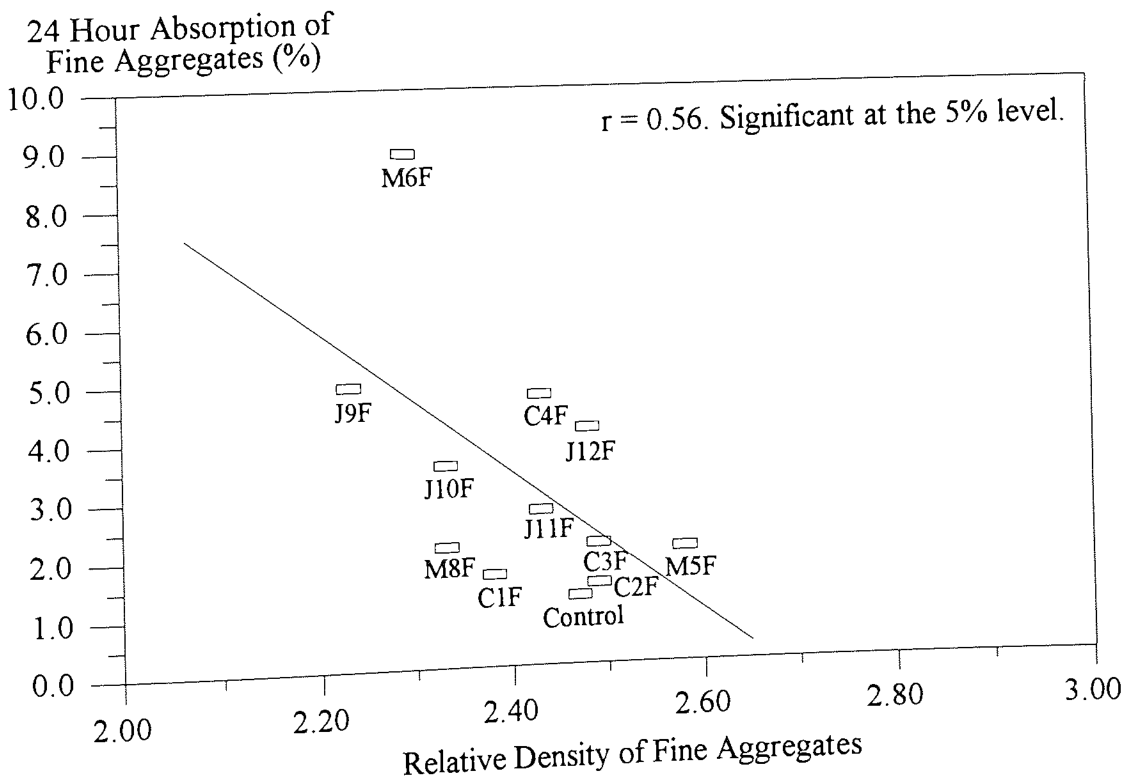

Figure 4.15. Relationship between relative density and absorption of the fine aggregates.

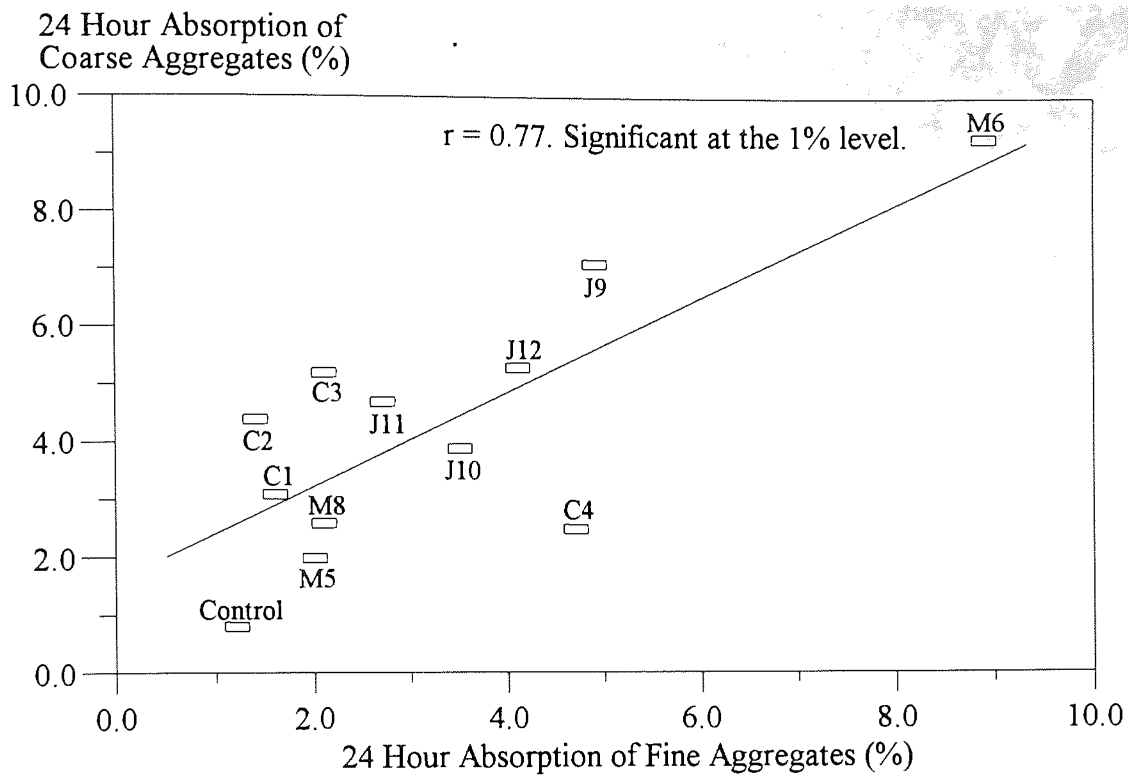

Figure 4.16. Relationship between absorption of crushed fines and absorption of coarse aggregate from the same source.

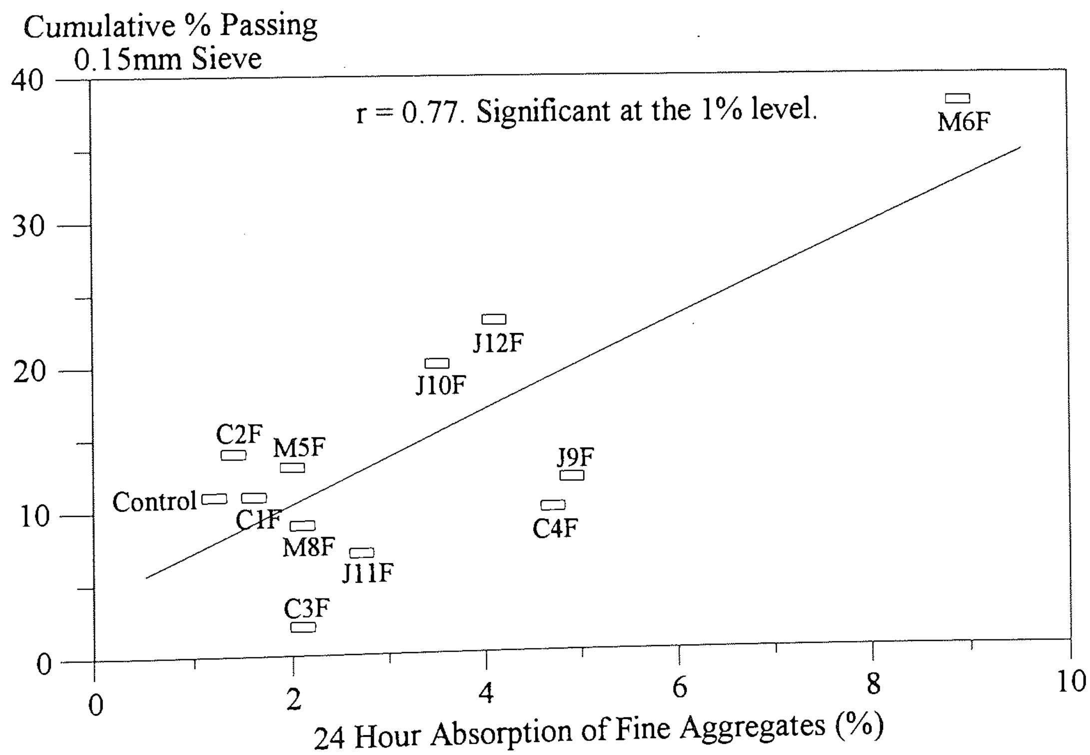

Figure 4.17. Relationship between percentage passing 150 μm and 24 hour absorption for fine aggregate.

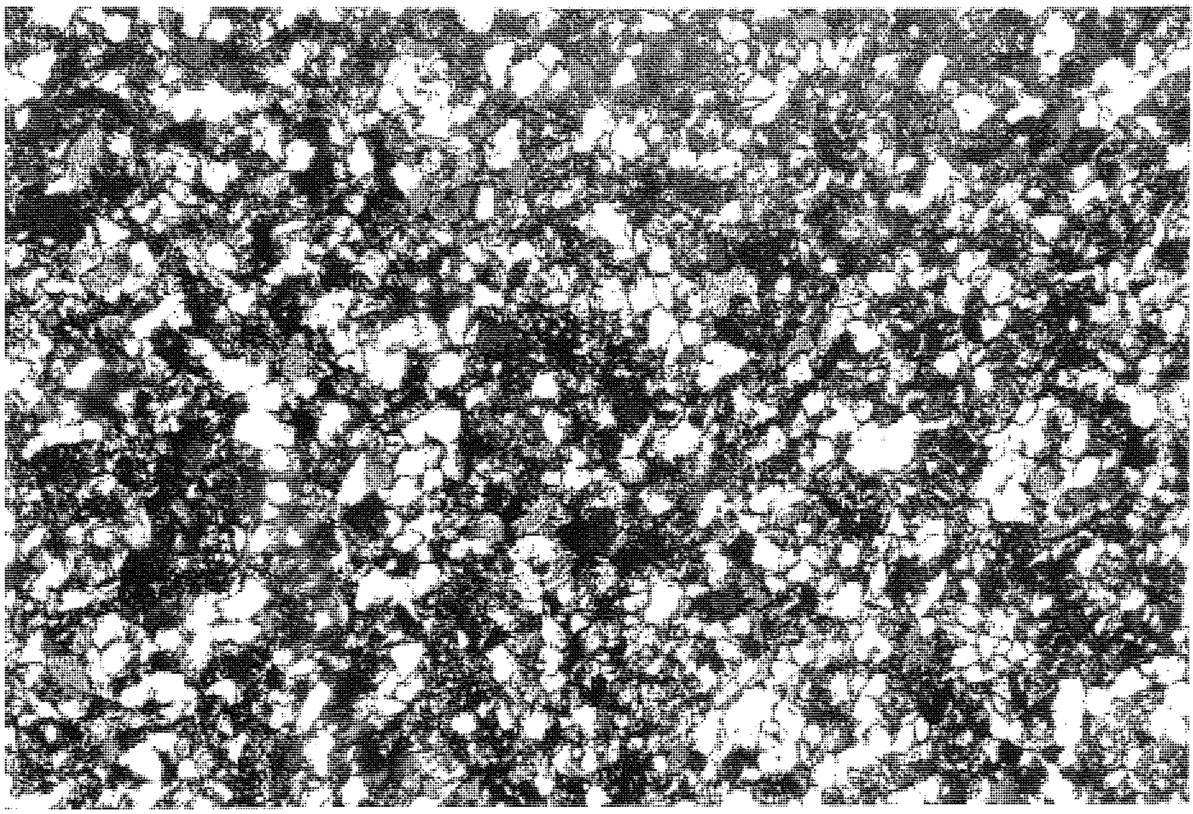

Plate 4.1 The microscopic appearance of aggregate C4 (x40).

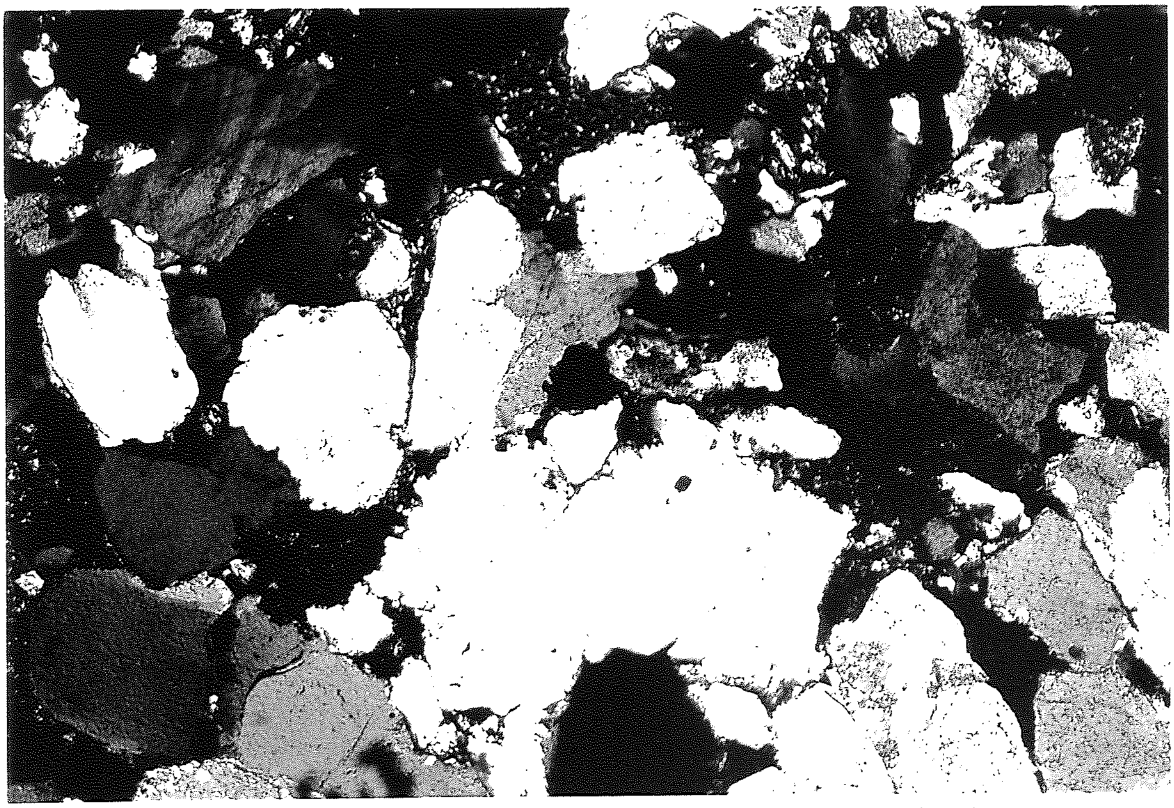

Plate 4.2 The microscopic appearance of aggregate C1 (x40).

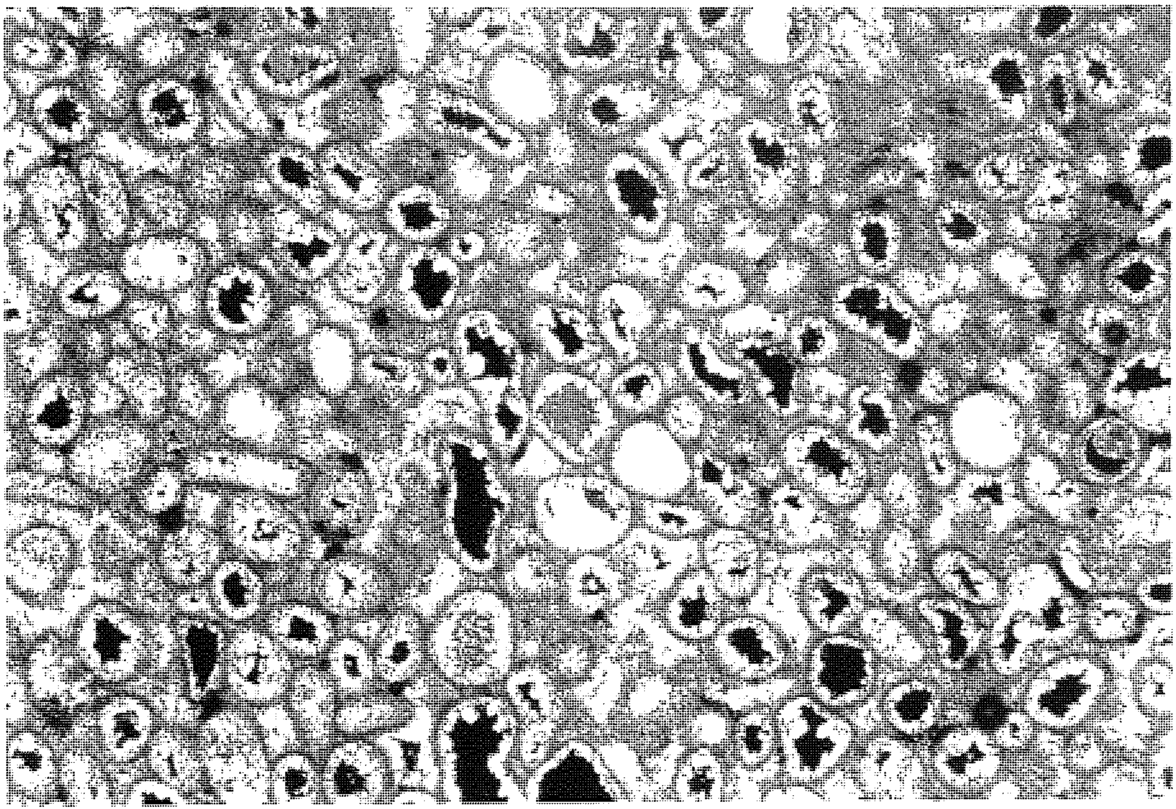

Plate 4.3 The oolitic texture seen in particles of sample M6a (x40). The dark areas are voids.

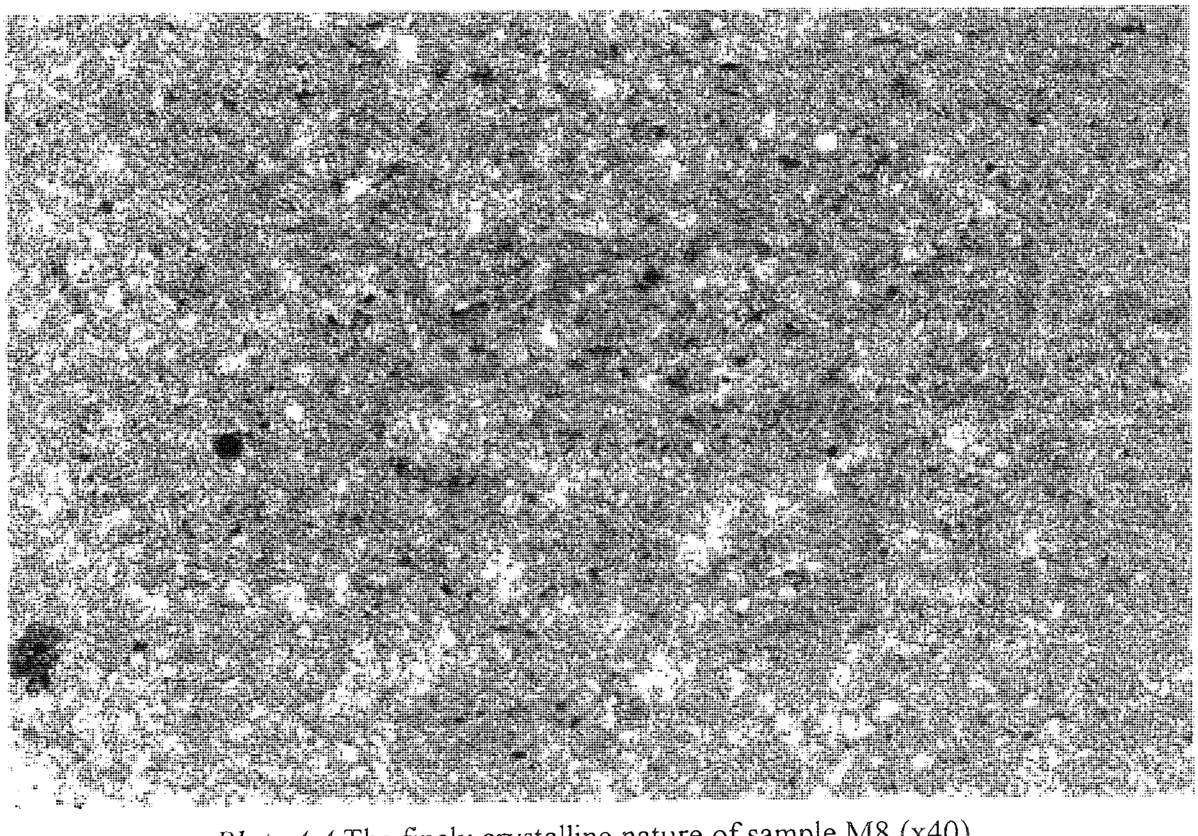

Plate 4.4 The finely crystalline nature of sample M8 (x40).

Plate 4.5 The microscopic appearance of sample J10 showing shell fragments and ooliths (x40).

Chapter 5 Test Results

5.1 Introduction

Initially, trial mixes were cast to check for workability and strength, so that mix designs could be prepared for the main test specimens. Details of the trial mixes and the reasoning for the subsequent mix designs are given in Section 5.2.

Subsequent sections of this chapter present the results from the cube strength and abrasion tests for all the coarse and fine aggregate mixes, and those from the microscopic, microhardness and mercury intrusion porosimetry analyses. An outline summary and initial discussion of the results are given.

5.2 Mix Design

After collecting the aggregates from the quarries, and performing the tests outlined in Chapter 3, it was necessary to produce a series of small trial mixes to establish the mix designs for use throughout the project. Due to the logistical problem of drying all the aggregates before mixing, all the aggregates used for both trial mixes and project mixes were used in an 'as received' condition. It was therefore necessary to determine the moisture content of the aggregates on the day of mixing so that the total water in the mix could be determined by adding this value to the quantity of added water. As discussed in

Chapter 3, Section 3.4.1.2, the water-cement ratios referred to in this, and subsequent, chapters represent the third batch of each mix. As the moisture contents varied from sample to sample, and all mixes were batched by weight, this produced very slight variations in the aggregate proportions between each mix. No significant relationships were found between these differences in aggregate proportion and either the cube strength or abrasion resistance of the concrete containing them. Exact mix proportions for the individual mixes are detailed in Appendix A.

5.2.1 Coarse Aggregate Mix Design

Two sandstone aggregates, C1 and C2, were chosen for this purpose as they clearly demonstrated the properties of low strength and high absorption, typical features of low-grade aggregates. Aggregate C1 was used for Mixes 1 to 3, with C2 being used for Mixes 4 to 6, summarised in *Tables 5.1a* and *5.1b*. An initial mix of 30 kg was designed using the standard procedures (Teychenné, Franklin and Erntroy, 1975) but this procedure proved inadequate as it did not cope with the shortcomings of the strength, surface roughness and water absorption of this aggregate. This trial mix, Mix 1, was far too wet with a free water-cement ratio of 1.10, a slump of 35 mm and had a very poor cube strength of 13.5 MPa at 28 days, as shown in *Table 5.1b*. For Mix 2 the same basic mix was used, except that the cement content was increased to the equivalent of 315 kgm^{-3}. This increase in cement content resulted in a cube strength of 29 MPa and a slump of 15 mm, but the mix was too harsh. For Mix 3 the coarse aggregate fraction was decreased and the fine fraction increased, details are given in *Table 5.1a*. This mix had a free water-cement ratio of 0.62, a slump of 10 mm and a cube strength of 26.5 MPa. The mix was deemed satisfactory for producing slabs, although the cube strength was still considered rather low. Mix 4 used aggregate C2 in the same proportions as Mix 3, but with the cement content increased to the equivalent of 325 kgm^{-3} to produce a slight increase in cube strength. The resultant concrete had a free water-cement ratio of 0.75, a slump of 10 mm and a 28 day cube strength of 22 MPa. As was the case with Mix 2, the mix was considered too harsh. Mix 5 again had an equivalent cement content of 325 kgm^{-3}, but the coarse aggregate fraction was reduced to 1121 kgm^{-3} and the fine fraction increased to 740 kgm^{-3}. This mix produced a free water-cement ratio of 0.75, a slump of 15 mm and a 28 day cube strength of 25 MPa. For Mix 6 it was decided to increase the cement content to the equivalent of 360 kgm^{-3}, leaving the other proportions as they were in Mix 5. This resulted in a dry mix with a free water-cement ratio of 0.64, a slump of 5 mm and an only slightly increased 28 day cube strength of 26 MPa. As satisfactory results were obtained during the trial mixes with a cement content of 325 kgm^{-3}, and previous research using these aggregates had used a cement content of 330 kgm^{-3} (Collins, 1986, 1989, 1991) it was decided to use the latter for the final mix design. Not only would this enable data, if necessary, to be compared with this earlier research, the value of 330 kgm^{-3} was within the cement content limits given in BS 8204: 1987 for class AR3 direct finished concrete, which specifies a minimum cement content of 325 kgm^{-3}. Although the characteristic strength specified in BS 8204: 1987 for class AR3 concrete is 40 MPa, a characteristic strength of 30 MPa was adopted for this work. This strength was chosen because previous research (Collins, 1989) had shown that a strength of 30 MPa should be attainable with the weakest of the aggregates used, the Carboniferous Sandstones, with a cement content of 330 kgm^{-3}. A strength of 40 MPa was attained by only 5 per cent of the aggregates tested by Collins at a cement content of 330 kgm^{-3}. It would also be possible to ascertain whether concrete made with these aggregates could attain abrasion resistance to class AR3, equivalent to a maximum (average) abrasion depth of 0.40 mm (Concrete Society, 1994) using a lower cement content than that currently specified. The aggregate proportions for the final mix design were 1141 kgm^{-3} of coarse aggregate and 720 kgm^{-3} of fine aggregate, these being the mean values of Mixes 3 to 6. From observations made during the trial mixes it was apparent that the free water-cement ratio would vary considerably between aggregate types, this being primarily the result of absorption and surface texture properties. For this reason it was decided to adjust the added water content of each subsequent mix to produce a specified level of workability, this to be measured by the 'slump' test (BS 1881: Part 102: 1983). The series of trial mixes showed a slump of 35 mm (Mix 1) to be potentially too wet for producing satisfactory power finished slabs, and that a slump of 5 mm (Mix 6) to be potentially too dry for producing satisfactory power finished slabs. From these observations it was decided that water would be added to all specimen mixes to produce a slump within the range 10 to 30 mm. The final mix design is shown below, with details of all the trial mixes being given in *Tables 5.1a* and *5.1b*..

Cement	330 kgm^{-3}
Coarse Aggregate	1141 kgm^{-3}
Fine Aggregate (Control)	720 kgm^{-3}
Free Water/Cement Ratio	To give slump in the range 10-30 mm
Aggregate/Cement Ratio	5.6:1
Cube Strength (28 Days)	Average Strength of 30 MPa

5.2.2 Fine Aggregate Mix Design

It was decided to base this mix design as closely as possible on that used in the coarse aggregate test programme, and three trial mixes were produced using a crushed Carboniferous Sandstone (C2F) and a crushed Jurassic Limestone (J11F). Trial Mix 7, using aggregate C2F, used the same mix design as that used for the coarse aggregate mixes, with the slump being 5 mm and the 28 day cube strength 25.5 MPa. This mix was considered to be too dry and possibly lacking in fine aggregate. Mix 8 again used the same mix but with aggregate J11F instead of C2F. This mix had a slump of 10 mm and a 28 day cube strength of 42 MPa, but the consistency of the mix was again too harsh. The final trial mix, Mix 9, used aggregate C2F with the coarse aggregate proportion reduced to 1025 kgm^{-3}, and the fine aggregate proportion increased to 840 kgm^{-3}. This mix gave a slump of 5 mm and a 28 day cube strength of 22.5 MPa, but was considered too sandy. For the final mix design it was decided to follow the design used in mixes 7 and 8, except that the fine aggregate proportion was increased to 780 kgm^{-3} to reduce the harshness observed in Mixes 7 and 8. The other mix properties such as slump and average cube strength were to be the same as those of the coarse aggregate mixes, so that comparisons could be made between the properties of mixes using a particular aggregate as both the coarse and fine aggregate. The final mix design is shown below, with details of the fine aggregate trial mixes given in *Tables 5.1a* and *5.1b*.

Cement	330 kgm^{-3}
Coarse Aggregate (Control)	1141 kgm^{-3}
Fine Aggregate	780 kgm^{-3}
Free Water/Cement Ratio	To give slump in the range 10-30 mm
Aggregate/Cement Ratio	5.8:1
Cube Strength (28 Days)	Average Strength of 30 MPa

One mix design was used for all of the coarse aggregate mixes and one design for all of the fine aggregate mixes, all designed with a constant cement content. Although the general practice is to design mixes for equal strength and workability by varying the cement content and the water-cement ratio, the use of a constant cement content is the same procedure as that used in previous research using low-grade aggregates (Teychenné, 1978 and Collins 1989).

5.3 Cube Strength

Six 100 mm cubes were cast from the third batch of each mix, this being the part of the mix that formed the surface layer of each slab, and cured according to BS 1881: Part 111: 1983. Three were tested at 7 days and three at 28 days. The results of these tests are presented in *Tables 5.4.* and *5.5*, together with an indication of strength gain between 7 and 28 days. For both the coarse and fine aggregate mixes there is a wide variation in this strength gain, with both limestone types generally exhibiting lower gains than the Carboniferous Sandstones. The aggregate C4 is unusual in that it had a particularly high strength gain (59 %) when present as the coarse aggregate, but a particularly low strength gain (22 %) when present as the fine aggregate. No single concrete or aggregate property could be found to explain this variation, but it may be due to a combination of aggregate properties such as strength, density, shape and texture.

5.3.1 Coarse Aggregate Mixes

The results in *Table 5.4* show a wide range of strengths were obtained at 28 days, ranging from a minimum value of 27.5 MPa to a maximum of 45.5 MPa, with the coarse aggregate control attaining a strength of 42.5 MPa. Specimens C2S1, C3S1 (both Carboniferous Sandstone) and J9S1 (Jurassic Limestone) did not attain the target strength of 30 MPa, each had a cube strength of 27.5 MPa. These lower strengths were attributed to poor grading characteristics and the relatively high free water-cement ratios of these particular specimens. In general the higher free water-cement ratios, necessary when using low-grade aggregates, produced lower cube strengths than similar concretes containing normal concrete aggregates, and this important factor is illustrated in *Figure 5.1*. Water-cement ratio is not the only factor to influence the cube strength of concrete containing low-grade aggregates. Density, strength and grading have all been shown to have an effect, and the relationships between cube strength, free water-cement ratio and these aggregate properties are explored more fully in Chapter 6, Section 6.2.1.1.

Concrete containing the Carboniferous Sandstone coarse aggregates were the poorest in terms of cube strength, with three of the four specimens (C1S1, C2S1 and C3S1) exhibiting strengths substantially lower than the control mix, CS2. Two of the four Jurassic Limestone specimens (J9S1 and J11S1) exhibited strengths substantially lower than the control, whereas the Magnesian Limestone specimens all attained strengths comparable to the control and exhibited the highest levels of cube strength of all the aggregates used.

5.3.2 Fine Aggregate Mixes

The cube strength results for this series of mixes given in *Table 5.5* show a wide variation, ranging from a minimum of 28 MPa for specimen C2FS1 to a maximum of 51.5 MPa for the control mix, CSF1. The target strength of 30 MPa was not attained by two of the specimens, those containing the Carboniferous Sandstone crushed fines C1F and C2F, which achieved strengths of 29 MPa and 28 MPa respectively. The Carboniferous Sandstone crushed fines generally exhibited the lowest cube strengths of all the aggregates examined, the values being in the range 28 to 35.5 MPa. The Magnesian Limestone crushed fines attained strengths in the range 39 to 47 MPa, which, as was the case with the coarse aggregate mixes, were the highest from the three aggregate types.

As the same mix design was used for all the fine aggregate mixes, the principal variable which affected cube strength was the free water-cement ratio, which varied from 0.50 to 0.79 for this series of mixes. The variation in the free water-cement ratios could not be attributed to one particular factor, but is likely to be due to a combination of differences in absorption, grading and surface texture of the aggregates.

5.4 Abrasion Resistance

All the specimens cast for both the coarse and fine aggregate test programmes were tested at 28 days using the three test techniques described in Chapter 3, Section 3.4.3. Measurements of abrasion depth were made after 5 and 10 minutes as well as the 'standard' period of 15 minutes. This was to enable differences in the rates of abrasion to be examined, if necessary. Due to considerable wear during the wet abrasion test, most of these were stopped after 10 minutes because of the instability of the test apparatus, and its consequent lack of sensitivity.

The abrasion resistance measurements recorded in Appendices C and D were analysed statistically so that values differing significantly from the mean could be excluded from the final determination of abrasion depth. These values typically occurred at measurement points where an aggregate particle had been plucked out or a void encountered. Values were excluded from the calculation if they were above or below 1.96σ i.e. 1.96 x the standard deviation (Kennedy and Neville, 1976). In the current study σ is taken to represent σ_{n-1} rather than σ_n i.e. the standard deviation of the sample rather than of the population. These upper and lower limits reflect the probability that 95 per cent of all the values will fall within the range ±1.96σ, assuming a normal Gaussian frequency distribution. The need for an appraisal of the statistics associated with the test method is highlighted in Chapter 8, Section 8.2.4.

Summaries of these results for each rock type are given in *Tables 5.6* to *5.11*, and graphs of rate of abrasion are shown in *Figures 5.2* to *5.21*. Detailed measurements from each abrasion test are given in Appendices C and D, together with a statistical analysis of variability and scatter.

The standard 3-body abrasion test which is considered to provide a satisfactory indicator of abrasion resistance, showed 84 per cent of the coarse aggregate mixes to be within the 0.40 mm limit recommended in Concrete Society Technical Report TR 34 (Concrete Society, 1994) for class AR3 direct finished concrete, whereas only 42 per cent of the fine aggregate mixes were within this limit. Concrete containing the Magnesian Limestone aggregates generally exhibited the best abrasion resistance of the coarse aggregate mixes, whereas the crushed Carboniferous Sandstone aggregates produced concrete with abrasion resistance marginally better than the other fine aggregates. The results also suggested that an increase in cube strength did not necessarily result in an increase in abrasion resistance, and a detailed discussion of this important factor and the 3-body test results is presented in Chapter 6, Sections 6.2.1 and 6.2.2.

The wet abrasion test results showed that the addition of water to the test surface during testing increased abrasion depth considerably, sometimes by as much as 1000 per cent. These significant increases in the depth of wear were common to all rock types, and to both coarse and fine mixes. The 2-body abrasion test showed less consistent results, with some results showing no significant differences from the 3-body results, whereas others showed reductions in abrasion depth. These results are discussed more fully in Chapter 6, Section 6.13.

A subsidiary series of abrasion tests using one aggregate source (C2) was carried out to examine the effect of varying the proportion of this material from zero to 100 per cent. Two sets of specimens were tested, the first varying the proportion of C2 as the coarse aggregate, the second varying the proportion of C2F as the fine aggregate. The resultant specimen slabs were tested under 3-body and wet test conditions and indicated that substantial replacement of aggregates, both coarse and fine, could still yield concrete with abrasion resistance within current specifications. A summary of the data obtained is given in *Tables 5.14* and *5.15*.

5.5 Microscopic Tests

5.5.1 Microscopic Examination

A microscopic examination was carried out on selected concrete specimens deemed representative of the various rock types and the individual abrasion test methods employed. The principal reason of the microscopic study was to examine the top few millimetres of the specimens to investigate whether exposure to the various test methods had affected the structure within the paste and/or the aggregates, and to examine the nature of the aggregate/paste interface. It was considered that microscopy would also offer the opportunity to determine the depth and extent of any surface cracks. Thin sections were made from specimens subjected to each of the three test methods for all of the coarse aggregate mixes. An initial examination of these thin sections at the conclusion of the coarse aggregate mix programme showed that they were not yielding as much information as had originally been anticipated. Subsequently, thin sections were only made from selected specimens from the fine aggregate mixes deemed to be representative of the rock types and test methods used.

As a whole, the thin sections showed the concretes to be well made, with good compaction and no segregation of the coarse aggregate. Shrinkage cracking within the paste was minimal. The sections also clearly showed the surface layer created by the power finishing process, with a concentration of cement minerals and fine aggregate particles, see *Plate 5.1.* At the beginning of the current work it was expected that the depth of this surface layer would be accurately measured from the thin sections, unfortunately however, during the manufacture of the sections a fractional amount of the sample was inevitably lost from the outer surface, thus making it impossible to establish the true depth of this layer. The results of the microscopic examinations are discussed in Chapter 6, Section 6.13, where they are used to help to establish and understand the mechanisms involved in the abrasion of concrete.

5.5.2 Microhardness

Representative samples from each rock group were selected for microhardness testing and the Vickers Hardness Numbers (VHN) for these samples are presented in *Table 5.12*, together with median values of Mohs' Hardness for all aggregates. They show the relatively good performance of the Carboniferous Sandstone aggregate C2, with a VHN not dissimilar to that of the control aggregate, and noticeably higher than the other aggregates tested. This is in contrast to its Los Angeles Abrasion loss of 87 per cent (Chapter 4, *Table 4.1*), being the second highest value recorded from all of the aggregates examined and classifying the aggregate as poor in terms of durability. The hardness of C2 is due to the high quartz content (described in Chapter 4, Section 4.2.1.2), whereas its weakness in the Los Angeles test is due to the poor bond between these constituent particles. This confirms the observations made by Popovics (1979) that a hard stone is not necessarily a strong stone. The abrasion test results for aggregates C2 and C2F reported in *Tables 5.6* and *5.7* highlight this difference clearly. When present as coarse aggregate, the hardness of the individual constituent particles of C2 is negated by their ability to break up readily under the impact loads associated with the abrasion tests. When this aggregate is crushed the problem of the weak particle bond is reduced, and so the hardness of the constituent particles becomes more important. The results when this aggregate is used as the fine fraction, C2F, show the abrasion resistance to be as good, if not better, than many of the concretes containing other crushed fines.

No correlation could be established between abrasion depth and hardness for the coarse aggregate mixes, but correlations were established between both the 3-body and 2-body abrasion depth and the VHN of the aggregate when used as crushed fines. These relationships are shown in *Figures 5.23* and *5.24*. Similarly, significant correlations were established between both 3-body and 2-body abrasion depth and the Mohs' Hardness of the aggregate when used as crushed fines, with these being shown in *Figures 5.27* and *5.28*. A good correlation exists between VHN and the results of the Mohs' Hardness test, and this is presented in *Figure 5.26*. The relationship between hardness and wet abrasion depth is less clear than the relationships with 2-body and 3-body abrasion. Although a significant correlation was established between wet abrasion depth and VHN, *Figure 5.25*, it is not considered truly representative. The values of wet abrasion are those measured after 10 minutes and do not include values for aggregates C2 and J9 whose tests were halted after 5 minutes. Extrapolated 10 minute values for these specimens estimated from *Figures 5.18* and *5.20*, approximately 2.0 mm and 1.2 mm respectively, would render the correlation in *Figure 5.25* insignificant. No significant relationship was found between wet abrasion depth and Mohs' Hardness. The relationships between fine aggregate hardness and abrasion resistance are discussed further in Chapter 6, Sections 6.2.1.2, 6.2.2.2 and 6.13.

5.5.3 Mercury Intrusion Porosimetry

Tests were carried out to determine the pore characteristics of all the aggregates used in the research programme. A summary of results is given in *Table 5.13.*, with the pore size distribution graphs for each aggregate presented in *Figures 5.29* to *5.32*. The purpose of performing this series of tests was to examine the microstructure of the aggregates, and to determine if any of these characteristics could be related to the abrasion resistance, either directly or indirectly. Other research has examined the microstructure of Magnesian Limestones (Collins and Pettifer, 1994) and Jurassic Limestones (Collins and Pettifer, 1982) and their influence on durability properties. Both studies showed that differences in microstructure can explain why superficially similar aggregates may exhibit different durability characteristics.

With the exception of the control aggregate, all the aggregates had the greatest proportion of their pores within the size range 0.1 to 5.0 μm. The control aggregate had the lowest level of microporosity at 0.0138 ccg^{-1}, with M6a and M6b having the highest levels at 0.1629 ccg^{-1} and 0.1089 ccg^{-1} respectively. Although the pore size distribution graphs for individual aggregates showed considerable variation, no microstructural property was found to have a significant direct effect on abrasion resistance for either the coarse or fine aggregate mixes. Good correlations were, however, found between total pore volume and 24 hour absorption, and between the average pore diameter and the 24 hour absorption for all aggregate types. Both of these relationships related to the coarse aggregate mixes, and are shown in *Figures 5.33* and *5.34*. The relationship between the 24 hour absorption and the total pore volume is not unexpected as both properties are a measure of the voids within the aggregate particles. The relationship with average pore size suggests that the presence of larger pores in the aggregate will result in a higher value of 24 hour absorption. The pore size characteristics can be considered to have an indirect effect on abrasion resistance because they have a significant effect on the absorption values of the aggregates, which in turn are influential upon the water-cement ratio of subsequent concrete mixes. The importance of water-cement ratio on the abrasion resistance of concrete is discussed fully in Chapter 6, Sections 6.2 and 6.11. A plot of total introduced volume of mercury against Los Angeles Abrasion loss is given in *Figure 5.35*. This graph suggests that increases in the total pore volume measured by porosimetry for both limestone types, results in only slightly increased Los Angeles Abrasion losses. Relatively small increases in the total pore volume of the Carboniferous Sandstones gave rise to significant increases in the Los Angeles Abrasion losses. This suggests that mercury intrusion porosimetry data for this type of sandstone aggregate may be a sensitive indicator of potential durability.

Mix No.	Aggregate Source	Cement (kgm^{-3})	Coarse (kgm^{-3})	Fine (kgm^{-3})
1	C1	279	1284	577
2	C1	315	1284	577
3	C1	315	1161	700
4	C2	325	1161	700
5	C2	325	1121	740
6	C2	360	1121	740
7	C2F	330	1141	720
8	J11F	330	1141	720
9	C2F	330	1025	840

Table 5.1a. Trial mix proportions (expressed in terms of a m^3 of concrete).

Mix No.	Total W/C Ratio	Free W/C Ratio	Slump (mm)	A/C Ratio	28 Day Cube Strength (MPa)
1	1.22	1.10	35	6.6:1	13.5
2	0.83	0.68	15	5.9:1	29.0
3	0.76	0.62	10	5.9:1	26.5
4	0.96	0.75	10	5.7:1	22.0
5	0.96	0.75	15	5.7:1	25.0
6	0.84	0.64	5	5.2:1	26.0
7	0.73	0.68	5	5.6:1	25.5
8	0.67	0.58	10	5.6:1	42.0
9	0.75	0.70	5	5.7:1	22.5

Table 5.1b. Trial mix properties.

Specimen	Total W/C Ratio	Free W/C Ratio	Slump (mm)
Control (CS2)	0.58	0.53	10
C1S1	0.76	0.63	15
C2S1	0.86	0.69	15
C3S1	0.80	0.59	15
C4S1	0.68	0.57	10
M5S1	0.64	0.54	15
M6aS1	0.86	0.51	25
M6bS1	0.75	0.54	45
M8S1	0.66	0.54	15
J9S1	0.89	0.62	20
J10S1	0.70	0.54	20
J11S1	0.76	0.57	20
J12S1	0.70	0.49	20

Table 5.2. Water-cement ratios and slump values of the coarse aggregate mixes.

Specimen	Total W/C Ratio	Free W/C Ratio	Slump (mm)
Control (CSF1)	0.56	0.50	10
C1FS1	0.65	0.59	20
C2FS1	0.85	0.79	15
C3FS1	0.65	0.57	25
C4FS1	0.72	0.59	25
M5FS1	0.67	0.60	15
M6FS1	0.75	0.52	30
M8FS1	0.58	0.51	30
J9FS1	0.79	0.64	20
J10FS1	0.68	0.56	20
J11FS1	0.63	0.54	20
J12FS1	0.77	0.65	20

Table 5.3. Water-cement ratios and slump values of the fine aggregate mixes.

Specimen	Mean Cube Strength (MPa)		Strength Gain
	7-Day	28-Day	7-28 Day (%)
Control (CS2)	30.5	42.5	41
C1S1	23.0	32.5	41
C2S1	19.0	27.5	45
C3S1	20.0	27.5	37
C4S1	24.5	39.0	59
M5S1	35.0	45.0	29
M6aS1	28.5	37.0	30
M6bS1	37.5(14 Day)	43.0	-
M8S1	30.0	38.5	28
J9S1	-	27.5	-
J10S1	-	45.5	-
J11S1	26.5	33.0	25
J12S1	29.5	40.0	36

Table 5.4. Cube strength of the coarse aggregate mixes.

Specimen	Mean Cube Strength (MPa)		Strength Gain
	7-Day	28-Day	7-28 Day (%)
Control (CSF1)	-	51.5	-
C1FS1	21.0	29.0	38
C2FS1	20.5	28.0	37
C3FS1	26.0	35.5	37
C4FS1	24.5	30.0	22
M5FS1	34.0	43.5	28
M6FS1	30.0	39.0	30
M8FS1	38.0	47.0	24
J9FS1	-	35.5	-
J10FS1	30.5	39.5	30
J11FS1	37.5	49.0	31
J12FS1	27.5	36.0	31

Table 5.5. Cube strength of the fine aggregate mixes.

Mix	Mean 3-Body Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CS2)	0.04	0.04	0.05
C1S1	0.08	0.15	0.22
C2S1	0.19	0.33	0.47
C3S1	0.05	0.16	0.32
C4S1	0.05	0.10	0.20
M5S1	0.04	0.06	0.14
M6aS1	0.03	0.04	0.05
M6bS1	0.10	0.12	0.18
M8S1	0.10	0.14	0.19
J9S1	0.16	0.36	0.59
J10S1	0.06	0.09	0.14
J11S1	0.10	0.13	0.19
J12S1	0.04	0.07	0.08

Table 5.6. Summary of the 3-body abrasion results for the coarse aggregate mixes.

Mix	Mean 3-Body Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CSF1)	0.12	0.14	0.18
C1FS1	0.19	0.29	0.39
C2FS1	0.14	0.25	0.41
C3FS1	0.20	0.28	0.37
C4FS1	0.12	0.23	0.29
M5FS1	0.16	0.34	0.42
M6FS1	0.20	0.38	0.48
M8FS1	0.17	0.31	0.38
J9FS1	0.11	0.29	0.50
J10FS1	0.11	0.32	0.46
J11FS1	0.30	0.45	0.56
J12FS1	0.17	0.32	0.41

Table 5.7. Summary of the 3-body abrasion results for the fine aggregate mixes.

Mix	Mean 2-Body Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CS2)	0.07	0.08	0.10
C1S1	0.02	0.05	0.07
C2S1	0.15	0.27	0.48
C3S1	0.04	0.05	0.07
C4S1	0.07	0.14	0.23
M5S1	0.04	0.06	0.08
M6aS1	0.04	0.05	0.06
M6bS1	0.11	0.13	0.17
M8S1	0.09	0.12	0.14
J9S1	0.09	0.15	0.24
J10S1	0.06	0.07	0.09
J11S1	0.10	0.14	0.16
J12S1	0.05	0.06	0.07

Table 5.8. Summary of the 2-body abrasion results for the coarse aggregate mixes.

Mix	Mean 2-Body Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CSF1)	0.11	0.14	0.15
C1FS1	0.19	0.25	0.32
C2FS1	0.09	0.19	0.26
C3FS1	0.14	0.19	0.23
C4FS1	0.15	0.25	0.31
M5FS1	0.21	0.36	0.50
M6FS1	0.19	0.29	0.37
M8FS1	0.16	0.27	0.32
J9FS1	0.15	0.27	0.39
J10FS1	0.12	0.27	0.39
J11FS1	0.21	0.30	0.38
J12FS1	0.16	0.40	0.54

Table 5.9. Summary of the 2-body abrasion results for the fine aggregate mixes.

Mix	Mean Wet Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CS2)	0.18	0.64	1.21
C1S1	0.16	1.17	-
C2S1	0.86	2.48	-
C3S1	0.75	2.06	-
C4S1	0.22	1.00	-
M5S1	0.12	0.62	0.98
M6aS1	0.06	0.36	0.56
M6bS1	0.44	1.42	-
M8S1	0.44	1.74	-
J9S1	0.93	-	-
J10S1	0.07	0.09	0.10
J11S1	0.15	0.92	-
J12S1	0.06	0.08	0.17

Table 5.10. Summary of the wet abrasion results for the coarse aggregate mixes.

Mix	Mean Wet Abrasion Depth (mm)		
	5 Min	10 Min	15 Min
Control (CSF1)	0.15	0.22	0.39
C1FS1	0.38	1.14	-
C2FS1	1.03	-	-
C3FS1	0.34	0.56	-
C4FS1	0.25	0.47	0.71
M5FS1	0.38	0.90	-
M6FS1	0.33	0.71	-
M8FS1	0.41	0.72	-
J9FS1	0.56	-	-
J10FS1	0.36	0.76	1.24
J11FS1	0.36	0.68	-
J12FS1	0.44	1.02	-

Table 5.11. Summary of the wet abrasion results for the fine aggregate mixes.

Aggregate Ref.	VHN	Median Mohs' Hardness
Control	625	6.8
C1	-	6.3
C2	586	6.3
C3	-	6.3
C4	-	4.8
M5	170	4.3
M6a	-	3.0
M6b	375	3.3
M8	154	3.3
J9	138	2.8
J10	158	2.8
J11	-	2.8
J12	-	3.3

Table 5.12 Vickers Hardness Number (VHN) for selected aggregate samples and median Mohs' Hardness for all aggregates.

Aggregate Ref.	Total Pore Volume (ccg^{-1})	Total Pore Area (m^2g^{-1})	Ave. Pore Dia. (μm)
Control	0.0138	3.5530	0.0156
C1	0.0501	4.3913	0.7205
C2	0.0602	4.2971	3.2320
C3	0.0708	3.9659	1.9029
C4	0.0348	6.0654	0.0771
M5	0.0337	2.7428	2.6958
M6a	0.1629	4.5317	0.5037
M6b	0.1089	4.5535	0.6141
M8	0.0220	4.6324	0.0467
J9	0.0564	4.2399	0.1481
J10	0.0560	4.0382	0.1629
J11	0.0924	5.5595	0.7348
J12	0.0701	5.3332	0.2414

Table 5.13 Summary data from the mercury intrusion porosimetry tests.

% C2	Free W/C Ratio	28 Day Str. (MPa)	Mean 3-Body Abrasion Depth (mm)	Mean Wet Abrasion Depth (mm)
0	0.60	46.0	0.14	0.82
12	0.53	41.0	0.31	0.95
25	0.66	36.0	0.19	0.68
38	0.52	39.5	0.30	0.97
50	0.72	42.0	0.36	1.21
75	0.64	36.0	0.60	1.47
100	0.69	27.5	0.47	2.48

Table 5.14 Data summary for the mixes containing varying proportions of C2 as the coarse aggregate

% C2F	Free W/C Ratio	28 Day Str. (MPa)	Mean 3-Body Abrasion Depth (mm)	Mean Wet Abrasion Depth (mm)
0	0.50	51.5	0.19	0.25
33	0.57	38.5	0.26	0.66
67	0.70	28.0	0.28	1.14
100	0.79	28.0	0.40	1.14(5 Mins)

Table 5.15 Data summary for the mixes containing varying proportions of C2F as the fine aggregate.

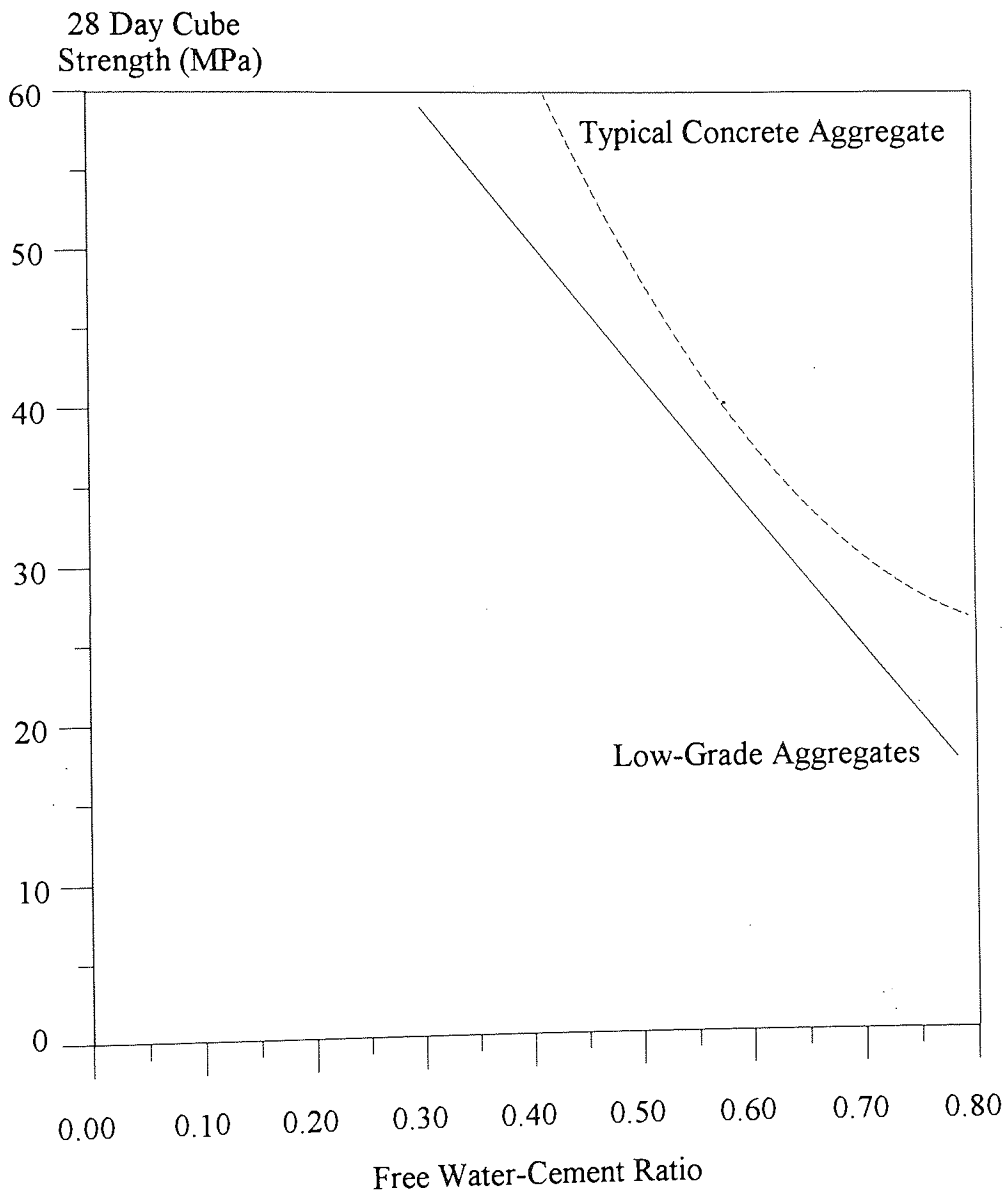

Figure 5.1. Illustration showing the relationship between 28 day cube strength and free water-cement ratio for typical crushed rock concrete aggregates and for the low-grade aggregates used throughout the current work. Data for the typical aggregates taken from Teychenné, Franklin and Erntroy (1975).

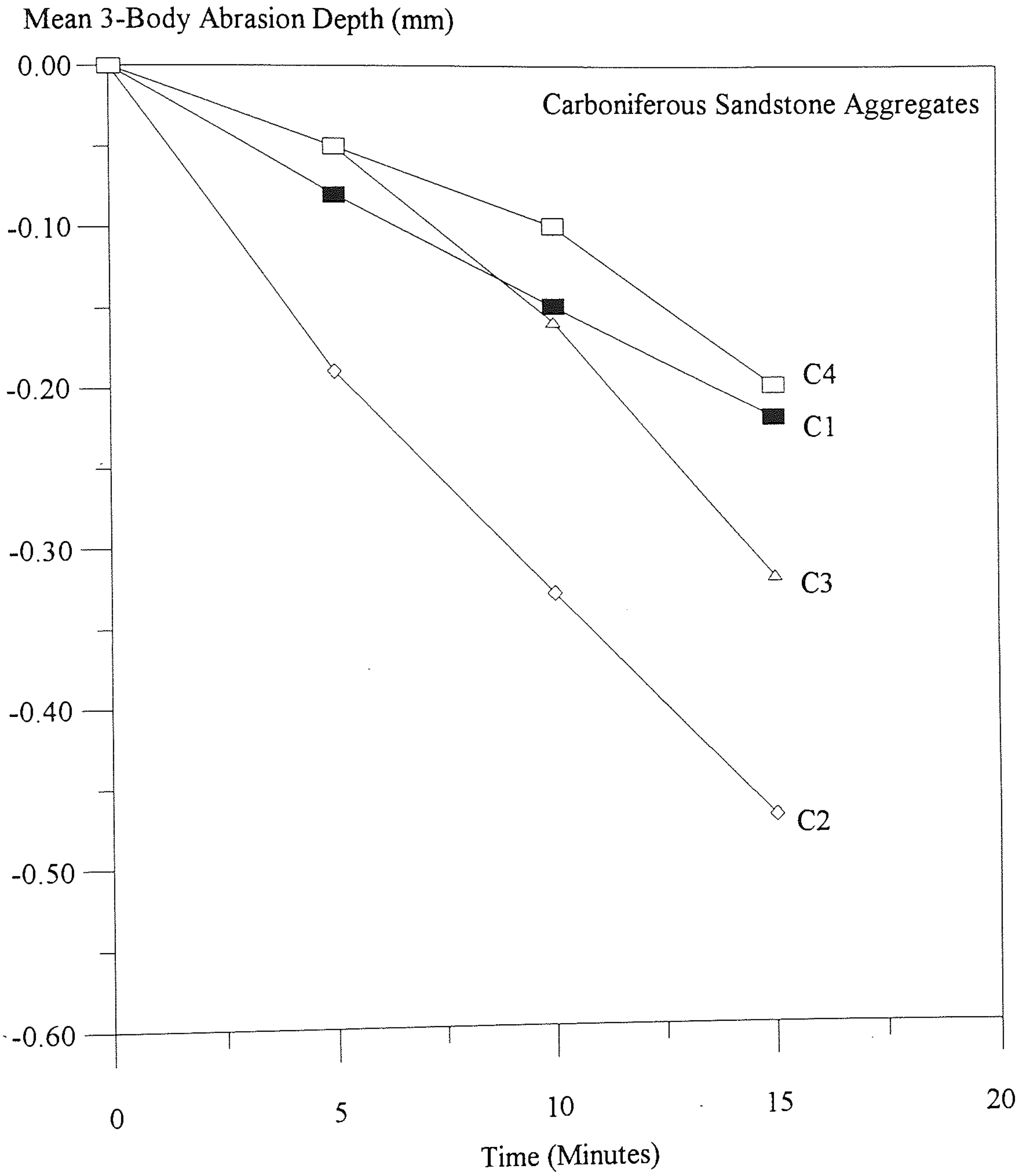

Figure 5.2. Rate of abrasion under 3-body test conditions for Carboniferous Sandstone coarse aggregates.

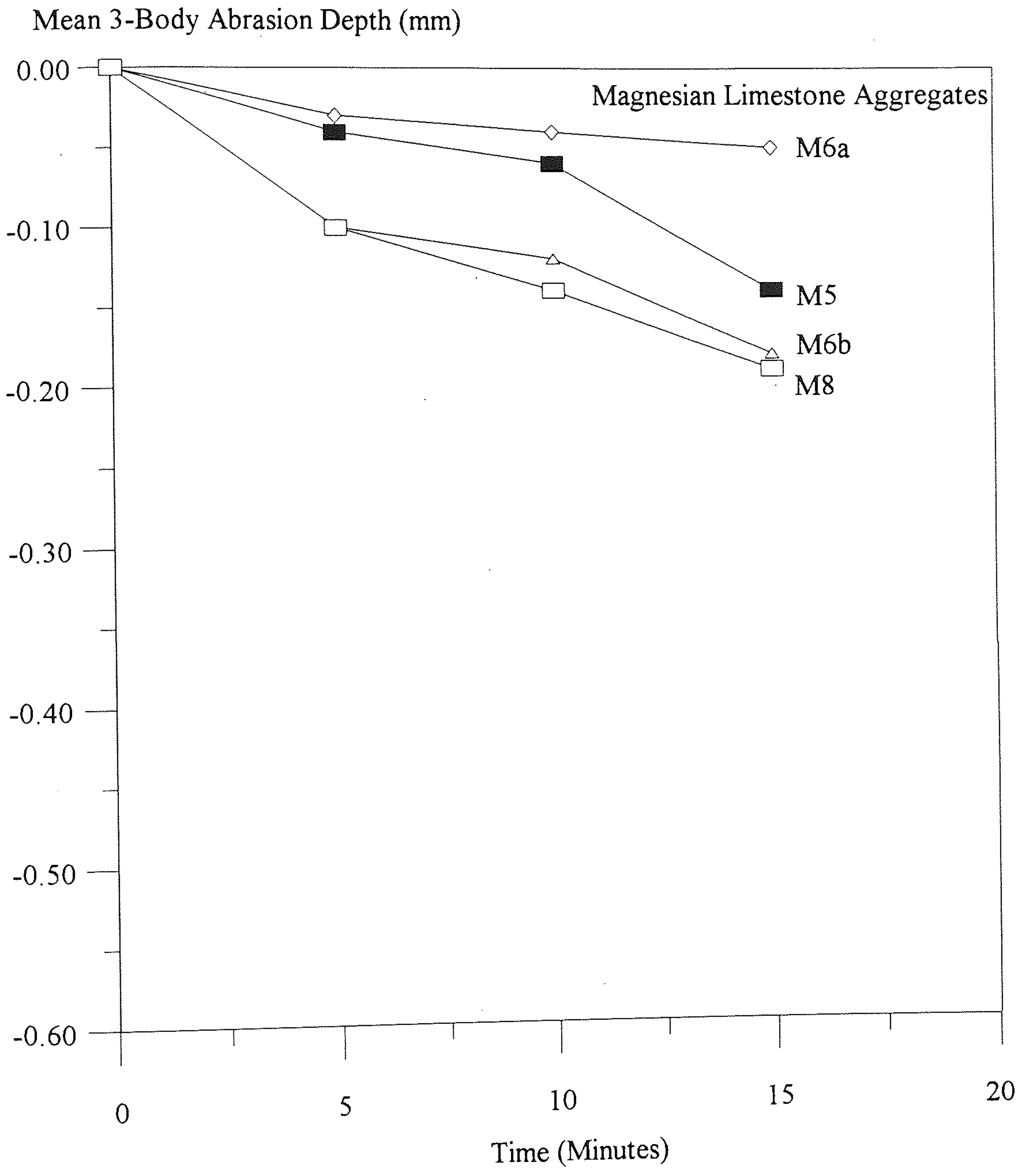

Figure 5.3. Rate of abrasion under 3-body test conditions for Magnesian Limestone coarse aggregates.

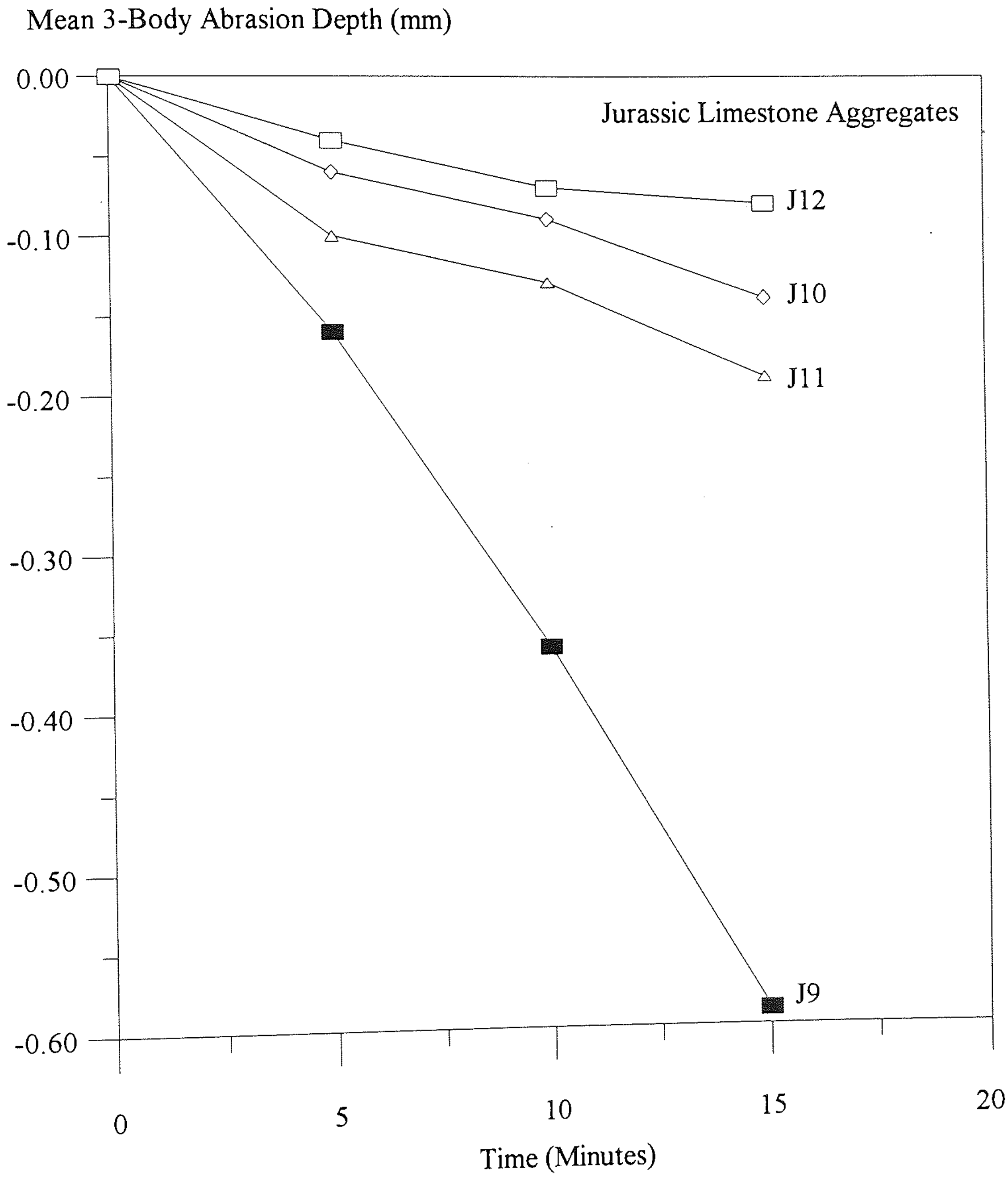

Figure 5.4. Rate of abrasion under 3-body test conditions for Jurassic Limestone coarse aggregates.

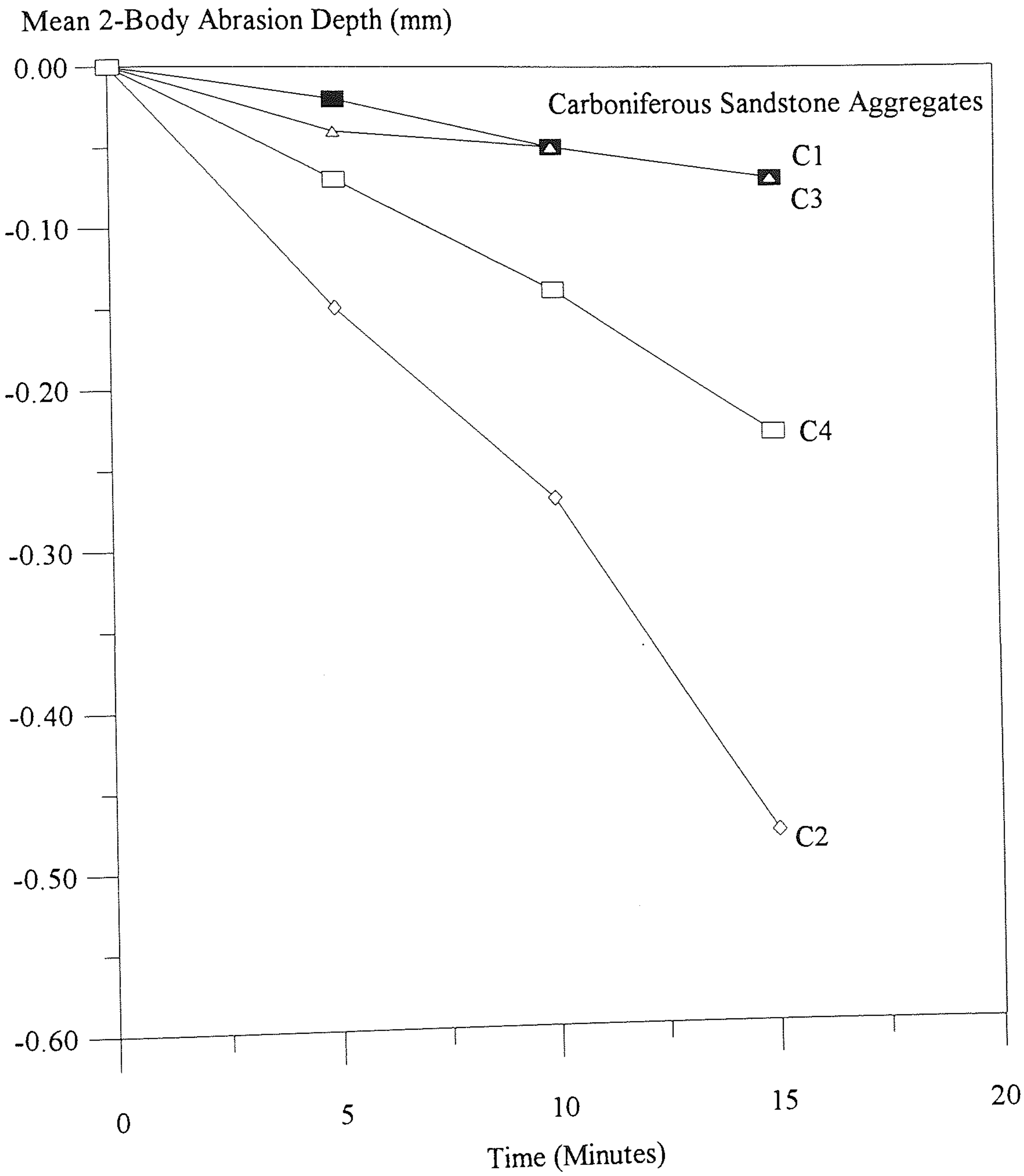

Figure 5.5. Rate of abrasion under 2-body test conditions for Carboniferous Sandstone coarse aggregates.

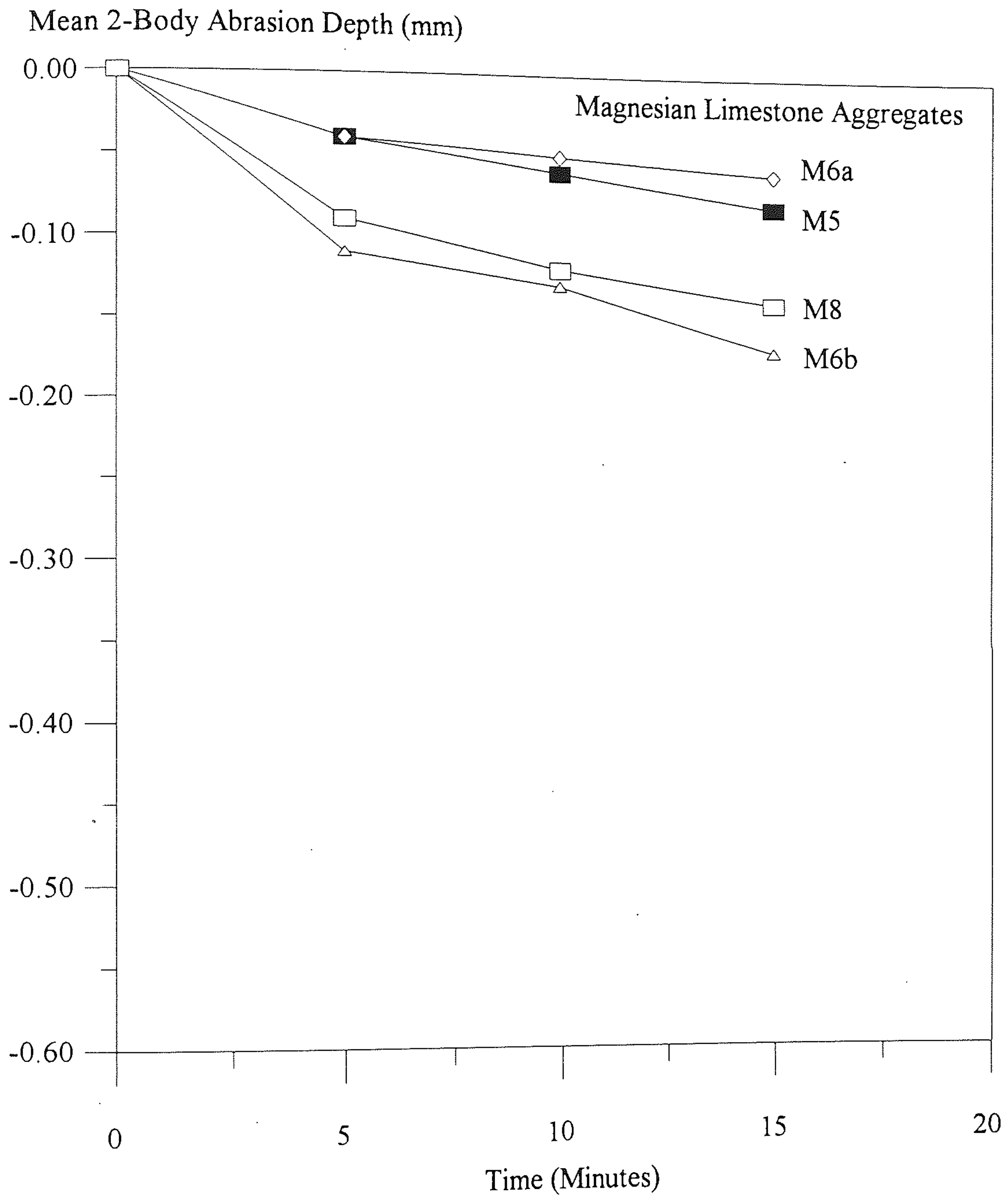

Figure 5.6. Rate of abrasion under 2-body test conditions for Magnesian Limestone coarse aggregates.

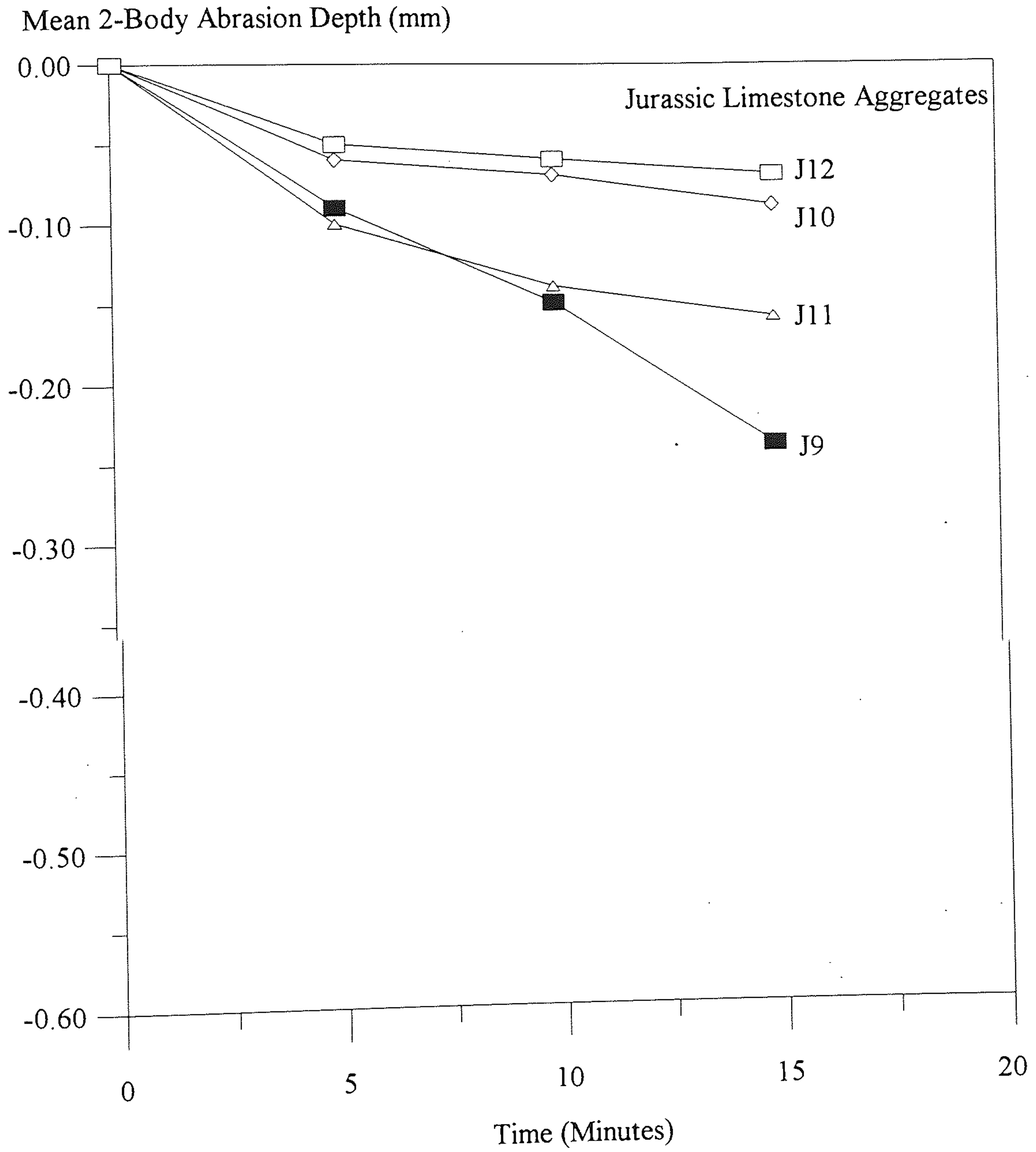

Figure 5.7. Rate of abrasion under 2-body conditions for Jurassic Limestone coarse aggregates.

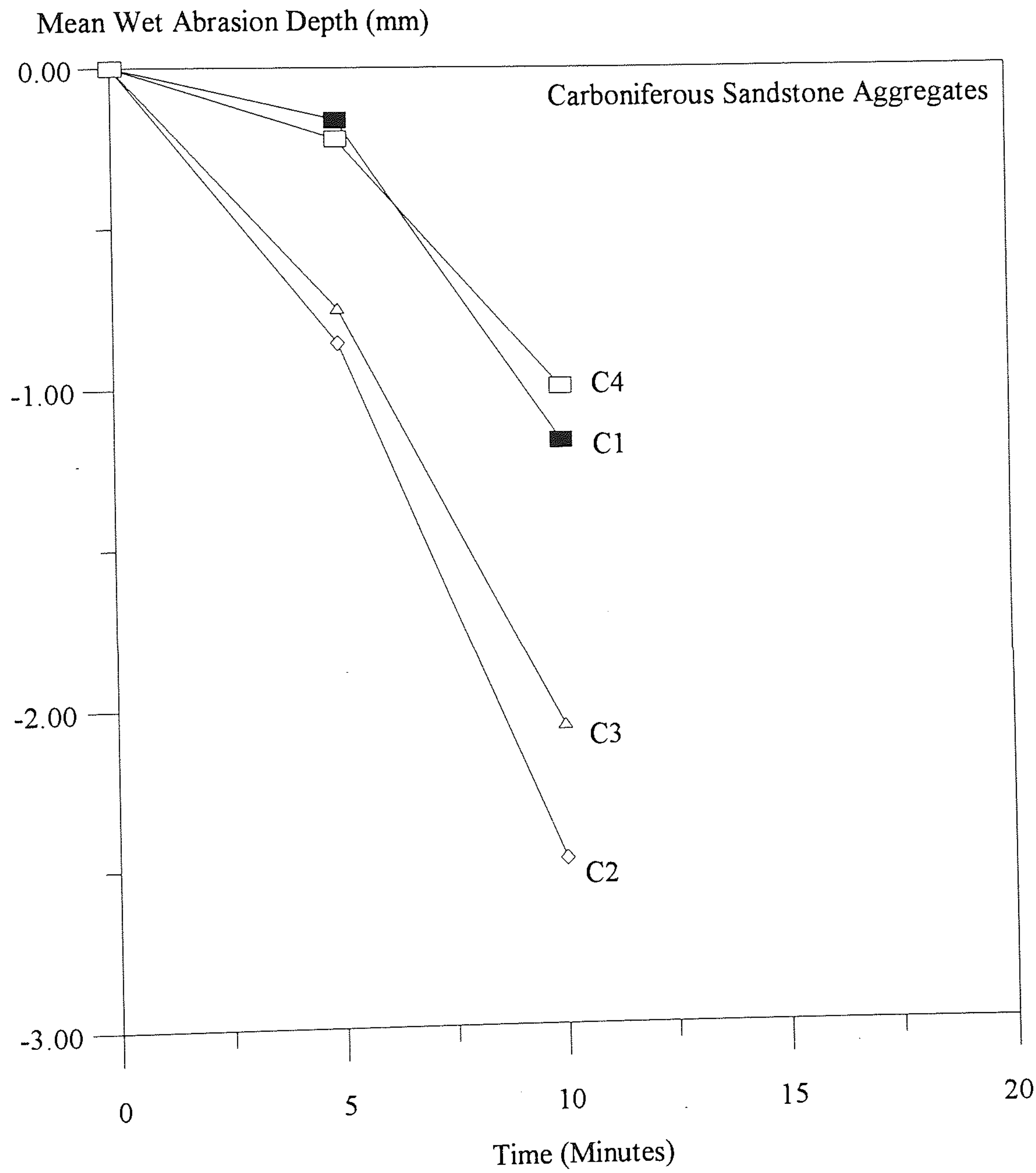

Figure 5.8. Rate of abrasion under wet test conditions for Carboniferous Sandstone coarse aggregates.

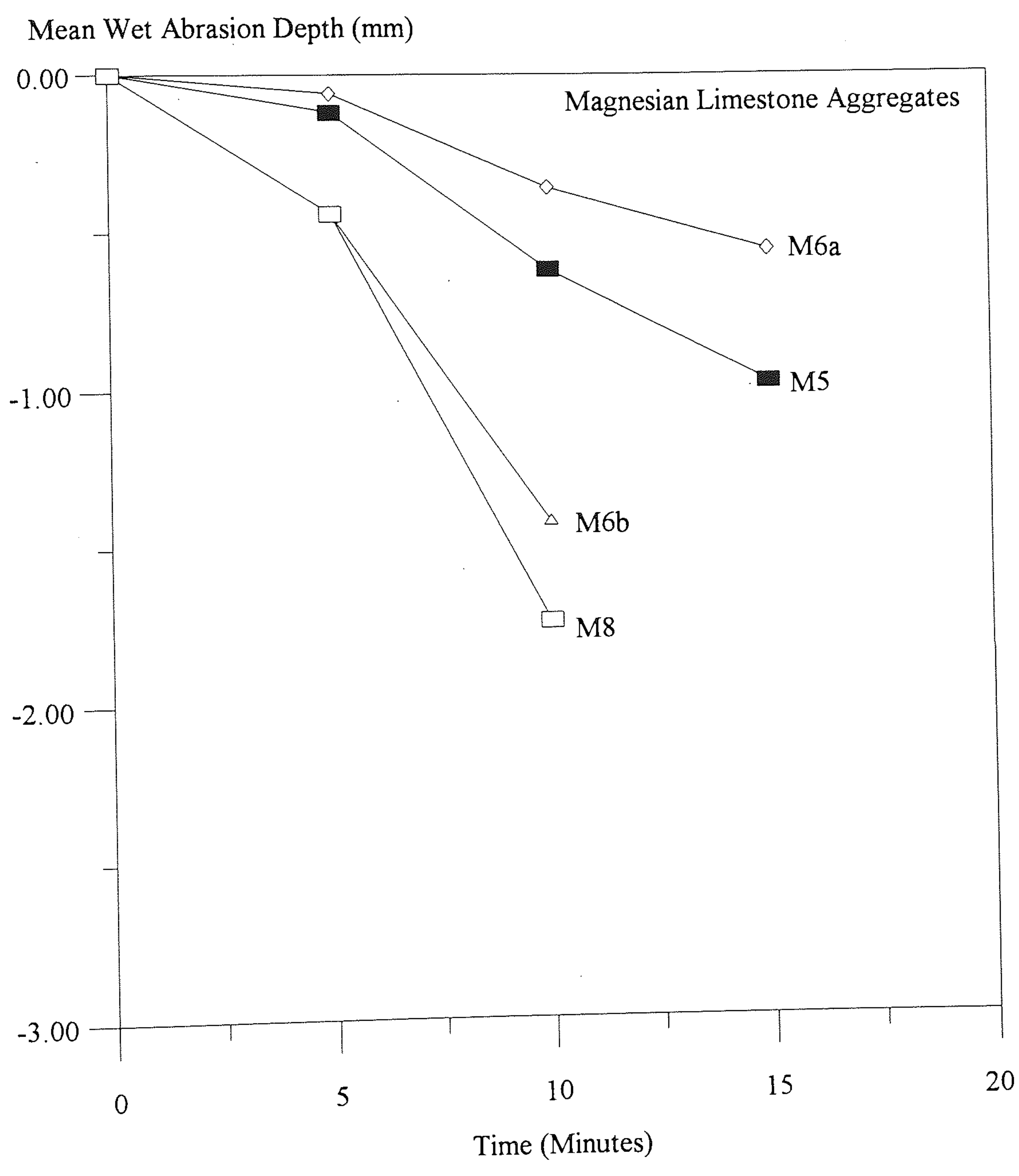

Figure 5.9. Rate of abrasion under wet test conditions for Magnesian Limestone coarse aggregates.

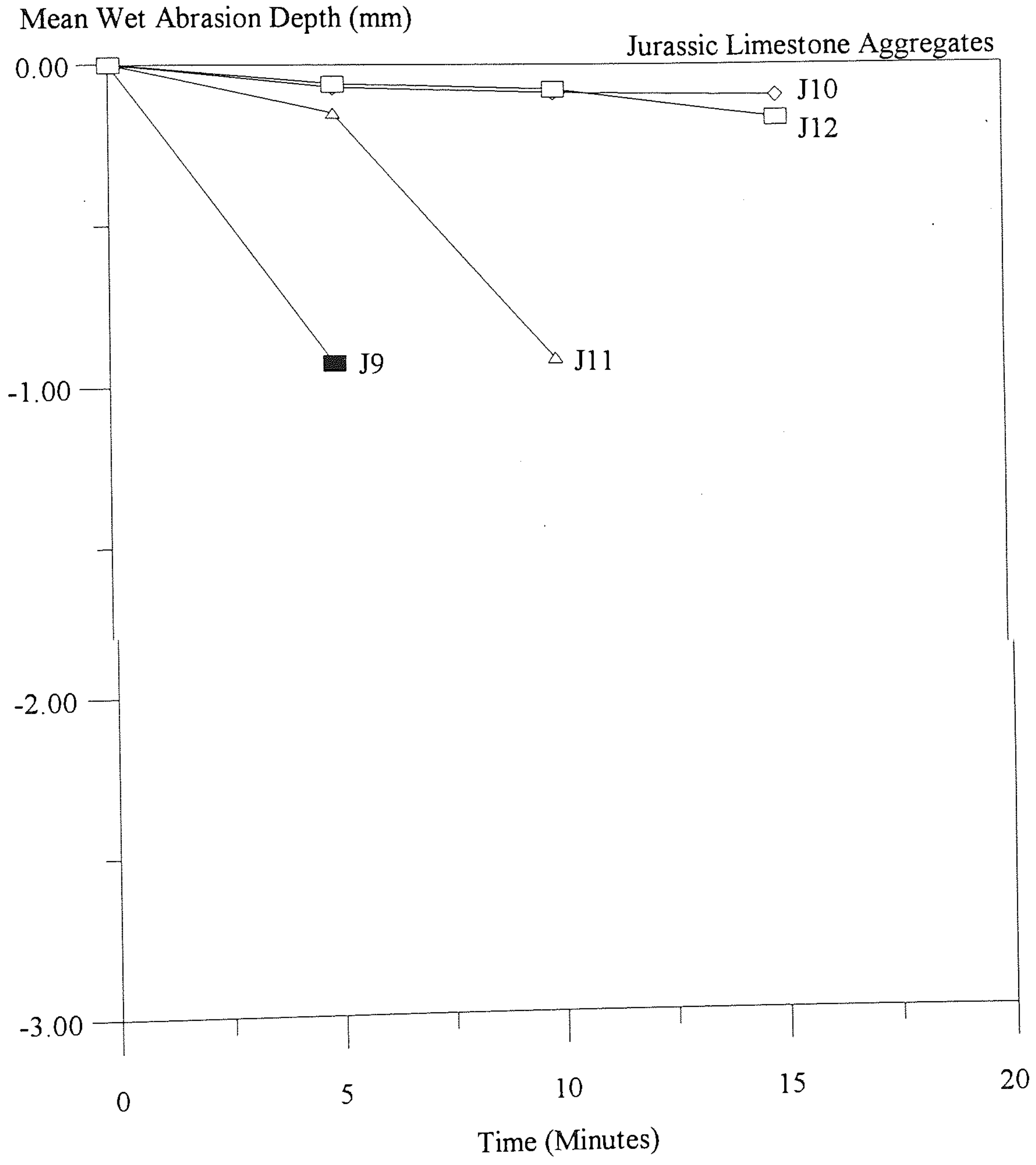

Figure 5.10. Rate of abrasion under wet test conditions for Jurassic Limestone coarse aggregates.

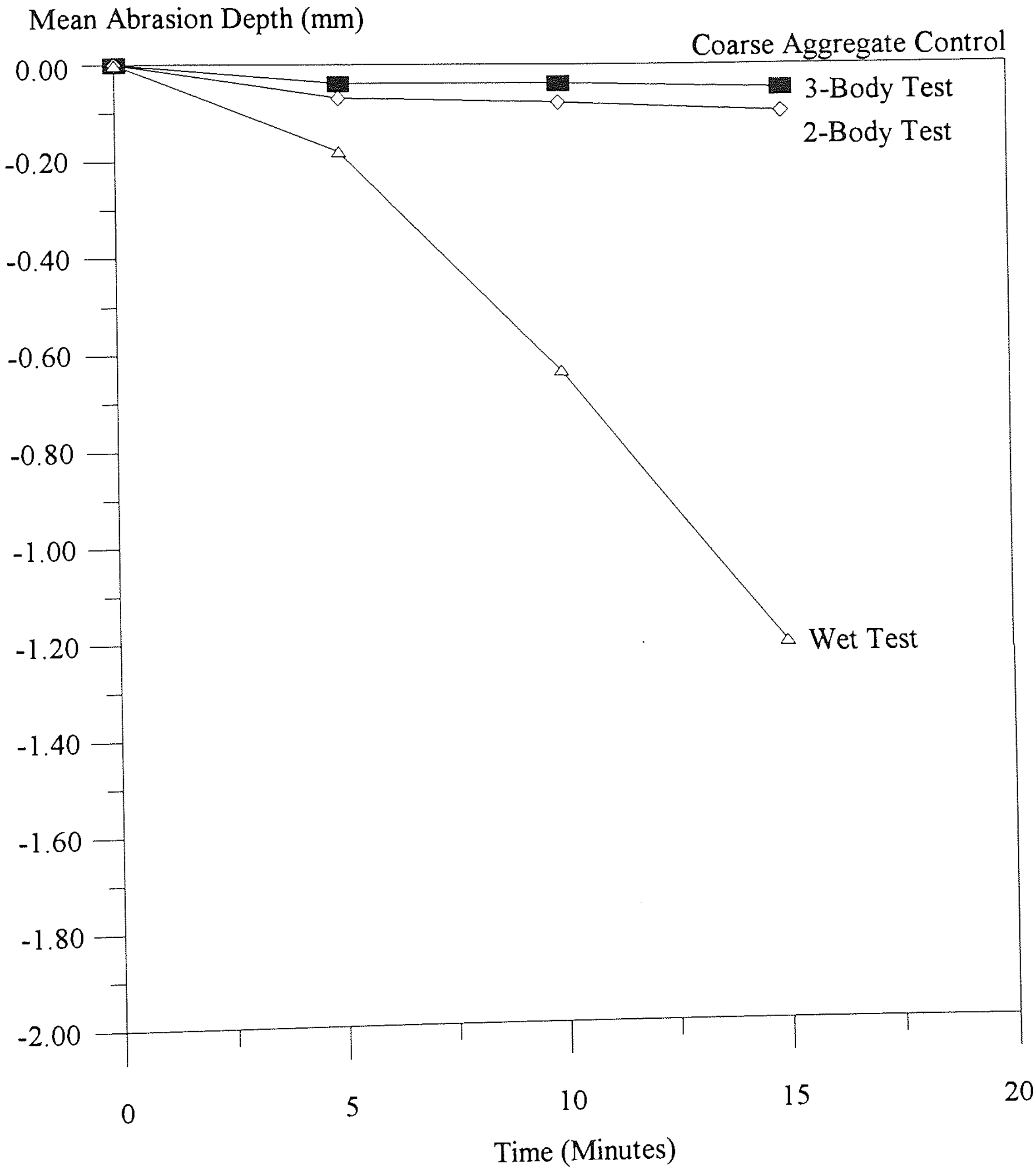

Figure 5.11. Rate of abrasion for the coarse aggregate control under the three test conditions.

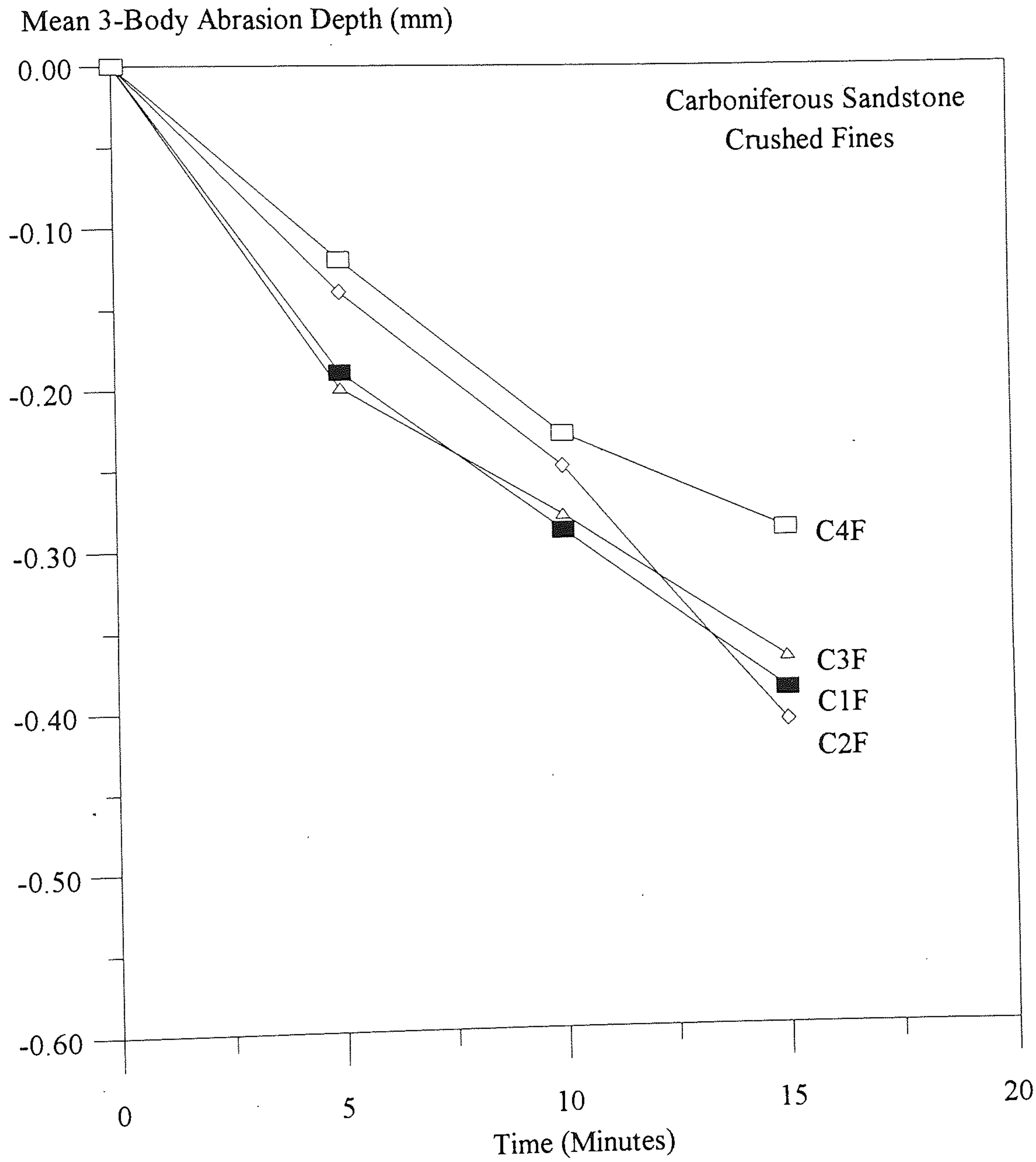

Figure 5.12. Rate of abrasion under 3-body test conditions for Carboniferous Sandstone crushed fines.

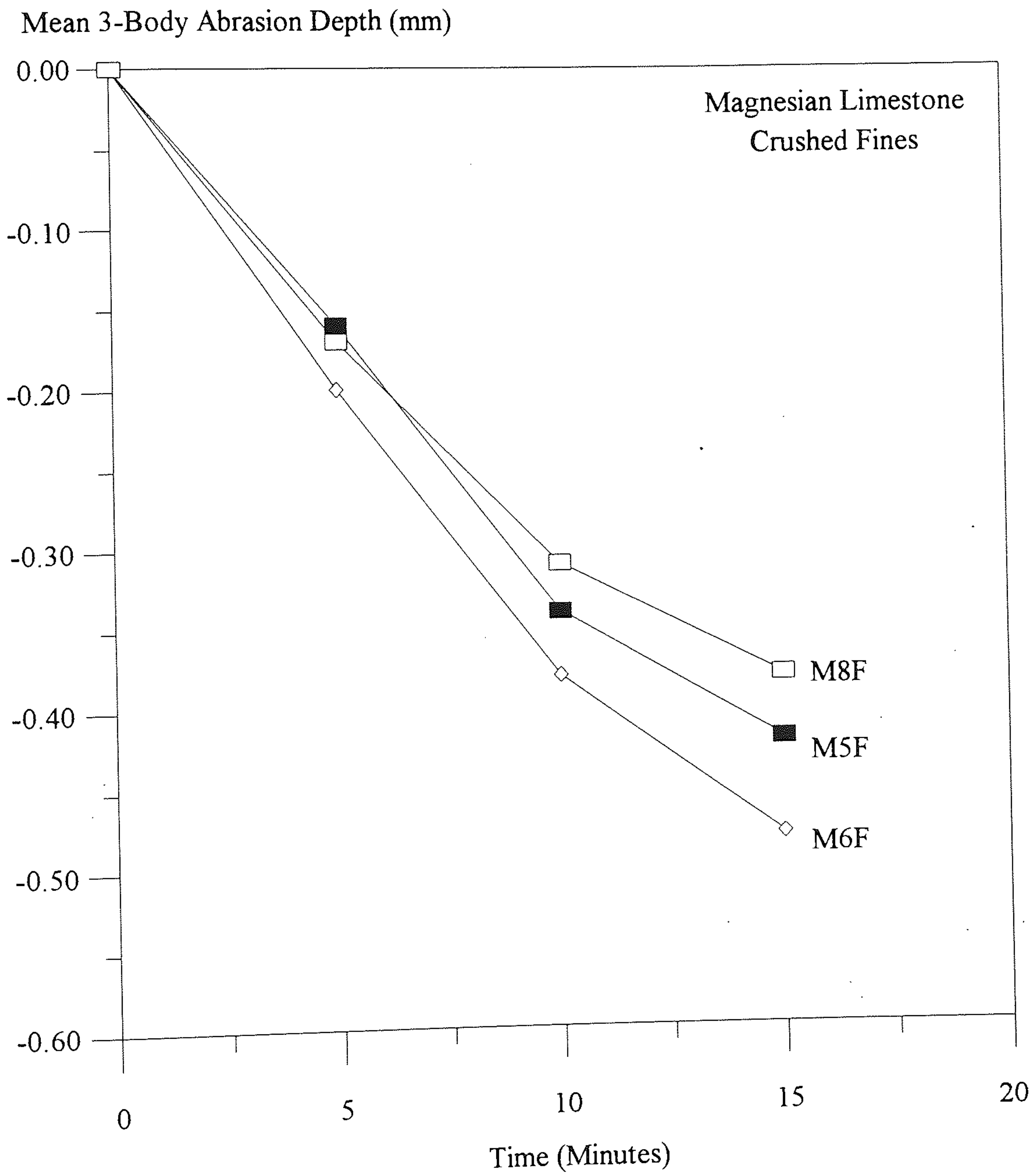

Figure 5.13. Rate of abrasion under 3-body test conditions for Magnesian Limestone crushed fines.

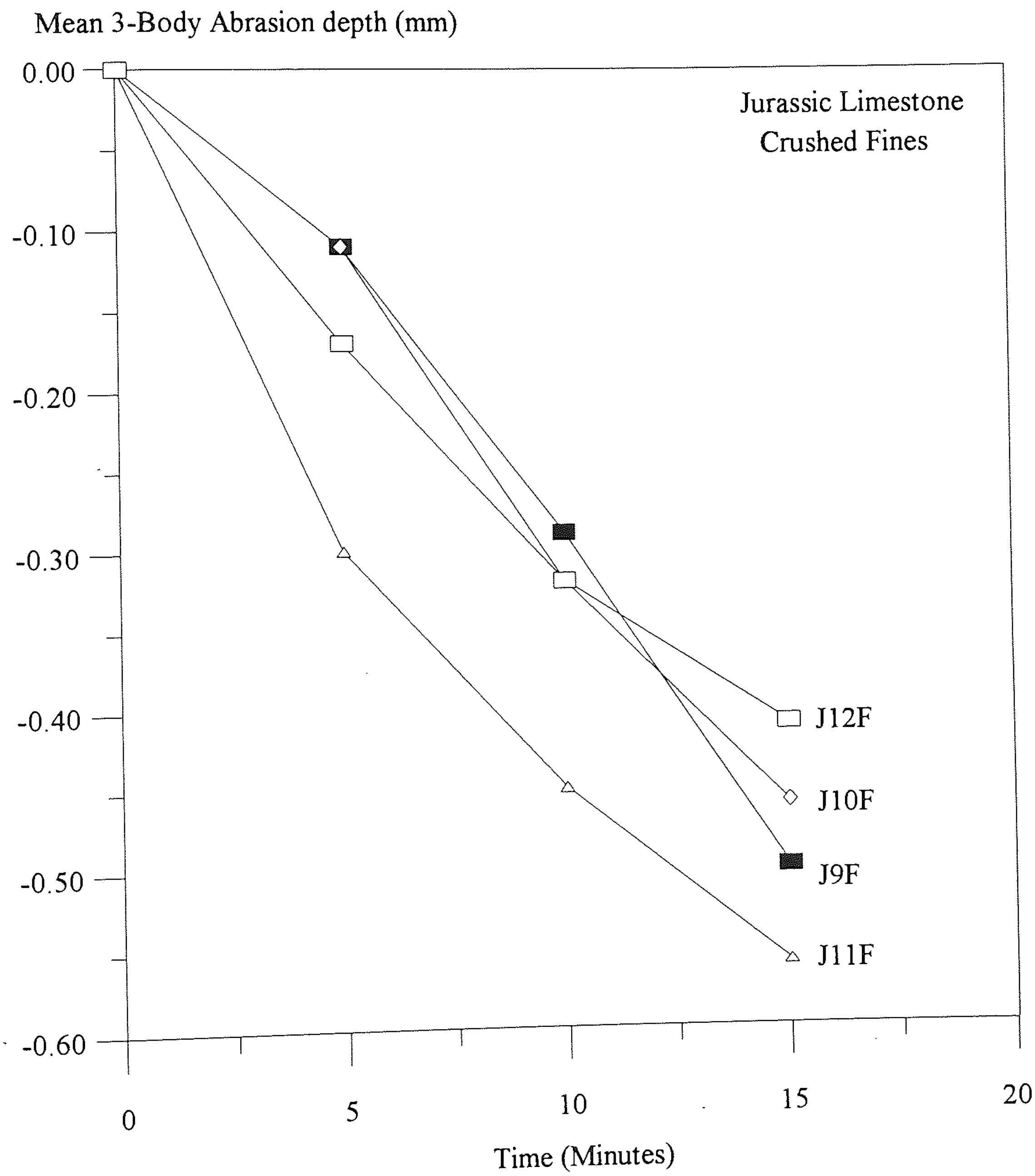

Figure 5.14. Rate of abrasion under 3-body test conditions for Jurassic Limestone crushed fines.

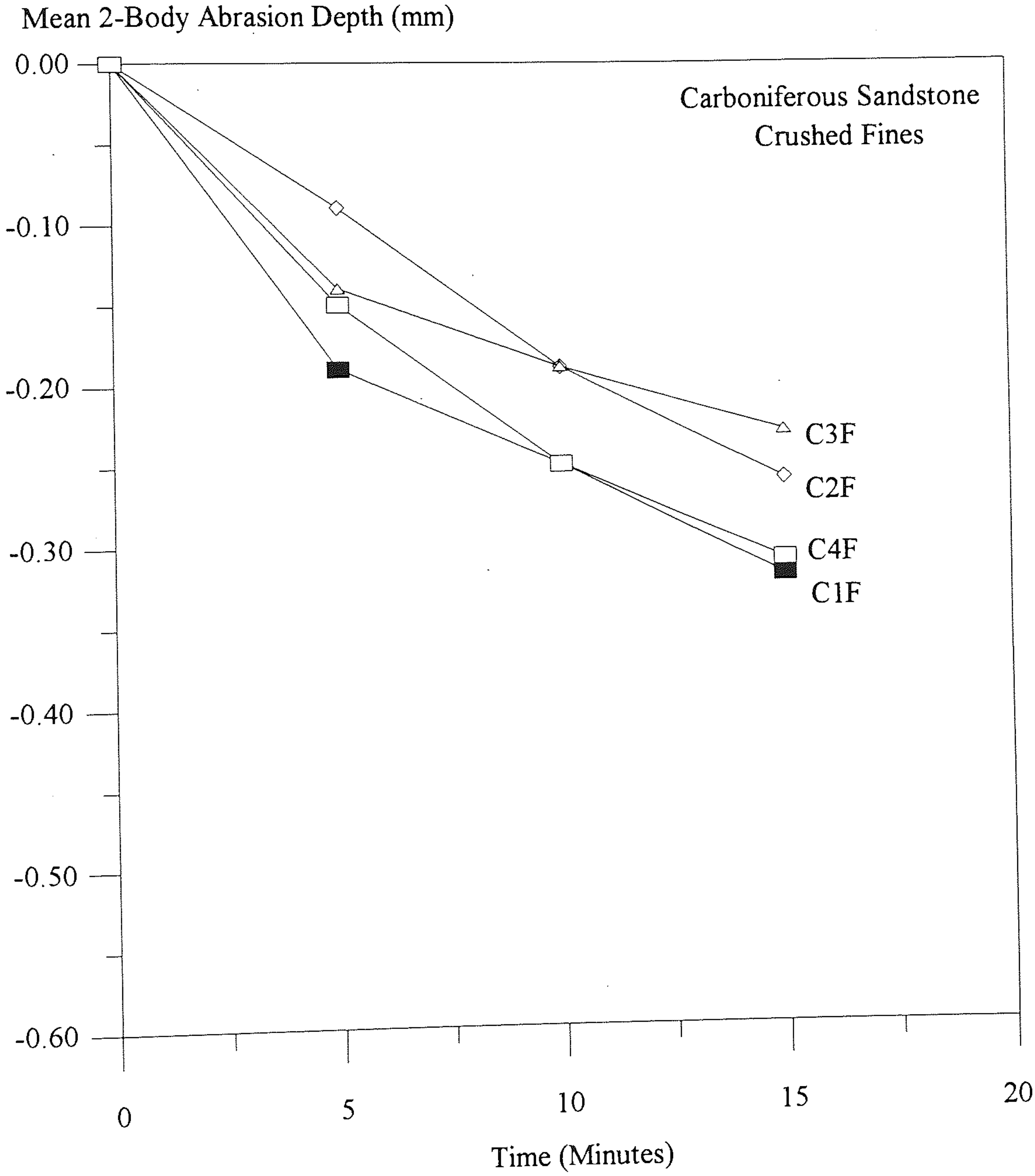

Figure 5.15. Rate of abrasion under 2-body test conditions for Carboniferous Sandstone crushed fines.

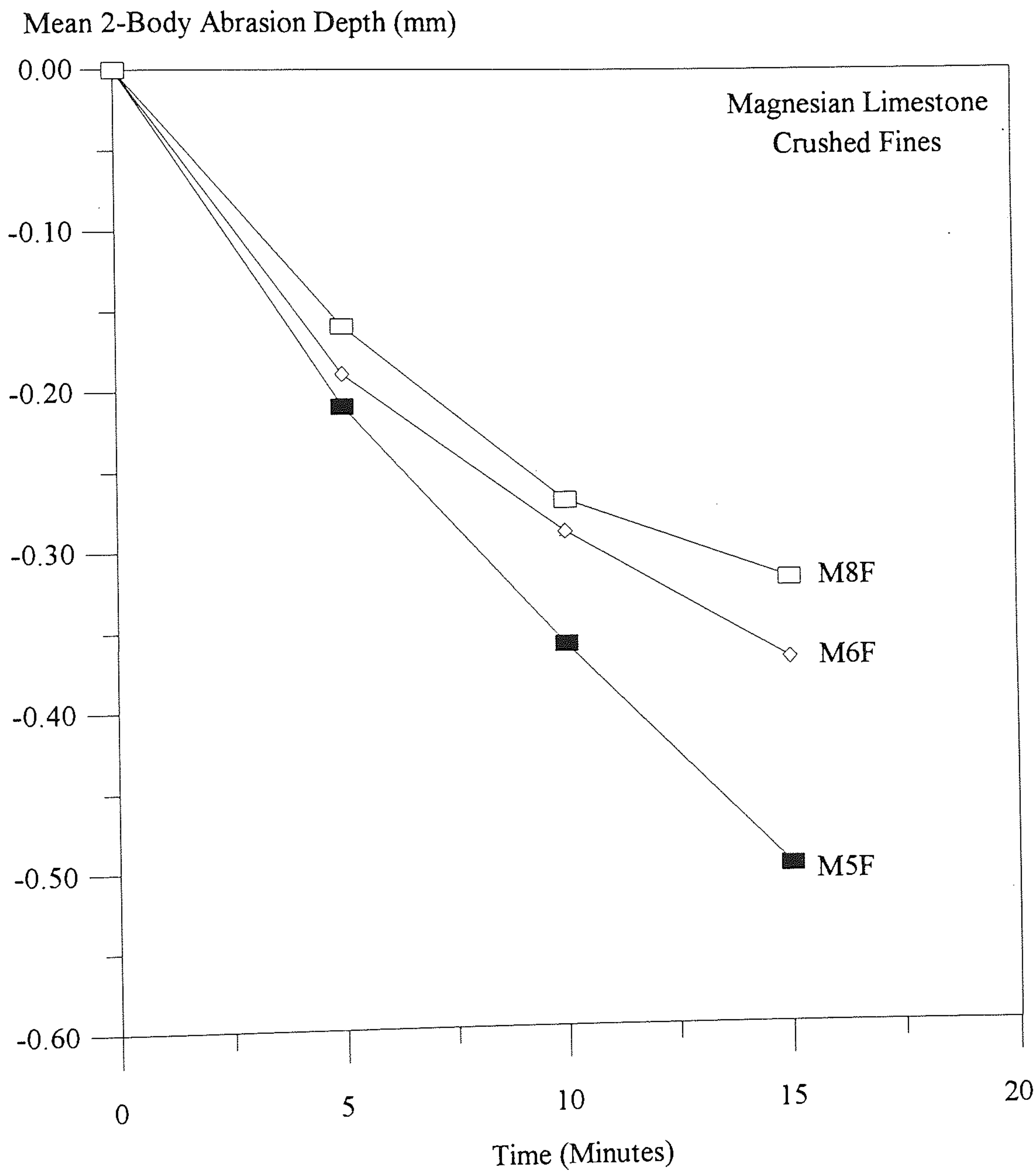

Figure 5.16. Rate of abrasion under 2-body test conditions for Magnesian Limestone crushed fines.

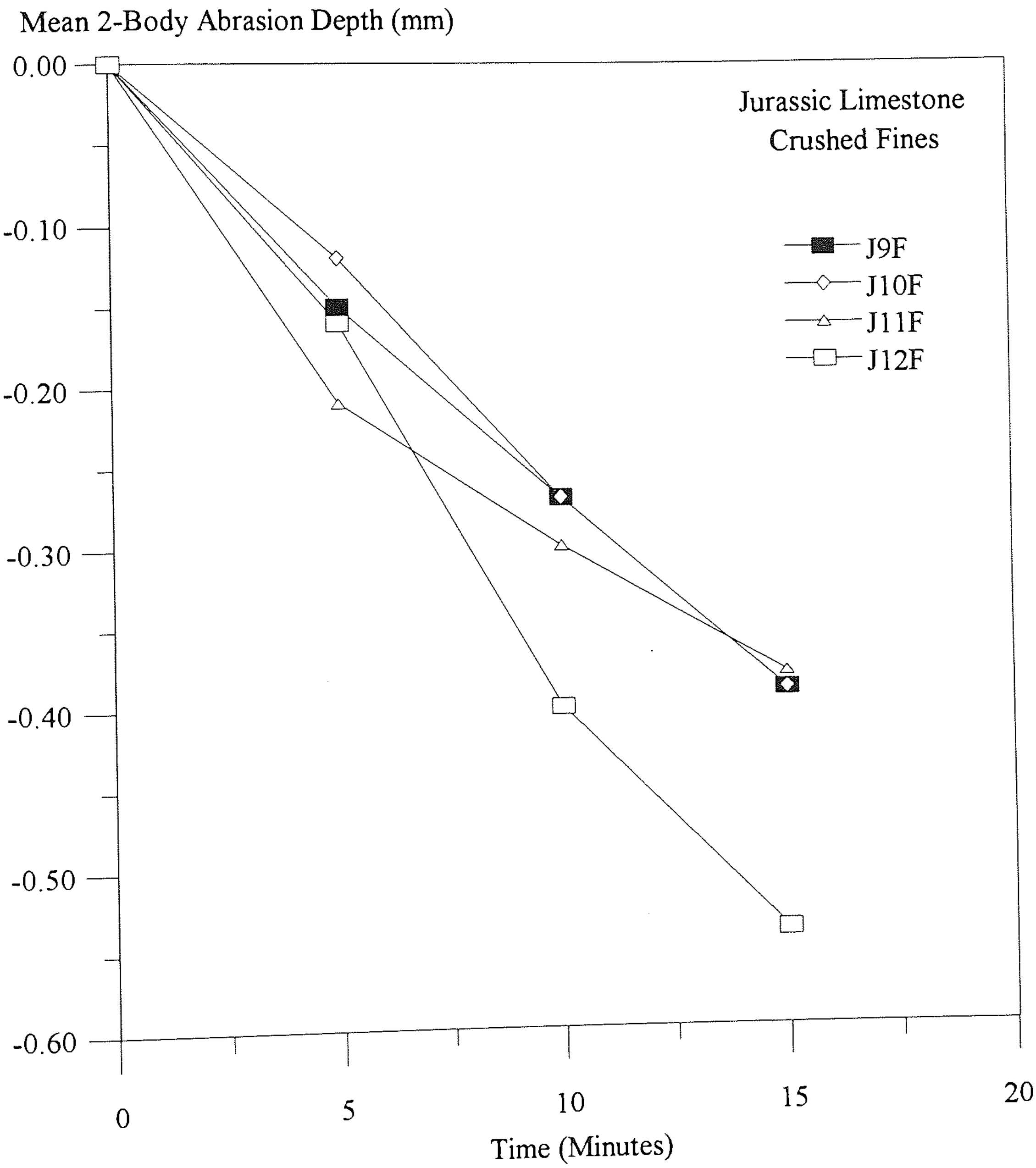

Figure 5.17. Rate of abrasion under 2-body test conditions for Jurassic Limestone crushed fines.

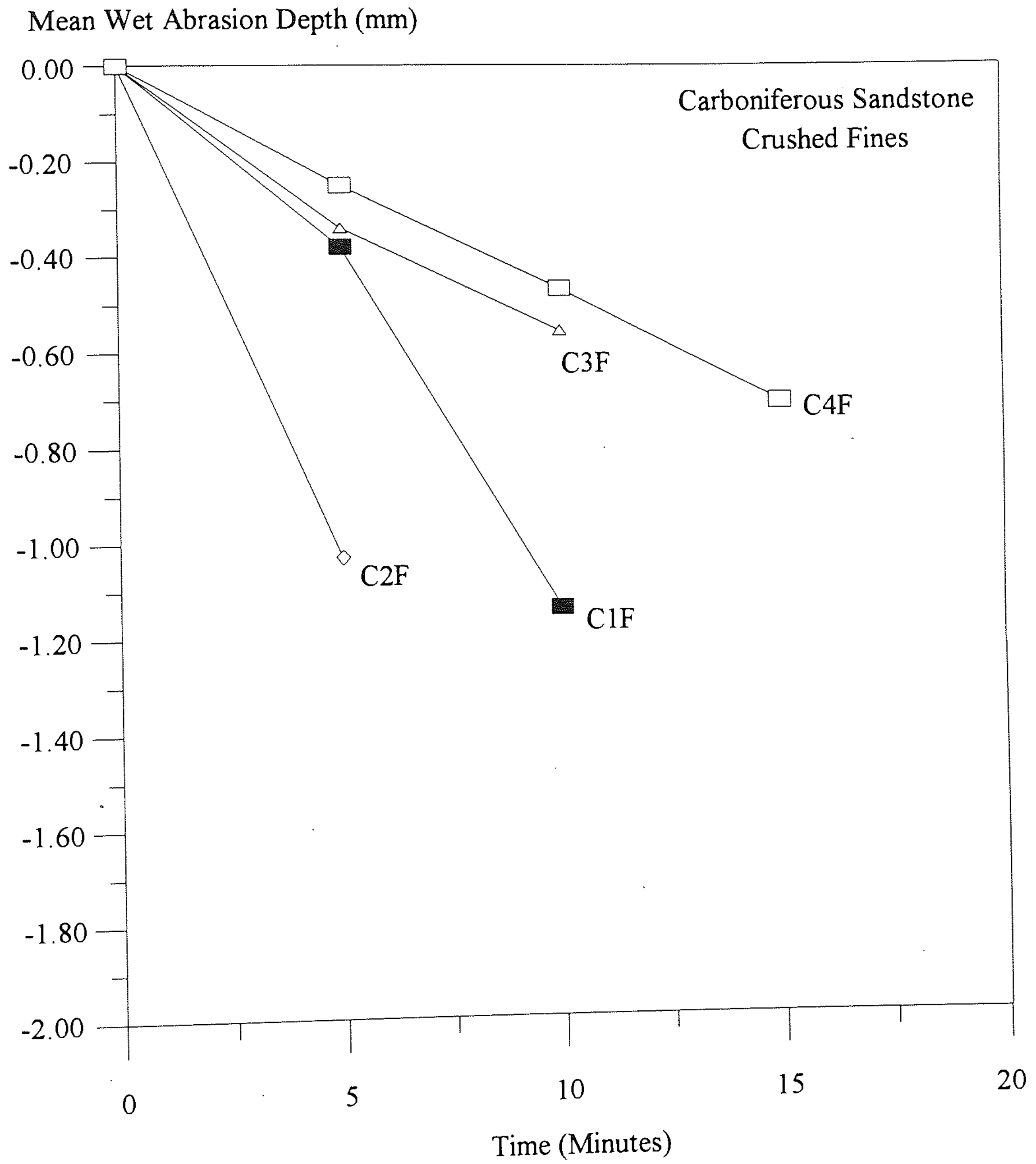

Figure 5.18. Rate of abrasion under wet test conditions for Carboniferous Sandstone crushed fines.

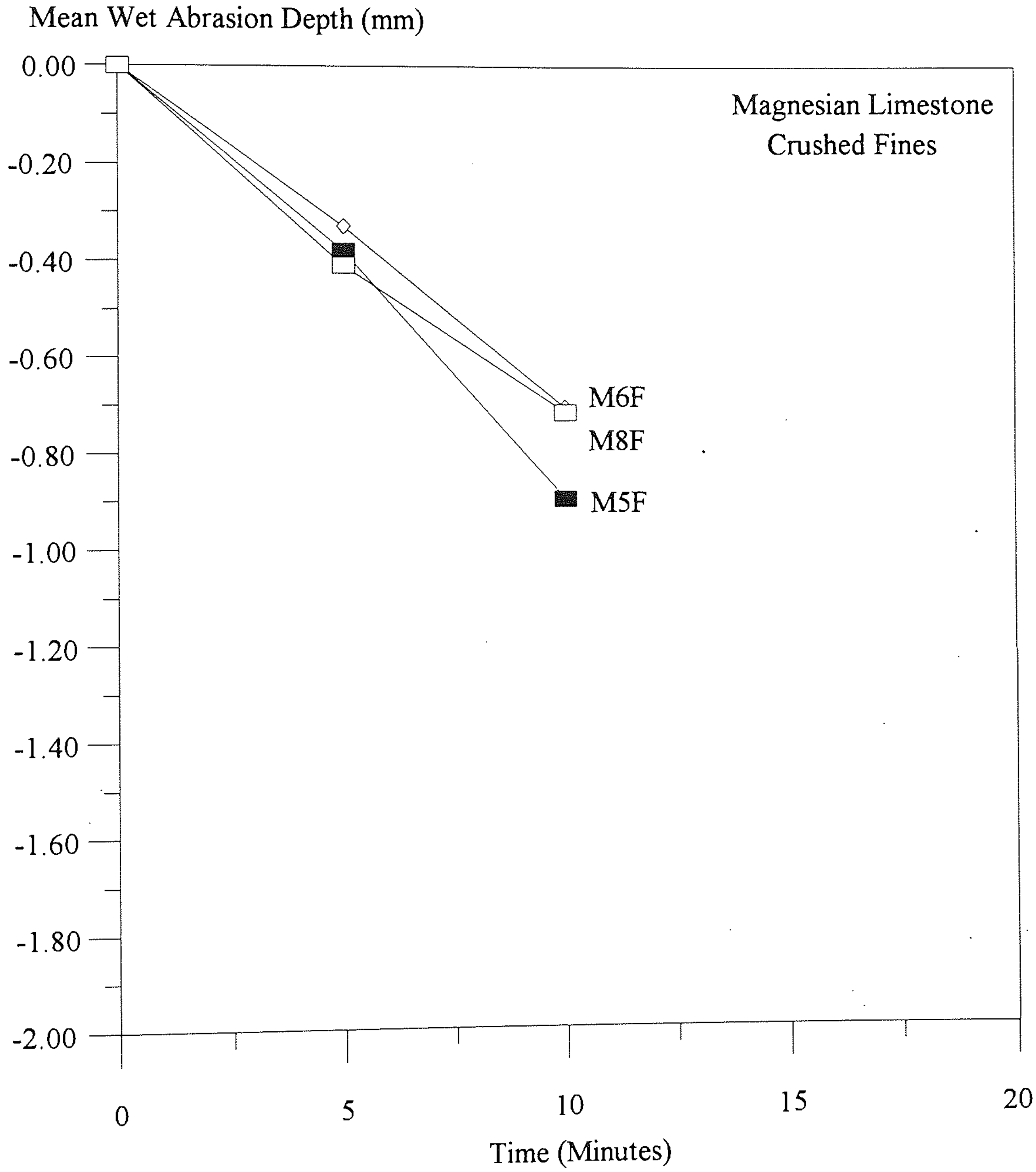

Figure 5.19. Rate of abrasion under wet test conditions for Magnesian Limestone crushed fines.

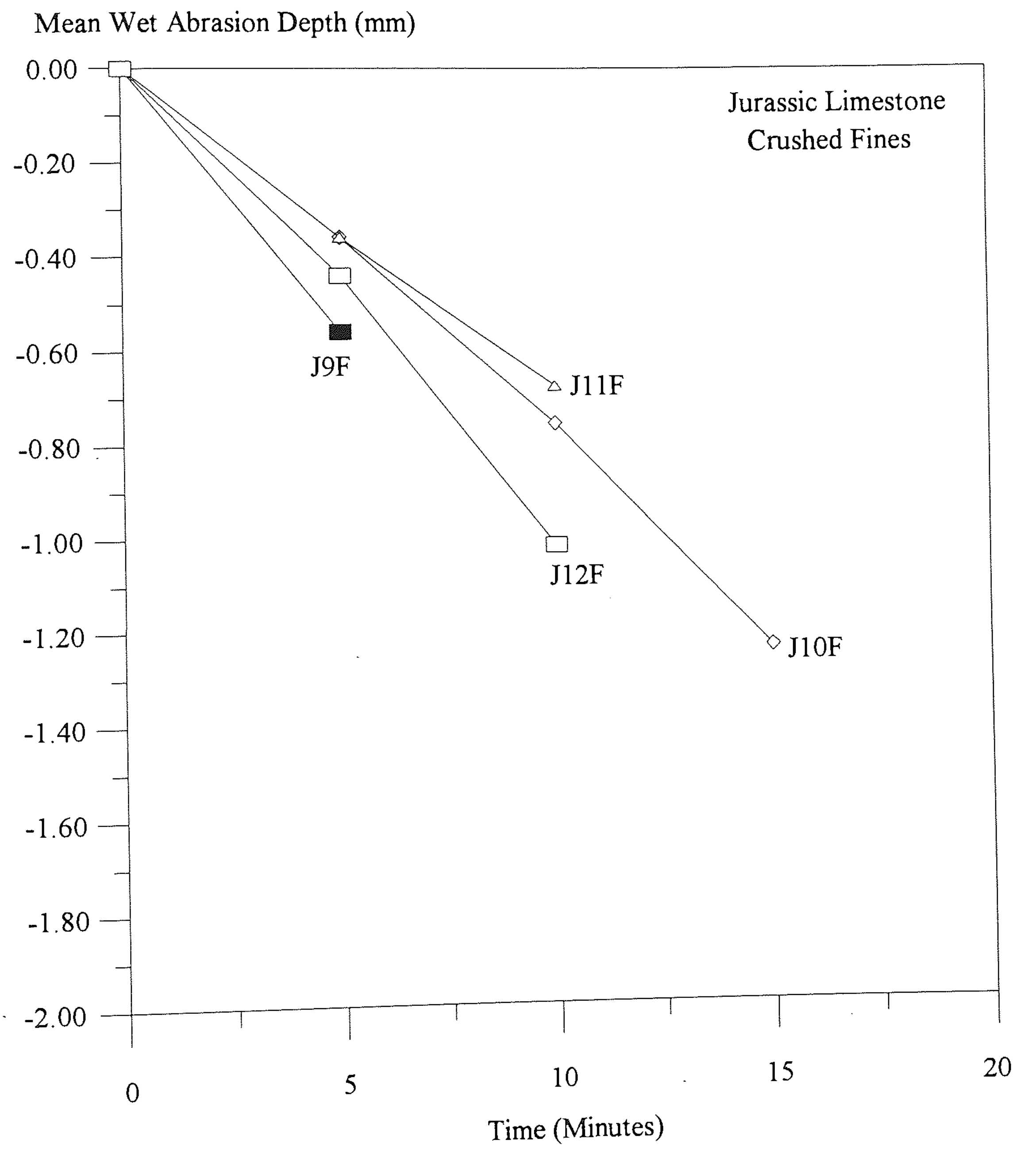

Figure 5.20. Rate of abrasion under wet test conditions for Jurassic Limestone crushed fines.

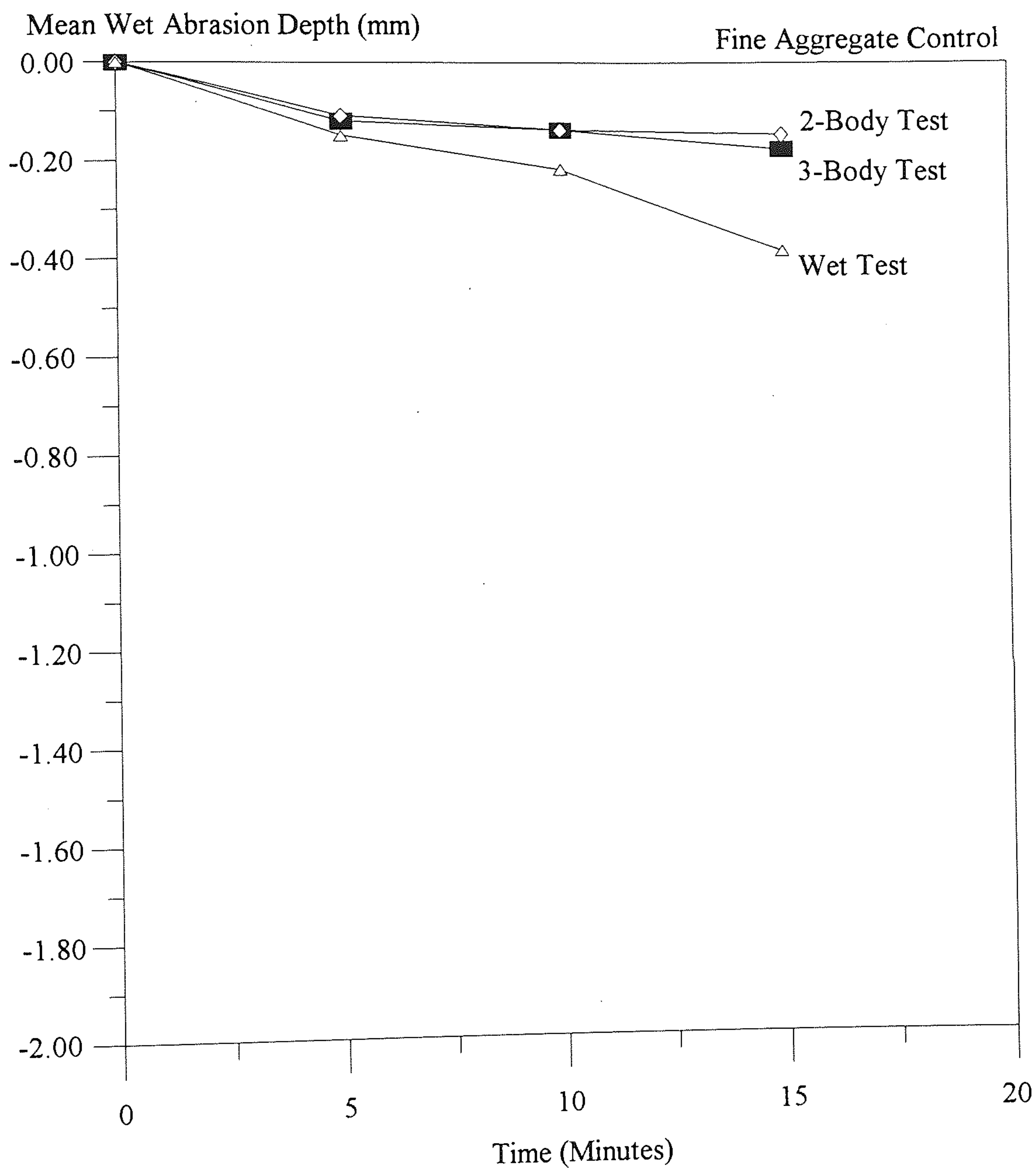

Figure 5.21. Rate of abrasion of the fine aggregate control under the three test conditions.

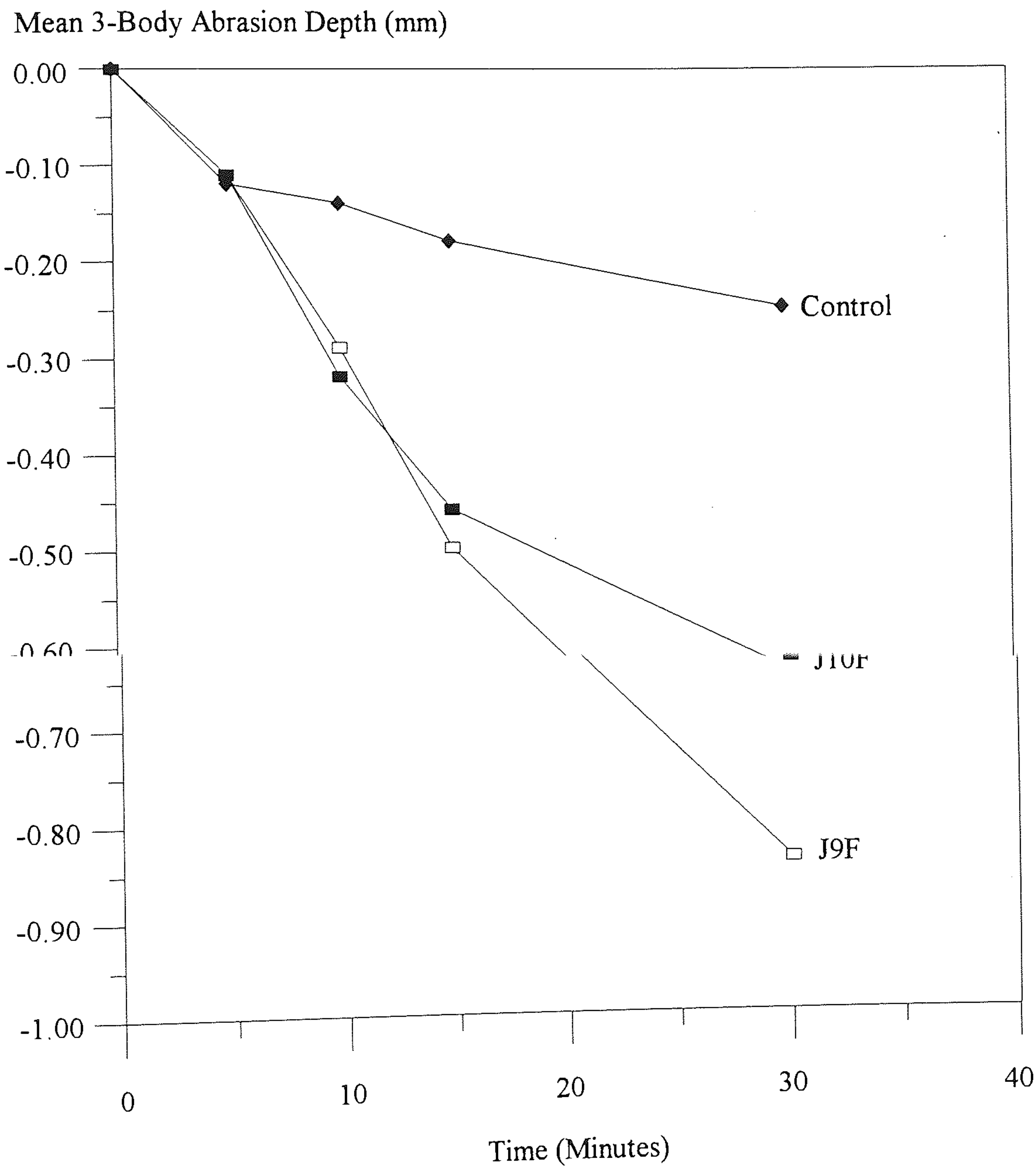

Figure 5.22. Abrasion/Time graphs for the specimens tested up to 30 minutes.

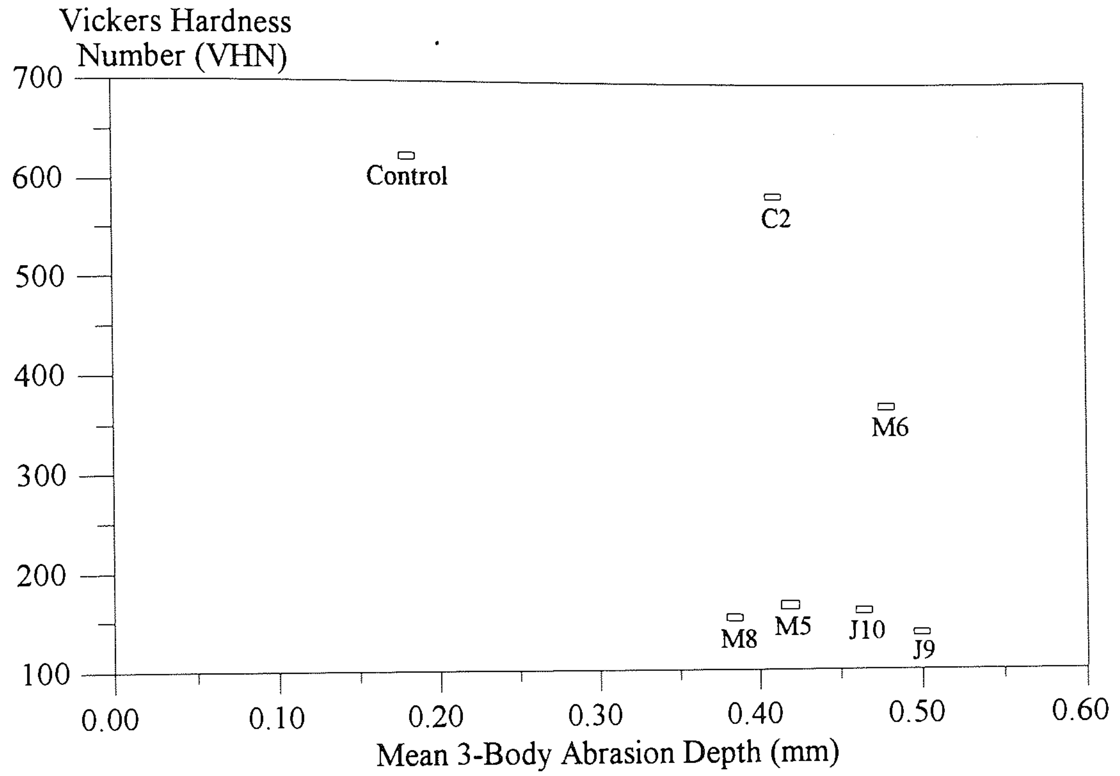

Figure 5.23. Relationship between Vickers Hardness Number (VHN) of the aggregates, when present as crushed fines, and 3-body abrasion depth.

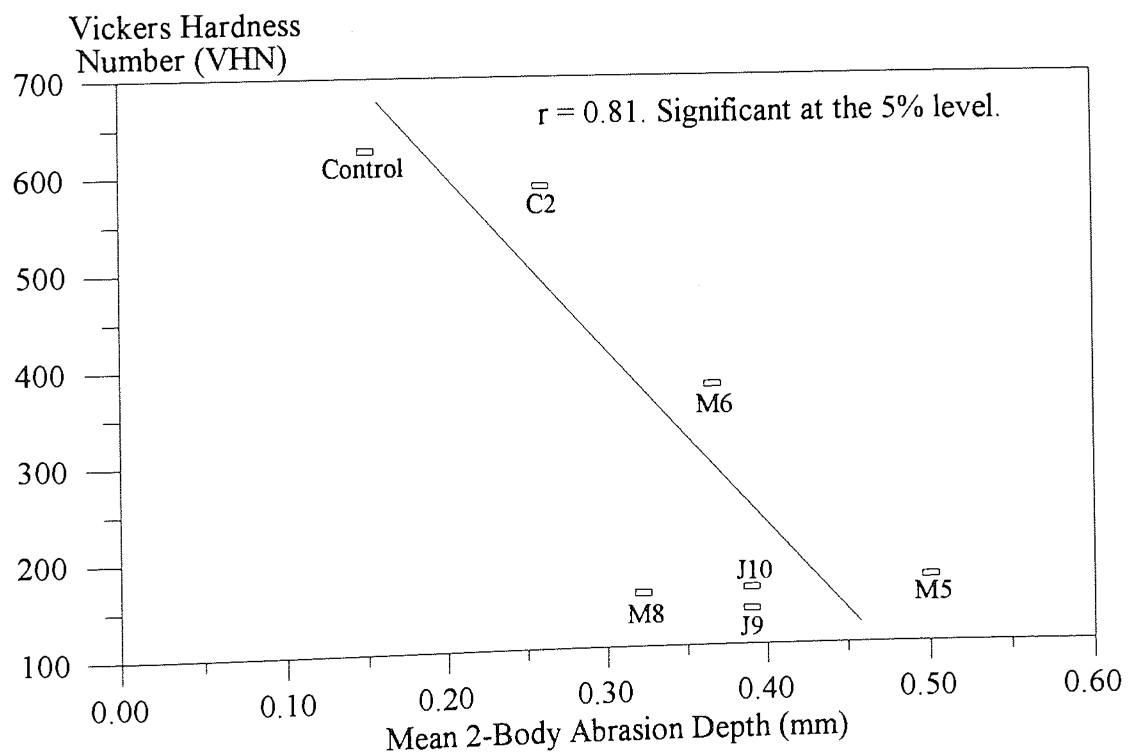

Figure 5.24. Relationship between Vickers Hardness Number (VHN) of the aggregates, when present as crushed fines, and 2-body abrasion depth.

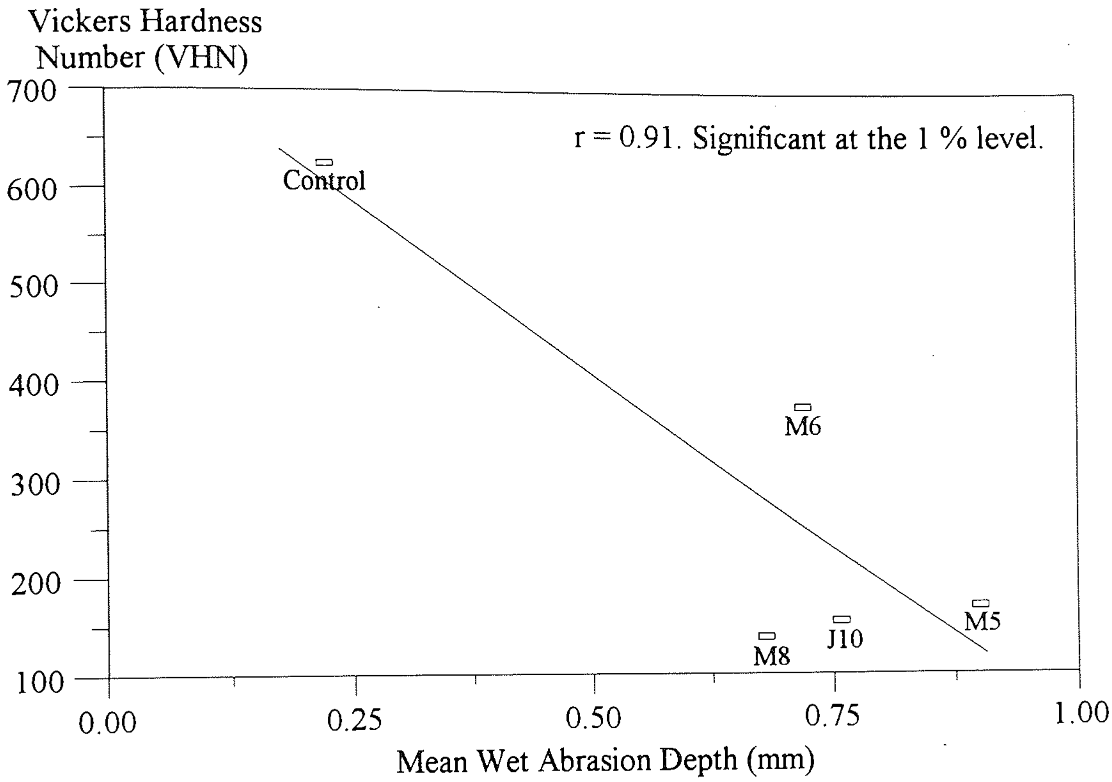

Figure 5.25. Relationship between Vickers Hardness Number (VHN) of the aggregates, when present as crushed fines, and wet abrasion depth.

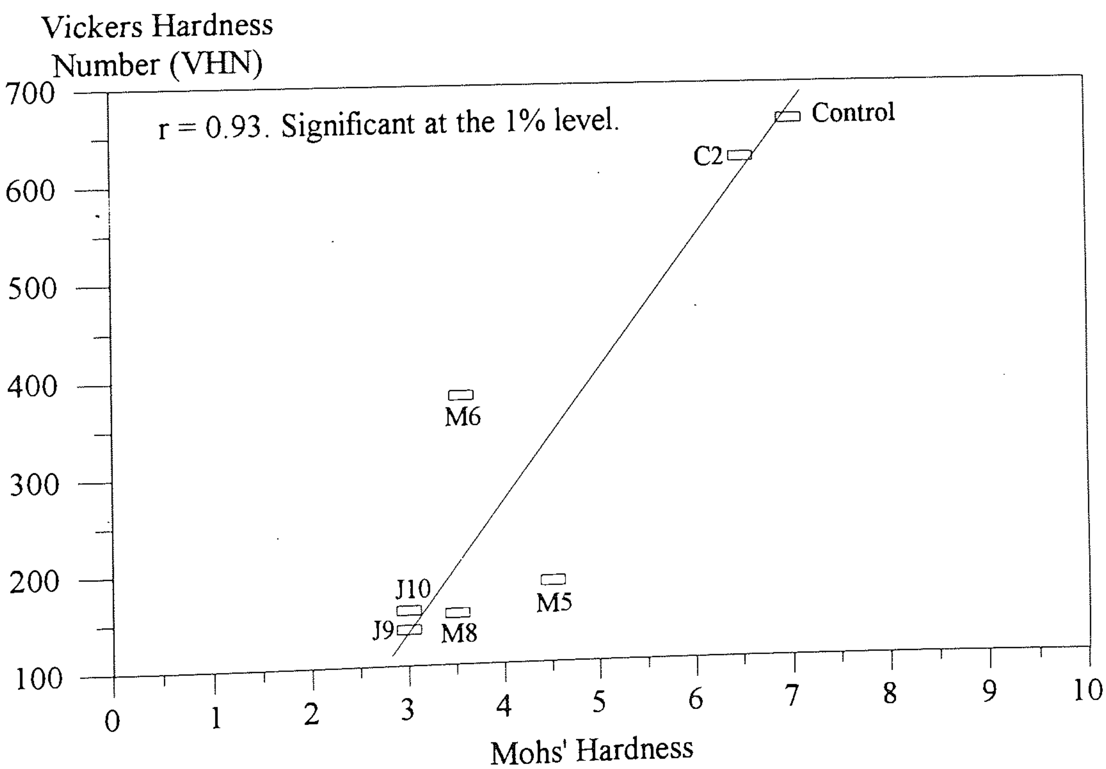

Figure 5.26. Relationship between Vickers Hardness Number and Mohs' Hardness.

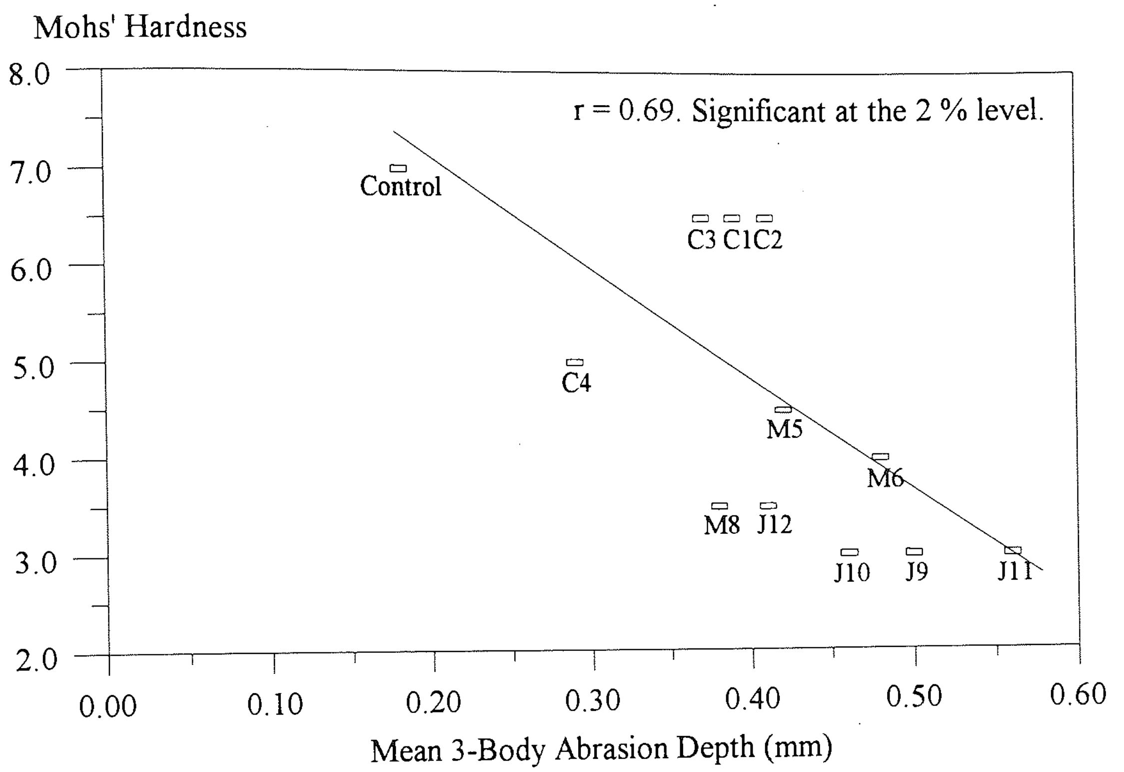

Figure 5.27. Relationship between Mohs' Hardness of the aggregates, when present as crushed fines, and the 3-body abrasion depth.

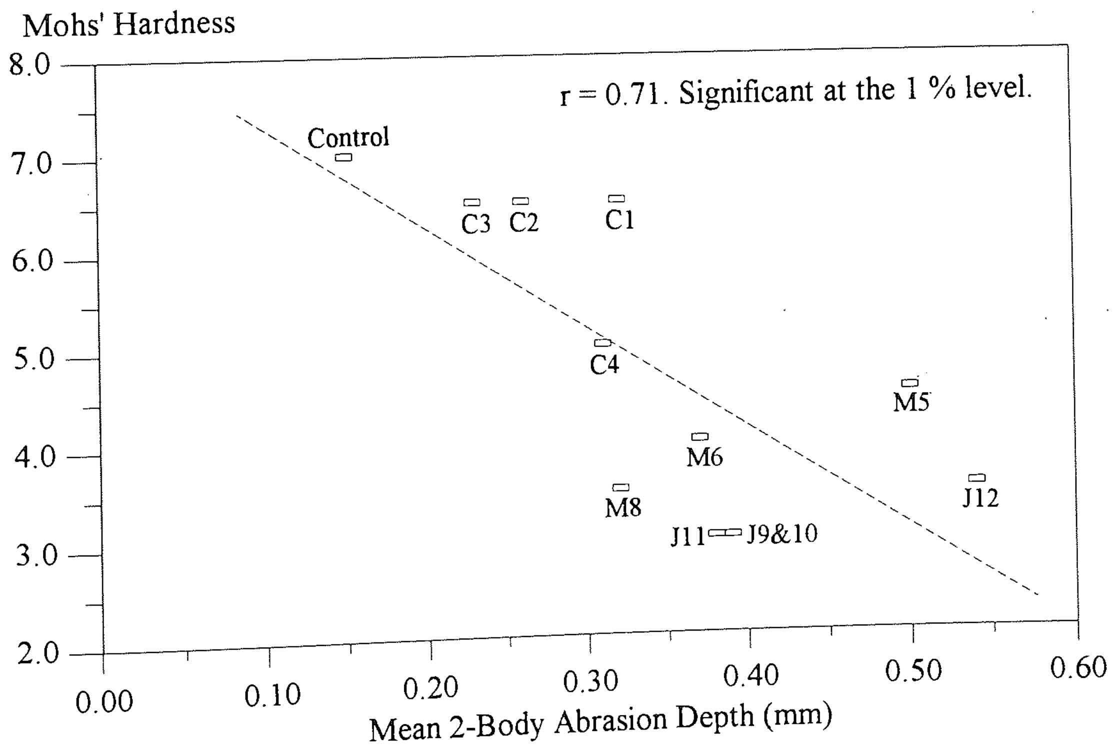

Figure 5.28. Relationship between Mohs' Hardness of the aggregates, when present as crushed fines, and 2-body abrasion depth.

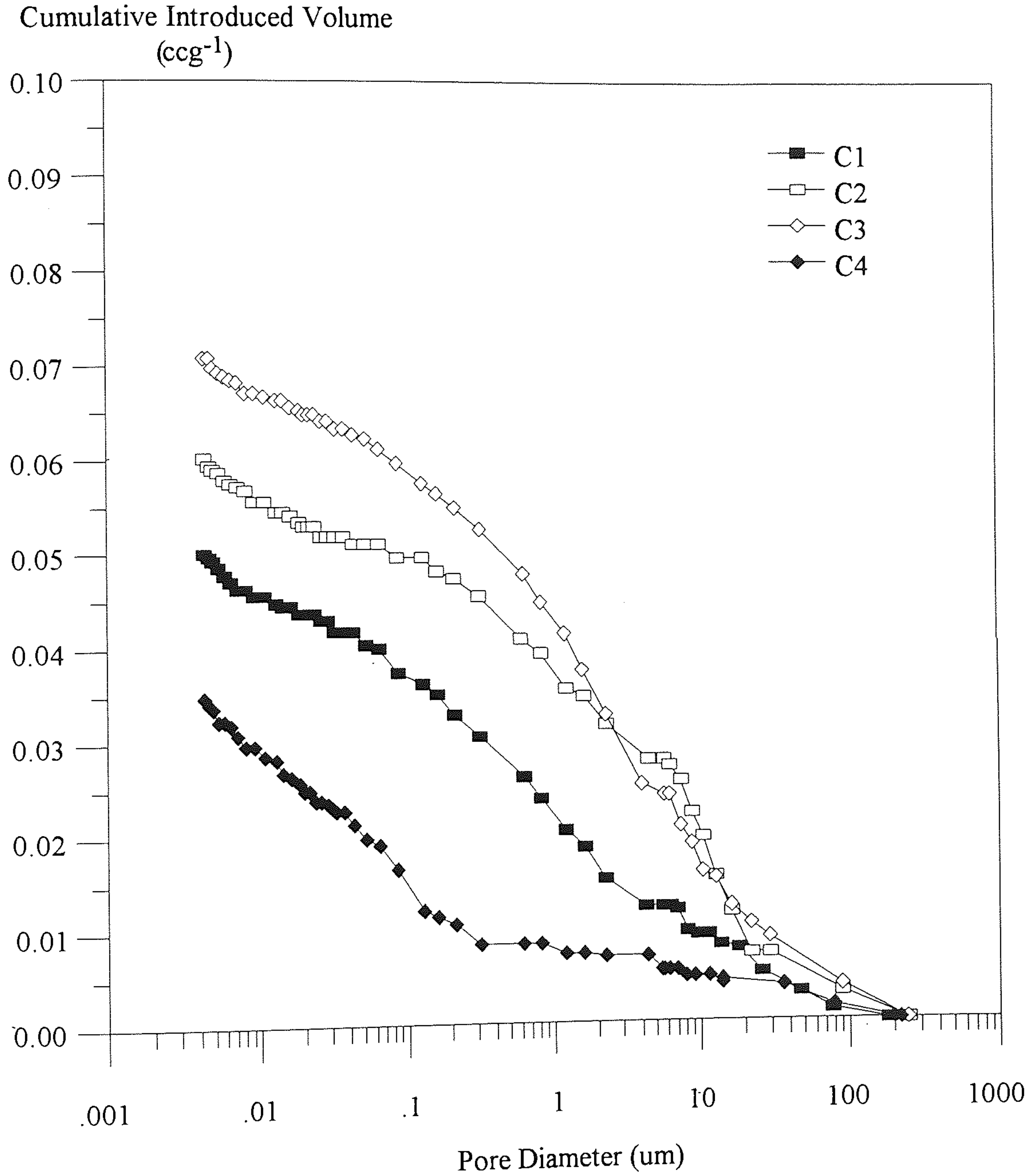

Figure 5.29. Pore size distribution of the Carboniferous Sandstone aggregates.

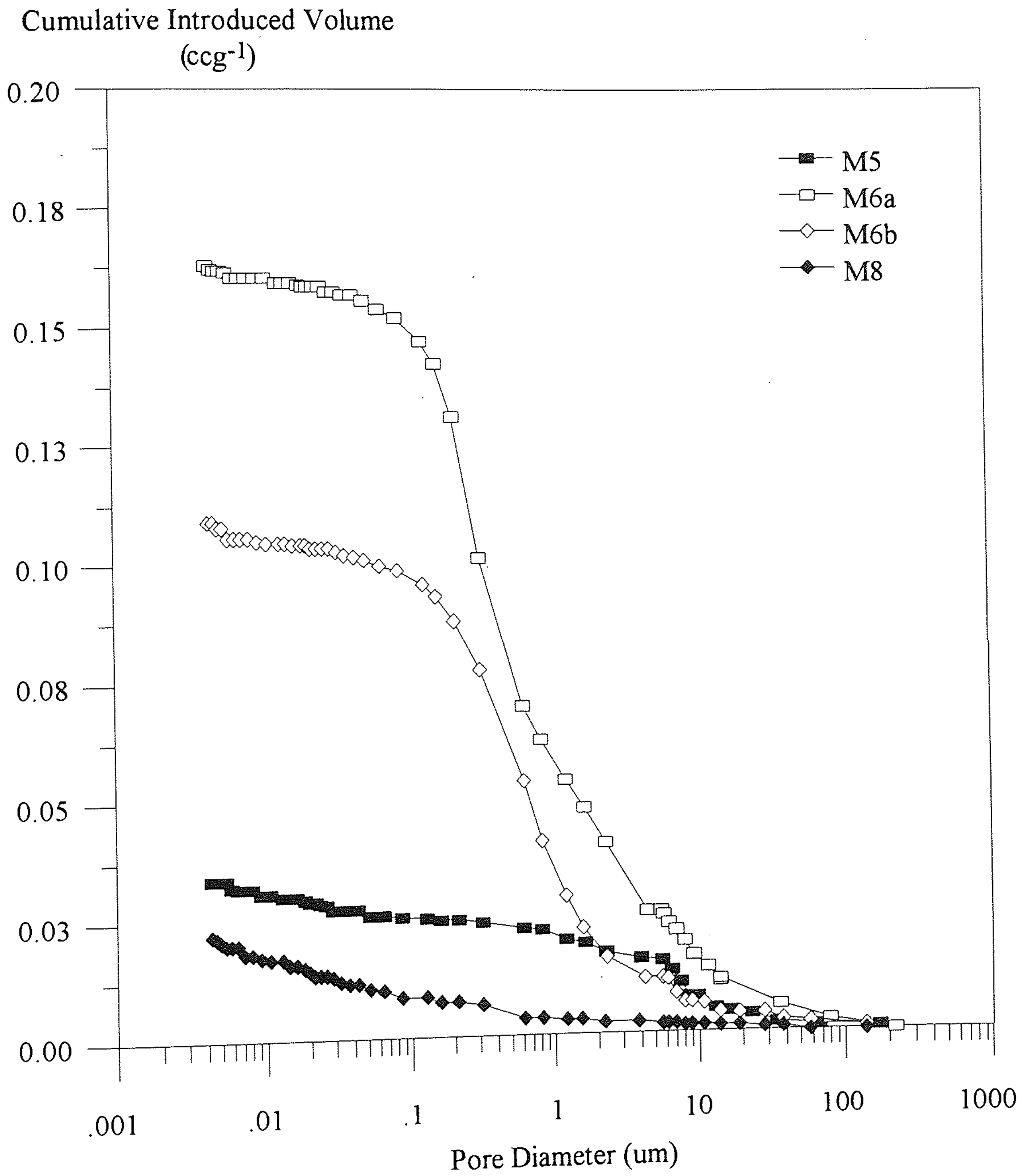

Figure 5.30. Pore size distribution of the Magnesian Limestone aggregates.

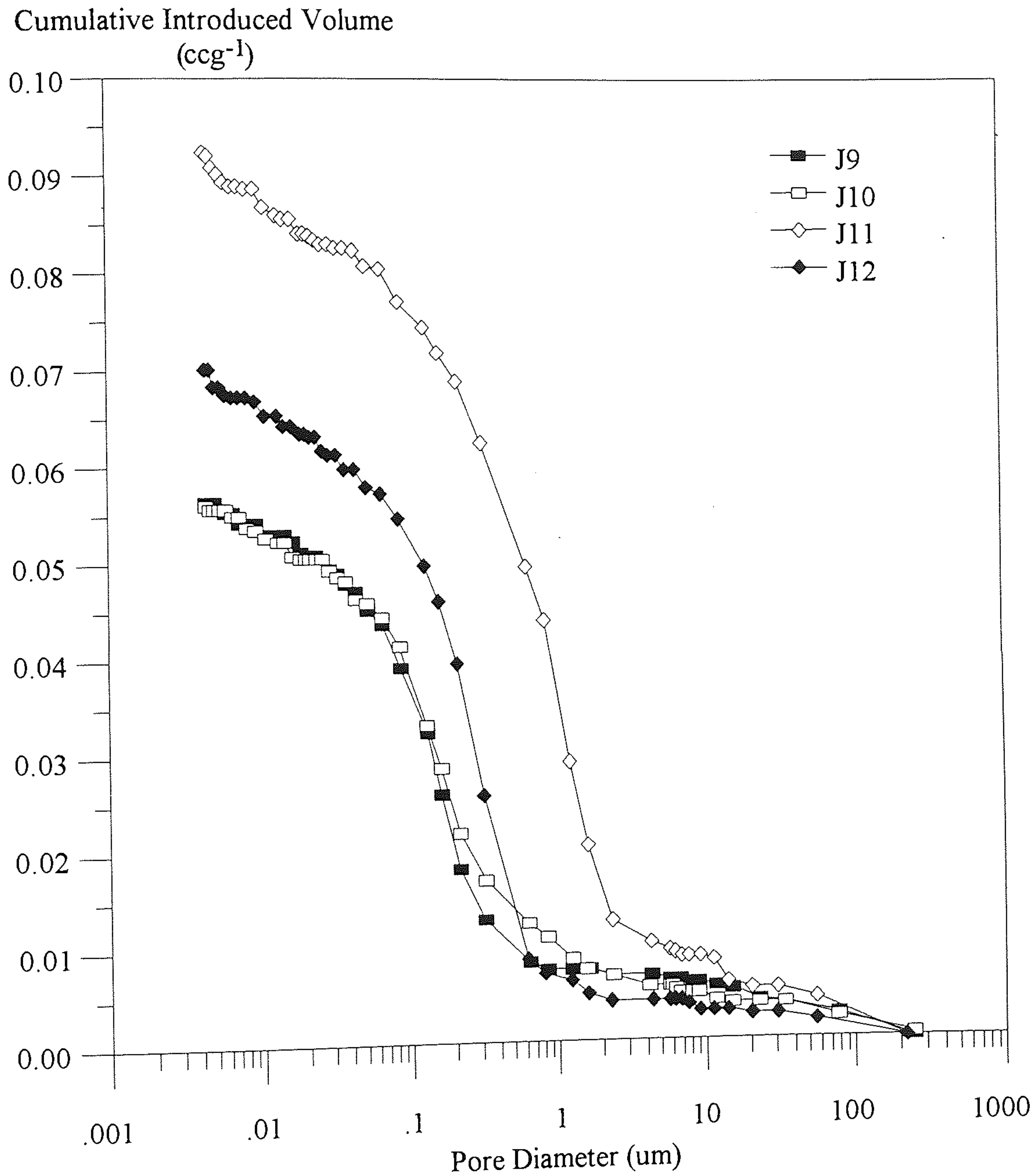

Figure 5.31. Pore size distribution of the Jurassic Limestone aggregates.

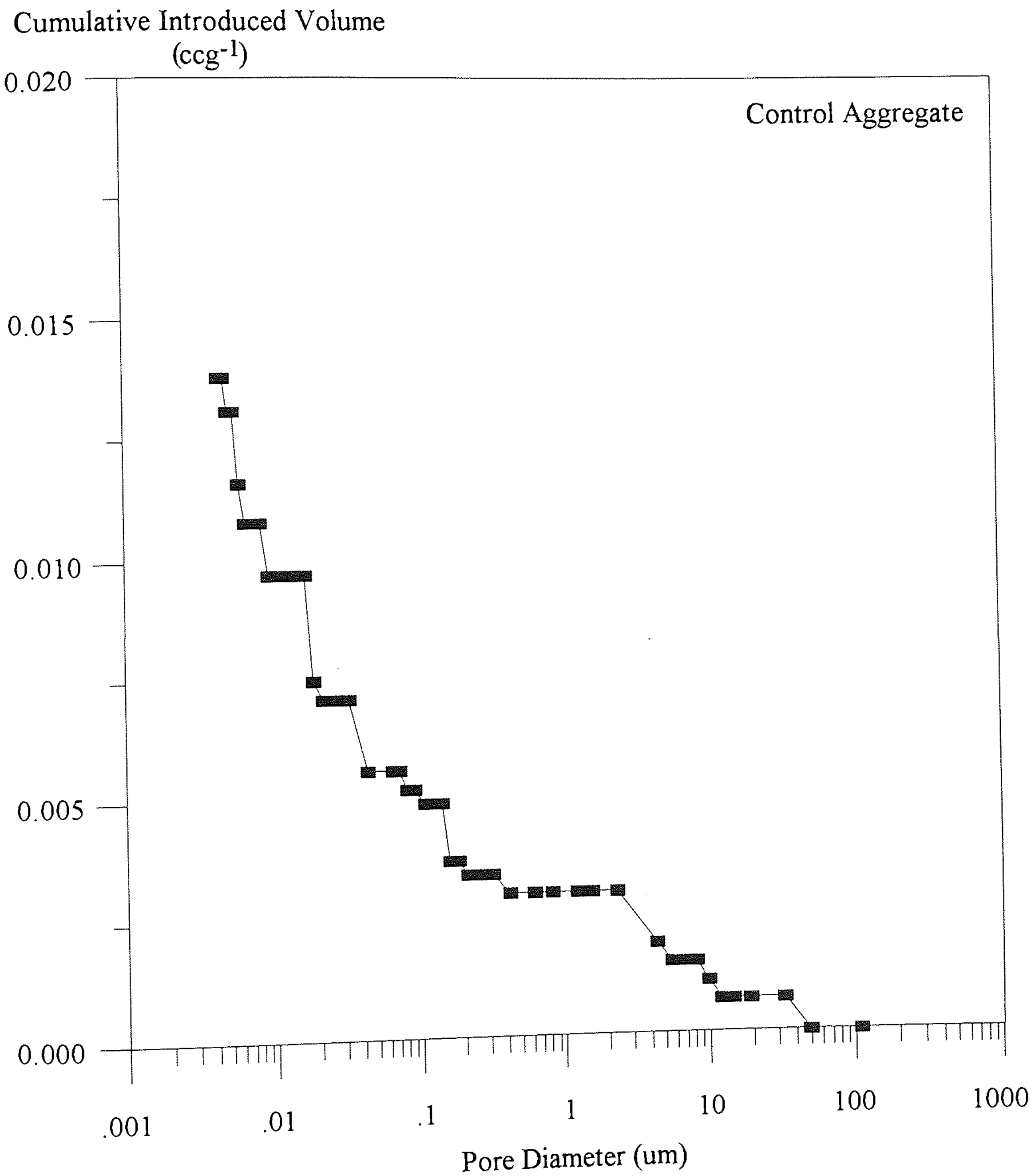

Figure 5.32. Pore size distribution of the control aggregate.

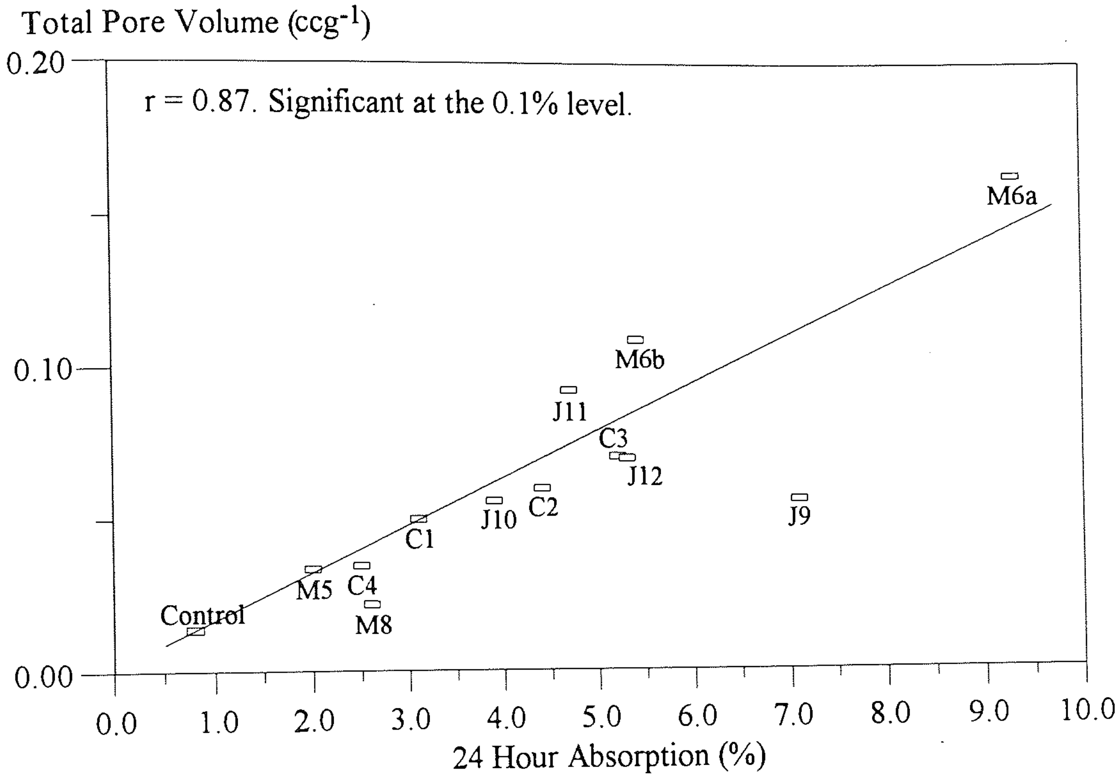

Figure 5.33. Relationship between 24 hour absorption and total pore volume of the coarse aggregates.

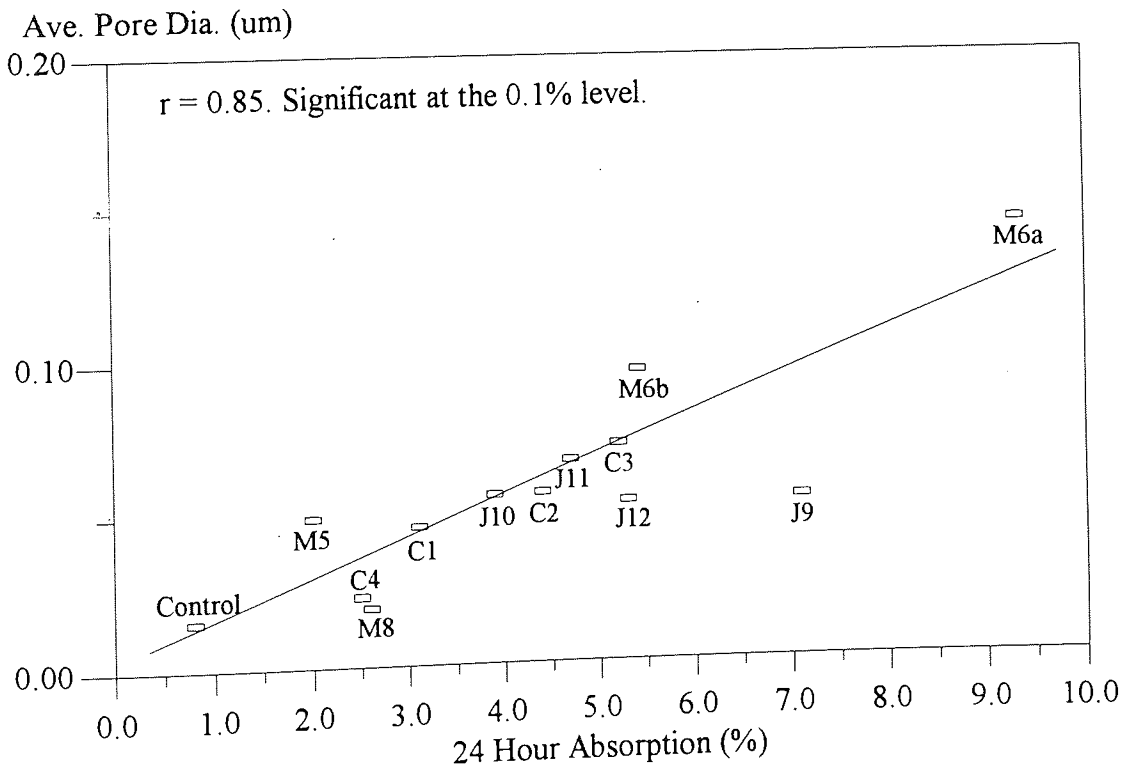

Figure 5.34. Relationship between 24 hour absorption and average pore diameter of the coarse aggregates.

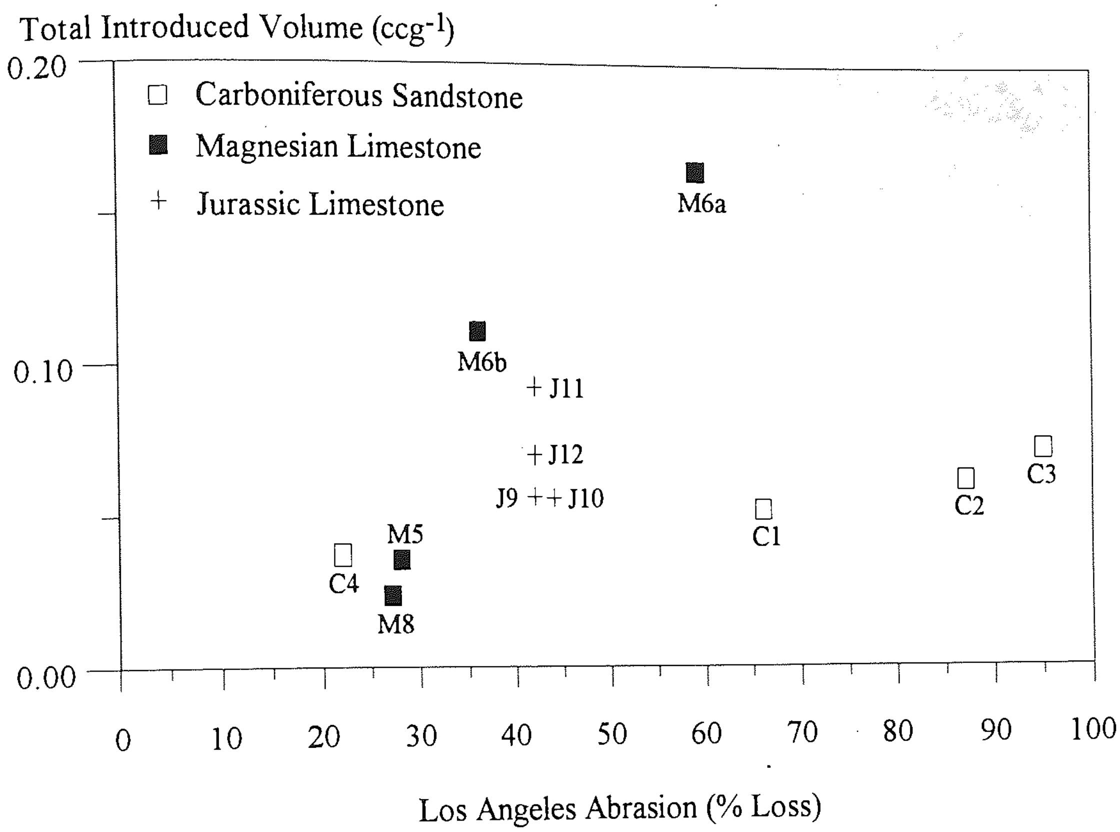

Figure 5.35. Relationships between total introduced volume of mercury and Los Angeles Abrasion loss for the three aggregate types.

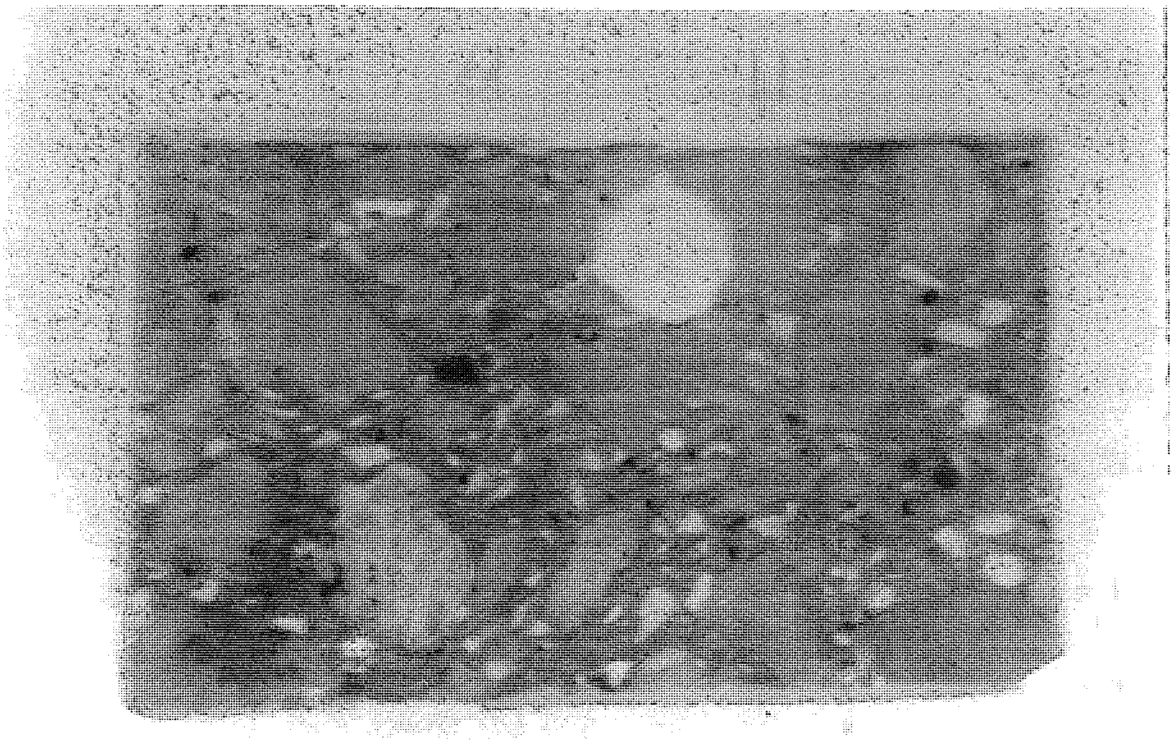

Plate 5.1. Photograph showing the concentration of cement minerals and fine aggregate (the darker zone) at the power finished surface of specimen J10S1.

Chapter 6 Discussion

6.1 Introduction

In this chapter the results presented in Chapter 5 are discussed and the analysis is initially structured to assess general trends which apply to all the aggregates. This section is sub-divided into those which apply to mixes relating to the role of the coarse aggregates, and subsequently to those which relate to the fine aggregates.

This is followed by an individual examination of each rock type dealing in particular with their effect on abrasion resistance when present as either the coarse or fine fraction. A separate section is devoted to assessing the effect on abrasion resistance of varying the proportion of a low-grade aggregate, both as the coarse and fine fractions, from zero to 100 per cent. The inter-relationship between factors which affect abrasion resistance is explored, and the final section describes some experimental observations pertaining to the possible mechanisms involved in abrasion under the three testing regimes. The correlations illustrated in *Figures 6.1* to *6.14* (with the exception of *Figure 6.3*) all show linear relationships, although it is recognised that in reality not all relationships are linear. Quadratic relationships were also fitted to the data, but it was found that their correlation coefficients hardly differed from those of the linear relationships. In the context of the present work the existence of a relationship rather than the exact nature of that relationship was deemed to be the more important. For this reason, and as linear plots are mathematically the most straightforward, it is these that have been plotted.

6.2 General Trends for all Aggregates

There are a number of trends which apply to all the aggregates examined during the research programme, and which can be shown to be statistically significant. The discussion of these results has been divided into those mixes containing the low-grade coarse aggregates and those containing the low-grade fine aggregates.

6.2.1 Coarse Aggregate Mixes

6.2.1.1 Cube Strength

For this investigation, it was generally the case that concretes containing low-grade coarse aggregates had lower values of cube strength compared to similar concretes, in terms of free water-cement ratio, containing normal concrete aggregate. It is possible to attribute this reduction in strength to a number of factors.

All of the aggregates, with one exception, have relative density values below that of the control aggregate, which is deemed to be representative of normal concrete aggregate. The lowest relative density values, obtained from C1, C2, C3, M6a and J9, are due to the presence of many voids between the constituent grains, and which were discussed in Chapter 4, Section 4.3.1.1. Voids are present in the other aggregates, but not to the same degree as in those listed above. The relationships between the relative density of each of the coarse aggregate types and the cube strength of the concretes containing those aggregates are shown in *Figure 6.1,* and they show that increasing relative density values are associated with increases in cube strength. In Chapter 4, Section 4.3.3, it was suggested that the abrasion toughness of an aggregate, as expressed by the Los Angeles Abrasion value, is related to relative density so it is appropriate to also examine its relationship to the cube strength of the concrete. Accordingly the relationships between the Los Angeles Abrasion value of the coarse aggregates and the cube strength of the corresponding concretes are shown in *Figure 6.2.* In a study involving four igneous rock aggregates having Los Angeles Abrasion losses of 25, 27, 56 and 57 per cent, Amirkhanian *et al.* (1992) found that only one concrete specimen prepared with aggregates having a low Los Angeles Abrasion loss (25 per cent) produced a significantly higher cube strength than those with higher Los Angeles Abrasion losses. They suggested that textural and mineralogical differences of the (unusual) igneous rocks and a high free water-cement ratio had contributed to this result.

It is evident from an examination of the aggregate grading data, summarised in Chapter 4 and detailed in Appendix B, and the cube strength data that the proportion of coarse aggregate passing the 5 mm sieve has a significant effect on the strength of the concrete in which it is placed. A strong correlation was obtained between the percentage passing the 2.36 mm sieve and the cube strength of concrete, as shown in *Figure 6.3.* The effect on cube strength appears greatest at percentages above 5 per cent. This is probably a reflection of the fact that the coarse aggregates with a higher percentage of material passing the 2.36 mm sieve required more water to attain a certain level of workability, *Figure 6.4,* and so may be an indirect consequence of the relationship between water-cement ratio and cube strength. The relationship between water-cement ratio and cube strength is a well known one (Teychenné, Franklin and Erntroy, 1975 and Neville, 1981) and has been demonstrated during the present work. The role of the water-cement ratio was discussed in Chapter 5, Section 5.3.1, and is illustrated in *Figure 6.5.*

It is a fundamental problem with the aggregates used throughout this project that they generally have high 24 hour absorption values and a rough surface texture. Although not directly affecting the strength of the concrete, these properties are important in determining the water requirement of a mix, and hence its water-cement ratio. When working to a uniform level of workability, these aggregate properties influenced the free water-cement ratio so that the higher water contents necessitated by some aggregates were reflected in the cube strength of the concretes.

6.2.1.2 Abrasion Resistance

The cube strength of concrete has long been used as a yardstick in determining how a given concrete will perform when subjected to abrasion (Smith, 1958; Taylor, 1977; Neville, 1981) although a few researchers have questioned its use as a sole measure of abrasion resistance (A'Court, 1954; Sadegzadeh, 1985; Langan, Joshi and Ward, 1990). The data from the present study also show good correlations between the cube strength and both the 3-body abrasion depth and the wet abrasion depth, as illustrated in *Figures 6.6* and *6.7.* This shows that an increase in the cube strength would be expected to produce a commensurate decrease in the abrasion depth and supports the work of Smith (1958) and others.

The free water-cement ratio has already been shown to influence the cube strength of these mixes and so it is necessary to consider its influence on abrasion resistance. Relationships between the 3-body, 2-body and wet abrasion depths and the free water-cement ratio are illustrated in *Figures 6.8, 6.9* and *6.10.* As the free water-cement ratio is a measure of the quantity of free water available in a mix, it is perhaps not surprising that it influences the abrasion resistance, since an increase in free water increases the porosity of the matrix (Sadegzadeh, 1985). While power finishing reduced the quantity of these voids in the surface matrix by recompacting it after the initial bleed water had evaporated, mixes with high free water contents were likely to exhibit further internal bleeding after power finishing was completed. This can result in a weakened surface due to the bleed water subsequently evaporating and leaving a pore space network within the surface microstructure (Sadegzadeh, 1985). This porosity in the surface layer has been shown to lead to an inferior abrasion resistance (Sadegzadeh, Kettle and Page, 1989).

The factors mentioned so far all relate to the properties of the concrete containing low-grade coarse aggregates, but it is also necessary to consider aggregate properties which may influence abrasion depth. Two aggregate properties were found to show a significant relationship with 3-body abrasion depth for all the coarse aggregates. The first was the grading, and more specifically the proportion of fine material. Correlations between both percentage passing the 2.36 mm and 5 mm sieves with 3-body abrasion depth are shown in *Figures 6.11* and *6.12* respectively. The second factor was the Los Angeles Abrasion loss, and is illustrated in *Figure 6.13.* The nature of the finishing procedures employed on floor slabs produces a surface layer which consists predominantly of the mortar matrix (sand, cement and water) with the coarser particles being located some 1 to 5 mm below this surface (Sadegzadeh, 1985). Thus, the characteristics of the fine aggregate are crucial in controlling the early stages of abrasion before contact is made with the coarse particles. The fine fraction of the low-grade coarse aggregates was expected to display similar characteristics to its parent particles and so would not have been as tough as the particles in the control fine aggregate. Thus, any increase in the amount of this fraction would impact adversely on the quality of this surface layer and this is borne out by the relationship. It is suggested that the influence of the Los Angeles Abrasion values would not become apparent until contact was made with the coarse aggregate particles themselves. Aggregates with high Los Angeles Abrasion losses break up readily when subjected to the loading of the abrasion apparatus, therefore rapidly increasing the quantity of loose abrasive particles, which have been shown to increase the rate of abrasion (Moore and King, 1980). Particles which have a lower value of Los Angeles Abrasion loss were more resistant to breakdown, leading to slower production of loose abrasive particles and consequently a slower rate of increase in the abrasion depth.

The lack of correlation between the coarse aggregate properties and the 2-body abrasion depth may be attributed to the fact that this test involved the removal of the loose third body particles. The majority of these particles were derived from both the fine and coarse aggregates, so their removal considerably reduced the influence of the aggregate. The addition of water in the wet abrasion test appears to have introduced a parameter which was much more influential upon abrasion resistance than the properties of the aggregate within the concrete. Possible reasons for this are discussed in Section 6.13.3.

6.2.2 Fine Aggregate Mixes

6.2.2.1 Cube Strength

Unlike the coarse aggregate mixes, there are no indications that the properties of the fine aggregates used for the project have had a direct effect on the cube strength of the individual concretes. The only factor which proved to have an effect on the cube strength was the free water-cement ratio of the mixes, although it is likely that this has been influenced by the grading of the fine aggregate. A graph showing the relationship between free water-cement ratio and 28 day cube strength for the crushed fines mixes is given in *Figure 6.14*. As discussed in Section 6.2.1.1. and in Chapter 5, Section 5.3.2, this relationship is not unexpected.

6.2.2.2 Abrasion Resistance

Unlike the coarse aggregate mixes, which showed a good correlation between cube strength and both the 3-body and the wet abrasion depths, the fine aggregate mixes do not exhibit similar correlations between cube strength and any of the abrasion conditions. Similarly, no correlation was found between the free water-cement ratio and any of the abrasion conditions. However, relationships have been established between the VHN and Mohs' Hardness of the parent rock and both the 2 and 3-body abrasion depths of the concretes containing the aggregates as crushed fines. These relationships were shown in Chapter 5, *Figures 5.23, 5.24, 5.27* and *5.28*. These results suggest that the hardness/quality of the fine aggregate is of great importance in determining the abrasion resistance of concrete and is discussed further in Section 6.13.

The 3-body abrasion results for the various fine aggregate mixes, summarised in *Table 5.7*, show the values after 15 minute ranging from 0.29 mm to a maximum of 0.56 mm, as compared to a range of 0.05 to 0.59 mm for similar coarse aggregate mixes. This suggests that the surface of the fine aggregate mixes abraded relatively quickly to a depth where contact was made with the coarse aggregate particles. Contact with these coarse particles effectively controlled the subsequent abrasion for the remainder of the test period. Evidence for this can be gleaned from the shape of the abrasion against time graphs illustrated in *Figures 5.12* to *5.14*. The 3-body abrasion plots for the fine aggregate mixes generally illustrate curves which tend to reach a plateau with time at abrasion depths between approximately 0.30 and 0.50 mm. This indicates that, once the surface layer had been abraded, the good quality coarse aggregate, although in combination with low quality fines, maintained a low rate of abrasion with further exposure to the test. Both the fine and coarse fractions are therefore influential upon abrasion resistance, although each is important at different stages of the abrasion process. The 2-body abrasion depth plots, *Figures 5.15* to *5.17*, follow the same general pattern as those of 3-body abrasion discussed above, the main difference being that the removal of the abrasive particles during testing has generally reduced the overall abrasion depth i.e. displaced the curves along the 'y' axis. As shown in Chapter 5, *Figures 5.23*, *5.24*, *5.27* and *5.28* higher values of hardness seems to improve both 2 and 3-body abrasion resistance.

The wet abrasion depth plots, *Figures 5.18* to *5.20*, are quite different to those of both the 2 and 3-body abrasion, with the graphs showing an almost linear increase of abrasion depth with time. It can be inferred from this that the addition of water to the test surface dramatically increased the abrasion depth, irrespective of the fact that the coarse aggregate in the mix was hard and durable. As discussed in Chapter 5, Section 5.5.2, the influence of fine aggregate hardness on wet abrasion resistance is less clear, and apparently less significant, than with both 2 and 3-body abrasion. Possible reasons for this are explored in Section 6.13.

6.3 Carboniferous Sandstone Coarse Aggregates

Although all of the sandstone aggregates are from the Carboniferous period, there are a number of intrinsic differences which may be considered important in determining their role when the concrete was subjected to abrasion. Samples C1, C2 and C3 all have rough surface textures and significant 24 hour absorption values, i.e. above 3 per cent. Sample C4 is much finer grained and has a smoother texture, but a more angular particle shape. The aggregates broadly satisfy the grading requirements of BS 882: 1992, with the exception that they have between 1 and 9 per cent by weight of material passing the 2.36 mm sieve. This is perhaps a reflection on the fact that samples C1, C2 and C3 consist of poorly cemented constituent particles which are easily broken down. This is demonstrated clearly by the Los Angeles abrasion results in which samples C2 and C3 were almost completely crushed during the test, resulting in losses of 87 per cent and 95 per cent respectively. Although these aggregates cannot be classified as particularly durable, they consist predominantly of quartz and have hardnesses within the range 6 to 6.5 on the Mohs' scale of hardness, and are therefore considered hard. Hardness, therefore, cannot be considered a satisfactory measure of durability. Details of the Mohs' scale of hardness is given in Appendix G.

The concrete mixes prepared from these aggregates generally required larger quantities of water than the control mix to attain the target workability. This factor together with the physical properties described above tended to produce concrete of relatively low strength, between 27.5 to 39 MPa. Although these aggregates were ranked as inferior in terms of absorption and durability, and concrete made from them did not develop high strength, the concrete slabs produced from aggregates C1, C3 and C4 would be suitable for use as flooring concrete to grade AR3 in BS 8204: 1987.

6.3.1 3-Body Abrasion Results

With reference to the abrasion depth results presented in Chapter 5, *Table 5.6,* it can be seen that specimens containing samples C2 and C3 showed appreciably greater abrasion depths, 0.47 mm and 0.32 mm, than specimens containing C1 and C4, 0.22 mm and 0.20 mm respectively. This may be due to certain aggregate properties, with C2 and C3 having the lowest relative density, the highest 24 hour absorption and the highest Los Angeles Abrasion loss. Specimens containing C2 and C3 also developed the lowest 28 day cube strength, each being 27.5 MPa. By referring to *Figure 5.2,* it can be seen that the increase in abrasion depth with time for all the aggregates was almost linear. As discussed in Section 6.2, the initial abrasion resistance was dependent upon the free water-cement ratio and the fine material present in the surface layer. The importance of the overall quality of the fine material present at the surface was clearly demonstrated by specimen C2S1 when compared to C1S1. These aggregates had broadly similar free water-cement ratios, 0.63 and 0.69, but had 9 per cent and 2.5 per cent by weight passing the 2.36 mm sieve respectively. After only 5 minutes of abrasion specimen C2S1 exhibited an abrasion depth some 200 per cent greater than that shown by the other sandstone aggregate, a difference which could not be attributed solely to differences in water-cement ratio. High Los Angeles Abrasion losses, as attained by C2 and C3, could be expected to cause break up during the mixing process, effectively producing more fines and so further reducing the quality of the surface layer. It is evident therefore that the abrasion resistance of the concrete containing Carboniferous Sandstone coarse aggregates was governed, at least in part, by the physical properties of the coarse aggregate.

As discussed in Section 6.2, the Los Angeles Abrasion loss became increasingly influential as abrasion depth increased. This is clearly shown by C2 and C3 which had losses of 87 per cent and 95 per cent respectively and show appreciably greater abrasion depths than C1 and C4 with losses of 66 per cent and 22 per cent respectively.

6.3.2 2-Body Abrasion Results

The relationships between the aggregate properties and abrasion depth under 2-body conditions are less clear than under 3-body conditions. Specimen slabs containing C2 and C4 showed very similar abrasion depths to those obtained with the 3-body abrasion test, whereas those containing C1 and C3 showed a marked decrease. Using the Student's 't' test to analyse these differences, the differences between the 3-body and 2-body abrasion depths for C2 and C4 were not statistically significant, whereas those for C1 and C3 did show a statistical difference. Full details of the statistical analyses are presented in Appendix E. An examination of the graphs of 2-body abrasion against time in *Figure 5.5* show that, as was the case for 3-body abrasion, the shape of the abrasion depth plots for all specimens is approximately linear. Although no aggregate or concrete properties were found to explain the differences in performance of these aggregates under 2-body conditions, a possible link has been found between time elapsed before the final stage of power finishing and the 2-body abrasion depth. The two specimens exhibiting a statistical difference from their 3-body abrasion depths i.e. C1S1 and C3S1 were left the longest before power trowelling, see Chapter 3, *Table 3.1.* This relationship was subsequently found with the other aggregate types, and is discussed more fully in Section 6.13.2.

6.3.3 Wet Abrasion Results

Due to the severity of this test regime and the subsequent instability of the apparatus, all the quoted measurements are for a 10 minute test period.

For all the specimens containing sandstone coarse aggregates the addition of water to the test surface produced abrasion depths in excess of 1.0 to 2.0 mm, these values representing increases of between 500 and 644 per cent compared to the 3-body tests, the details are summarised below:-

Slab reference	Percentage increase over 3-body abrasion depth
C1S1	532
C2S1	528
C3S1	644
C4S1	500

The graphs of wet abrasion against time given in *Figure 5.8* show quite clearly the dramatic increase in abrasion rate that occurred after 5 minutes, primarily once contact was made with the coarse aggregate particles, with samples C2 and C3 exhibiting particularly poor performance under wet test conditions. It is likely that the low durability of the sandstones, particularly C2 and C3, had a major influence during wet testing. Once contact was made with the coarse aggregate particles, the accentuating effect of the water enabled the particles to break up more readily, leading to much more rapid breakdown as the test progressed. The effect of water on the test surface is discussed further in Section 6.13.

6.4 Carboniferous Sandstone Crushed Fines

The fine aggregates produced from crushing the Carboniferous Sandstone aggregates consist almost entirely of quartz, either as individual grains or within small sandstone fragments, with C2F and C3F showing the presence of iron oxides in the form of orange-brown staining. When crushed, C1F, C2F and C3F produced a variable particle shape from sub-rounded to angular, whereas the C4F particles were noticeably more angular, as was also observed with C4 demonstrating that the fine aggregates reflect the characteristics of their coarse parent particles. Samples C1F, C2F and C3F all satisfy the coarse and medium grading requirements detailed in BS 882: 1992, with C4F satisfying the medium grading requirement.

A high free water-cement ratio was recorded for mixes containing C2F, which also showed the lowest 28 day cube strength figure of 28 MPa. The other aggregates in this group also produced low strengths, varying from 29 to 35.5 MPa.

6.4.1 3-Body Abrasion Results

When present as crushed fines, the abrasion depth values after 15 minutes for each source were broadly similar i.e. within the range 0.29 to 0.40 mm. This may be a reflection on the similar quartz content of all the aggregates for the effect of any detrimental rock fabric, such as the weak cementing agent present in the coarse aggregate, would have been reduced in the crushing process. An analysis of the abrasion depth against time graphs in *Figure 5.12* show, in general, that the abrasion was rapid at the beginning of the test as the surface layer was abraded but, as the coarse aggregate particles were subsequently encountered, the graphs tend to level off between 0.30 and 0.50 mm. An exception to this was the specimen containing C2F which showed an almost linear trend throughout the testing period and which is very similar to that shown by C2 as a coarse aggregate and described in Section 6.3.1.

When compared to their use as coarse aggregates, C1F, C3F and C4F all exhibited decreases in abrasion resistance of 77 per cent, 16 per cent and 45 per cent respectively, whereas C2F showed a slight improvement of 13 per cent. All the crushed sandstone aggregates produced concrete slabs which gave abrasion resistance at or around 0.40 mm which is the criterion (Concrete Society, 1994) associated with satisfying the performance required for class AR3 concrete in BS 8204: 1987.

6.4.2 2-Body Abrasion Results

The 2-body tests produced broadly similar abrasion depths for each source, ranging from 0.23 to 0.32 mm. The results for C1F and C4F show no statistical difference from those obtained with the 3-body test, whereas those for C2F and C3F both show a 38 per cent decrease in abrasion depth and this difference is significant at the 5 per cent level. Details of the statistical analysis are given in Appendix E. The aggregates C2 and C3, from which C2F and C3F are derived, exhibited the highest Los Angeles Abrasion losses of all aggregates tested. It is possible that during the 3-body abrasion further breakdown occurred of both C2F and C3F, with this material becoming loose abrasive particles. Under 2-body conditions this material was removed, which resulted in the statistically significant improvement in abrasion resistance described above. Section 6.13 discusses all the factors thought to be influential on abrasion resistance under all test conditions.

When the graphs of 2-body abrasion against time in *Figure 5.15* are compared to those of 3-body abrasion given in *Figure 5.12,* it is immediately apparent that they are very similar, even down to the linear trend for aggregate C2F. The only noticeable difference being that the plots tend to level off between 0.20 and 0.40 mm, which is at a slightly shallower depth than for the 3-body results. This indicates that, although the removal of loose abrasive particles during the 2-body test slightly reduced the overall abrasion depth, it did not significantly alter the manner in which the specimens abraded.

6.4.3 Wet Abrasion Results

As was the case when present as the coarse fraction, the crushed Carboniferous Sandstone fine aggregates produced concretes that abraded much more rapidly when water was present. *Figure 5.18* shows clearly that these rapid rates of abrasion followed almost linear trends with the performance of C2F being particularly poor, achieving an abrasion depth of over 1.0 mm after only 5 minutes.

Unlike the results from the 2 and 3-body tests, which showed that the abrasion plots levelled off between 0.20 and 0.50 mm, the wet abrasion tests show an increasing rate of abrasion even though the fines were in combination with a good quality coarse aggregate. This is a similar situation to that reported when the Carboniferous Sandstone aggregates were used as the coarse fraction. It is possible that factors other than quality of aggregate are important in determining wet abrasion resistance, and that different failure mechanisms are operating when water is present. It is possible that under these test conditions the weak mortar is being abraded from around the good quality coarse aggregate particles, enabling their removal to occur more readily and thus further increase the rate of wear. This possible mechanism is discussed in Section 6.13.3.

6.5 Magnesian Limestone Coarse Aggregates

This group of aggregates is generally quite soft, consisting primarily of dolomite and/or calcite and having a dusty surface coating. Sample M6a was distinctive within the group in that it had a clay content of between 5 and 10 per cent by volume. The clay was present as lumps approximately 10 mm across. Sample M6b was from the same source as M6a but had been through the crushing process twice, and this had clearly reduced the clay content to a figure below approximately 2 per cent.

These aggregates generally produced concrete with satisfactory cube strength, ranging from 37 MPa for M6a up to 45 MPa for M5. The free water-cement ratio of the mixes containing M6a was 0.51, with that of the other aggregate mixes being 0.54. Overall the Magnesian Limestone aggregates performed well in concrete, and each mix produced specimen slabs with 3-body abrasion depths less than 0.20 mm, which indicates (Concrete Society, 1994) that these concretes have the performance requirements for AR2 concretes used in floor slabs (BS 8204: 1987). This improved performance may be partly due to the crystalline nature of the rock types used, whereas the sandstone aggregates were generally composed of weakly cemented grains.

6.5.1 3-Body Abrasion Results

All the specimens yielded 3-body abrasion depths less than 0.20 mm, with the mixes from all four aggregates showing a decreasing abrasion rate with time, *Figure 5.3,* which reflects the modest Los Angeles Abrasion losses of these aggregates. The performance of M6a was slightly better than that of M5, M6b and M8 which is perhaps surprising as M6a had a significantly lower relative density, an appreciably higher 24 hour absorption value of 9.3 per cent and a higher loss by Los Angeles Abrasion. The only other major difference between M6a and the other aggregates in this group was its high clay content described in

Chapter 4, Section 4.2.2.2. It is possible that the clay lumps went into solution during mixing and subsequently migrated to the surface during power finishing. They would then be present at the surface and may have had the effect of improving abrasion resistance. It is conceivable that the clay content may have had a pozzolanic effect on the concrete, although an improvement in abrasion resistance through the effect of a pozzolan is unlikely to become evident at only 28 days. Another possibility is that the platy nature of the clay minerals has caused them, during power finishing, to align parallel to the surface of the concrete, thus forming a platy interlocked zone within the surface layer. No previous work examining the behaviour of clay minerals in this role has been found.

6.5.2 2-Body Abrasion Results

All the specimens produced abrasion depths less than 0.19 mm, with M5 and M6a being marginally better than M6b and M8. The results for M6a, M6b and M8 showed no statistical difference from those obtained by the 3-body test, whereas M5 showed a 43 per cent decrease in abrasion depth which was statistically significant. A full statistical analysis is given in Appendix E. As described in Section 6.3.2, the only specimen to exhibit a significant reduction in abrasion depth under 2-body conditions was M5S1, the mix with the greatest time elapsed before the commencement of power trowelling. Possible reasons for this are discussed in Section 6.13.2.

6.5.3 Wet Abrasion Results

Specimens containing M6b and M8 showed very high abrasion depths of 1.42 and 1.74 mm respectively after 10 minutes of testing, while those containing M5 and M6a showed appreciably better performances with depths of 0.62 and 0.36 mm respectively after 10 minutes. As with the 2-body and 3-body tests the best results were obtained with M6a, the aggregate with the lowest relative density, highest absorption value and lowest strength together with a significant clay content. As described previously in Section 6.5.1, it is suggested that the clay content has had an effect on the abrasion test, with this effect being even more marked during wet testing. As described in Section 6.5.1, the platy nature of the clay minerals may be improving abrasion resistance, possibly by dissipating the load of the test apparatus across the crystals rather than onto a point load, thus reducing the rapid rate of abrasion typically seen during testing in the presence of water. It is possible that the poor performance, of specimens containing M6b and M8, when compared to their 3-body performance, may be due to their finely crystallised structure. The water, probably under pressure as the wheels pass over, may be forced into microscopic discontinuities between crystal grains, which may lead to these particles becoming displaced and therefore an increase in abrasion depth. The presence of such discontinuities is suggested by the 24 hour absorption values for M6b and M8 of 5.4 and 2.6 per cent respectively, and by these two aggregates exhibiting the highest total pore areas of the Magnesian Limestones of 4.5535 and 4.6324 m^2g^{-1} respectively.

6.6 Magnesian Limestone Crushed Fines

Although four Magnesian Limestone aggregates were used in the coarse aggregate programme, only three sources of crushed fines were used in the crushed fines programme. As M6a and M6b were from the same quarry, the fine material used was designated M6F.

The three samples displayed a wide range in aggregate properties, with the relative density varying from 2.29 for M6F to 2.58 for M5F and 24 hour absorption varying from 2.0 per cent for M5F to 8.9 per cent for M6F. The gradings also varied, with M6F having a finer grading than the other aggregates, the details being given in Appendix B. The free water-cement ratios varied from 0.51 to 0.60, and 28 day cube strengths were within the range 39 to 47 MPa.

6.6.1 3-Body Abrasion Results

Despite differences in characteristics such as relative density, absorption, grading and concrete strength, the three aggregates produced very similar abrasion resistance results. All are around the maximum (average) limit of 0.40 mm (Concrete Society, 1994) associated with class AR3 concrete in BS 8204: 1987. As discussed earlier in Section 6.2.2.2, the relatively soft Magnesian Limestone crushed fines enabled the abrasion depth to increase quite quickly at the beginning of testing but, as contact was subsequently made with the coarse aggregate particles, the rate of increase slowed. This is clearly shown in *Figure 5.13*. The graphs reached a plateau at abrasion depths between 0.40 and 0.50 mm, which is slightly deeper than was achieved by the specimens containing the crushed fines from the sandstone sources. This can be attributed to the mineralogy of the sandstone crushed fines which consist primarily of quartz (Mohs' Hardness 7), whereas the Magnesian Limestone crushed fines consist primarily of calcite and dolomite (Mohs' Hardness 3 to 4).

6.6.2 2-Body Abrasion Results

Testing under these conditions produced graphs of abrasion depth against time of the same shape as those obtained under 3-body conditions. These are illustrated in *Figure 5.16*. Furthermore there are no significant statistical differences between the results obtained by the two test methods. Details of the full statistical analysis are given in Appendix E.

As no relationship has been found between free water-cement ratio and both 2-body and 3-body abrasion depth using these crushed fines, it is suggested that fine aggregate hardness/quality is the dominant factor in this instance. In both cases the initial rates of wear are rapid, but these then reduced as progressive contact was made with the good quality coarse aggregates. The influence of fine aggregate hardness/quality on 2-body abrasion resistance is discussed further in Section 6.13.2.

6.6.3 Wet Abrasion Results

All three aggregates showed significantly greater abrasion depths when tested in the presence of water, the depths of wear being approximately twice the corresponding values obtained under 3-body conditions. The abrasion/time graphs are shown in *Figure 5.19* and are quite different in shape to those obtained with both 3-body and 2-body tests. The plots for wet abrasion testing are almost linear and show no tendency to level off at any particular depth. This suggests that contact with the good quality coarse aggregate does not reduce the rate of abrasion under wet conditions. It is possible that the weak mortar is being abraded from around the good quality coarse particles, enabling their removal and thus further increase the rate of wear. This possible mode of wear is discussed further in Section 6.13.3.

6.7 Jurassic Limestone Coarse Aggregates

Certain characteristics of the aggregates within this group are broadly similar, with the relative density only ranging from 2.45 to 2.56 and the 24 hour absorption varying between 3.9 and 7.1 per cent. The gradings for J10, J11 and J12 are similar, but that of J9 is quite different, with some 20 per cent by weight passing the 2.36 mm sieve. It is thought that this material may have been supplied in error as 20 mm to dust rather than 20 to 5 mm. Details of individual aggregate gradings are presented in Appendix B. The Los Angeles Abrasion losses ranged from 42 to 44 per cent but, for reasons discussed earlier in Chapter 4, Section 4.3.3, the value pertaining to J9 has not been included in the determination of possible correlations.

Although all the mixes using these aggregates were mixed to the same workability, each having a slump of 20 mm, the free water-cement ratios showed a wide variation from 0.49 for specimens containing J12, to 0.62 for those containing J9. This is reflected in the values of cube strength which also show a wide variation, from 27.5 MPa for those containing J9 to 45.5 MPa for those containing J10.

6.7.1 3-Body Abrasion Results

With the exception of specimens cast with J9, the Jurassic Limestones performed very well, with specimens containing J10, J11 and J12 producing abrasion depths of 0.14, 0.19 and 0.08 mm respectively. These values are within the limits (Concrete Society, 1994) associated with class AR2 concrete for floors given in BS 8204: 1987. The poor performance of J9 may be attributed to a combination of its high dust content, low relative density, high absorption and low 28 day cube strength. The graphs of abrasion against time given in *Figure 5.4* show how the rate of abrasion depth increase for specimens containing J9 is linear, whereas the rates of the other specimens exhibit a tendency to level off at a depth between 0.10 and 0.20 mm. This indicates that J10, J11 and J12 are sufficiently stable to enable the abrasion depth to increase at a slower rate once contact is made with them. The relatively low free water-cement ratios of these mixes is also an important contributory factor in regulating the magnitude and rate of increase of abrasion depth. The high fines content of J9 effectively reduced the quality of the fine aggregate fraction as a whole and this, together with the low quality of J9 as a coarse aggregate, produced an inferior concrete, with a subsequently poor abrasion resistance.

6.7.2 2-Body Abrasion Results

In comparison with the results from the 3-body tests, the results for specimens containing J9 and J10 show statistically significant decreases in abrasion depth, 59 and 36 per cent respectively, when tested under 2-body conditions. No significant statistical difference was recorded for specimens containing J11 and J12. A full statistical analysis is presented in Appendix E, and graphs of abrasion against time are presented in *Figure 5.7*. The increase in abrasion depth for specimens containing J9 is linear with time, but the rate of increase is slower than under 3-body conditions. Specimens containing the other aggregates show rates of increase that level off at depths between 0.05 and 0.20 mm. Due to the high proportion of material passing 2.36 mm with aggregate J9, the power finishing process tended to bring much more of this poorer quality fine material to the surface than with the others. This enabled abrasion to occur at a faster rate from the outset of testing, which in turn produced loose abrasive particles. By comparison of results from *Figures 5.4* and *5.7* it can be seen that for specimens containing aggregates J9 and J10 the removal of loose particles significantly improved their abrasion resistance. In a similar manner to the Carboniferous Sandstones and Magnesian Limestones, specimen J10S1, which exhibited the greatest elapsed time before the commencement of power trowelling, showed a significant reduction in abrasion depth under 2-body conditions. Discussion of the possible mechanisms involved during 2-body abrasion is given in Section 6.13.2.

6.7.3 Wet Abrasion Results

Wet abrasion testing of these aggregates showed two aggregates, J10 and J12, to perform very well, with specimens containing them producing abrasion depths of 0.09 and 0.08 mm respectively after 10 minutes. The other two aggregates, J9 and J11, performed poorly, with the specimen containing J9 producing an abrasion depth of 0.93 mm after only 5 minutes, and that containing J11 producing a depth of 0.92 mm after 10 minutes. The graphs of abrasion against time are presented in *Figure 5.10*. As discussed in Sections 6.7.1 and 6.7.2, the poor grading characteristics of J9 seem to have had a detrimental effect on the abrasion resistance, with this effect being most pronounced under the wet test conditions. The specimens containing J10 and J12 are the only ones throughout the project to maintain or improve upon their 3-body abrasion resistance during wet testing. Specimens containing these aggregates exhibited significantly higher cube strengths than the other Jurassic Limestones, and it is possible that these higher strengths may be partly due to better bonding between the coarse aggregate particles and the matrix. A better bond at this interface would reduce degradation of this zone as abrasion depth increased, thus reducing the likelihood of coarse particle removal due to the mechanisms associated with wet abrasion, which are discussed in Section 6.13.3.

6.8 Jurassic Limestone Crushed Fines

The crushed fines obtained from the Jurassic Limestone aggregates produced concrete with cube strengths in the range 35.5 MPa for J9F to 49 MPa for J11F. The aggregates have fine gradings, with each sample being within the limits for crushed rock sand given in BS 882: 1992. Detailed grading curves for individual aggregates are presented in Appendix B. The relative density values all fall within a narrow range from 2.45 to 2.56 and the 24 hour absorption values for these aggregates ranged from 2.7 per cent for J11F to 4.9 per cent for J9F.

6.8.1 3-Body Abrasion Results

These fine aggregates produced abrasion depths in the range 0.41 to 0.56 mm, which are outside the limits (Concrete Society, 1994) associated with the classes of concrete floor detailed in BS 8204: 1987. It is interesting to note that the aggregate with lowest absorption, J11F, and which produced the strongest concrete actually gave the greatest abrasion depth at 0.56 mm. This indicates that cube strength is not the sole factor governing abrasion resistance in this case. The increase in abrasion depth with time shown in *Figure 5.14*, for specimens containing the aggregates J10F, J11F and J12F, shows a tendency to level off between 0.45 and 0.65 mm. The exception to this behaviour is the specimen containing J9F which continues along a linear trend for the whole of the testing period. In order to gain further information about this particular trend, the abrasion testing was continued for an extra 15 minutes, making a total test time of 30 minutes. This was repeated for the specimen containing J10F. The trends discussed above were confirmed by these extended tests, and the results are shown in *Figure 5.22*.

It is evident from the above that the low quality of J9F has enabled abrasion to continue at a continuous rate, regardless of the quality of the coarse aggregate with which it is combined. It is possible that the poor quality of J9F weakens the mortar sufficiently so that breakdown readily occurs. As abrasion depth increases the coarse aggregate particles are encountered, but the mortar is quickly eroded from around them. This enables these particles, or fragments thereof, to be removed by continued testing, subsequently resulting in increased abrasion depth.

6.8.2 2-Body Abrasion Results

The specimens containing the fine aggregates J9F, J10F and J11F exhibited abrasion depths which are very similar, these being 0.39, 0.39 and 0.38 mm respectively, with 0.54 mm being recorded for the slab containing J12F. Furthermore no significant statistical differences were noted between the 2-body and 3-body abrasion test results for slabs containing J9F and J12F, whereas statistically significant differences were noted for specimens containing both J10F and J11F, full details of which are given in Appendix E. The two specimens containing J10F and J11F had free water-cement ratios, 0.56 and 0.54 respectively, appreciably lower than the specimens containing J9F and J12F, 0.64 and 0.65 respectively. It would appear in this instance that when the loose abrasive particles are removed, the free water-cement ratio becomes increasingly important. This is discussed further in Section 6.13.2.

6.8.3 Wet Abrasion Results

The specimens containing J9F showed poor abrasion resistance under wet conditions, with a recorded depth of 0.56 mm after only 5 minutes, which again could be due to a combination of poor grading, low relative density and high absorption. The slabs containing J10F, J11F and J12F all showed a rapid increase in abrasion depth with time, the graphs of which are presented in *Figure 5.20.* The shallow depths recorded for J10 and J12 when present as coarse aggregates were not repeated when these aggregates were present as crushed fines, although the results for the Jurassic Limestone crushed fines compare favourably with the other crushed fines results.

6.9 Control Mixes

Two control mixes were cast for comparison with the test mixes, one following the mix design used for the coarse aggregate test programme and the second following the mix design used in the fine aggregate test programme. Both mixes used the same coarse and fine aggregates, as described fully in Chapter 4, Section 4.2.4.

6.9.1 Coarse Aggregate Control

The coarse aggregate was a gravel derived from the Bunter Pebble Beds of the Permo-Trias period, consisting almost entirely of quartz and quartzite. The material had a high relative density of 2.61, low 24 hour absorption of 0.8 per cent and a low Los Angeles Abrasion loss of 20 per cent. This aggregate is considered typical of that used in concrete, and was therefore used to provide 'benchmark' abrasion depth results for the coarse aggregate test programme. Graphs of abrasion against time for the coarse aggregate control mix are given in *Figure 5.11.*

6.9.1.1 3-Body Abrasion Results

Testing under 3-body conditions produced a minimal abrasion depth of 0.05 mm, a level that was achieved by only two other aggregates during the project, and is within the limits (Concrete Society, 1994) associated with class AR2 concrete for floors detailed in BS 8204: 1987. Although on a different scale, the graph of 3-body abrasion in *Figure 5.11* shows a similar decrease in abrasion rate with time to that seen with the other test aggregates. The low values of abrasion are probably due to the fact that both the coarse and fine aggregate are composed of essentially the same material, which is of good quality and is hard and durable.

6.9.1.2 2-Body Abrasion Results

The abrasion depth of 0.10 mm measured under 2-body conditions is statistically different to that recorded for 3-body conditions, with the full statistical analysis given in Appendix E. Unlike other specimens when a statistical difference has been determined, the 2-body abrasion resistance of the coarse aggregate control mix is poorer than the 3-body abrasion resistance. This unusual (when compared to the test aggregates) result may be attributed to the effect of the test debris. Under 3-body conditions the test debris which remains within the abrasion path may have a cushioning effect, effectively dissipating the load of the test apparatus. Under 2-body conditions this debris is removed, which allows more intimate contact between the test head and the aggregate particles. As quartz particles possess a conchoidal fracture, i.e. forms curved fracture planes (Read, 1970) they may splinter and break up more readily due to the impact of the machine, thus increasing the abrasion depth.

6.9.1.3 Wet Abrasion Results

Wet testing of the control specimens produced an abrasion depth of 0.64 mm, which although outside the 0.40 mm limit (Concrete Society, 1994) associated with class AR3 concrete for floors in BS 8204: 1987, compares favourably with the other aggregates tested. This wet abrasion depth, however, is a 1500 per cent increase over the depth obtained under 3-body conditions and is the largest percentage increase of all the aggregates tested. As described in previous sections the addition of water has had a profound effect on the abrasion resistance of the control specimen, and possible reasons for this are discussed in Section 6.13.3. The graph given in *Figure 5.11* shows how the graph steepens with time, as opposed to 3-body and 2-body abrasion/time graphs which tend to level off with time.

6.9.2 Fine Aggregate Control

The fine aggregate control mix consisted of a crushed Bunter quartzite in combination with a Bunter quartzite coarse aggregate, described fully in Chapter 4, Section 4.2.4, with the fine particles having an angular shape. The concrete produced from this aggregate gave the lowest free water-cement ratio of 0.50, and the highest cube strength at 51.5 MPa of all the fine aggregate test mixes. The grading characteristics place this aggregate within the fine category of BS 882: 1992. Abrasion against time graphs are presented in *Figure 5.21*.

6.9.2.1 3-Body Abrasion Results

Testing under 3-body conditions gave the lowest abrasion depth of all the aggregates in the fine aggregate test programme, with a depth of 0.18 mm. This result is within the 0.20 mm limit (Concrete Society, 1994) associated with class AR2 concrete for floors in BS 8204: 1987. This aggregate was one of only three in which testing was extended to a total of 30 minutes, with the result of 0.25 mm being shown graphically in *Figure 5.22*. The graph shows initially high rates of abrasion which tended to level off with time, a pattern which was seen with most fine aggregate types in the project.

6.9.2.2 2-Body Abrasion Results

Testing under 2-body conditions showed no significant statistical difference in abrasion depth to those obtained under 3-body conditions. The shape of the graph, given in *Figure 5.21* is almost identical to that discussed above for 3-body conditions and suggests that removal of the loose abrasive particles is having a negligible effect in this instance. The factors influential upon 2-body abrasion are explored in Section 6.13.2.

6.9.2.3 Wet Abrasion Results

At 0.22 mm after 10 minutes, the wet abrasion depth value is low in comparison with most of the test specimens and shows no statistical difference with the 3-body result (15 minute value), see Appendix E. A statistical difference is recorded when both 15 minute values are compared, these being 0.18 mm (3-body) and 0.39 mm (wet) respectively. It is possible that at 10 minutes the test apparatus had not 'broken through' the recompacted surface layer, which in this case contained a hard sand of good quality and a low water-cement ratio of 0.50. The graph of wet abrasion against time given in *Figure 5.21* shows the plot to be almost linear, again this is a commonly seen trend for wet abrasion testing in the fine aggregate test programme, the possible reasons for which are discussed in Section 6.13.3.

6.10 Summary of Abrasion Test Results

With the exception of the aggregates C2 and J9, all of the coarse aggregates produced concrete within current abrasion limits (Concrete Society, 1994) associated with class AR3 concrete for floors in BS 8204: 1987, with the Magnesian and Jurassic Limestones generally performing better than the Carboniferous Sandstones. The performance of the crushed fines was less good, with only four of the specimens achieving abrasion depths within the specifications detailed above, these being C1F, C3F, C4F and M8F. Crushed Carboniferous Sandstones gave marginally better performance than both limestone types.

The 2-body abrasion depths for the coarse aggregate mixes are of a similar order to those attained under 3-body conditions, with many specimens exhibiting no significant differences between the two test types. Some, however, do show a significant reduction in abrasion depth under 2-body conditions, and this has been observed for all three aggregate types. This difference has been related, for coarse aggregate mixes, to the time elapsed before the commencement of power trowelling. Some fine aggregate mixes also show a statistical difference to the 3-body results, although for these mixes the differences do not appear to relate to the time elapsed before power trowelling, but to the water-cement ratio and the hardness/quality of the fine aggregate. Factors influential to both 2-body and 3-body abrasion are discussed in Section 6.13.

Wet abrasion testing of the coarse aggregate mixes produced abrasion depths appreciably greater than both 3-body and 2-body conditions, with only specimens J10S1 and J12S1 achieving depths within current specifications. As a group the Carboniferous Sandstones exhibited the greatest wet abrasion depths, while the Jurassic Limestones (excluding J9) showed the lowest values. The wet abrasion depths of the crushed fines mixes were all greater than those obtained under both 3-body and 2-body conditions. None of the test aggregates showed especially good performance, but the fine aggregate control exhibited an abrasion depth one half that of the best performing test aggregate (C4F). The influence of water on abrasion is discussed in Section 6.13.3.

6.11 Variable Proportions of Low-Grade Aggregate

All the concrete mixes described thus far have incorporated low-grade aggregate as 100 per cent replacement of either the coarse or the fine fraction. It was decided it would be useful to investigate the effect on the abrasion resistance of varying the content of a low-grade aggregate between zero and 100 per cent for both the coarse and fine fractions, the remainder of the aggregate content to be made up with the standard control aggregates. The Carboniferous Sandstone, C2, was chosen for this series of mixes because it showed particularly poor abrasion resistance, and may therefore accentuate any differences that could arise from varying its proportion in the concrete. Standard 100 mm cubes were cast from all the mixes for cube strength testing, and the results are presented in *Tables 5.14* and *5.15*. Unexpectedly large variations in free water-cement ratio were recorded for this series of mixes. Although no single factor could be found to account for such large differences, it is possible that aggregate variability may have a significant influence.

6.11.1 Variation of the Low-Grade Coarse Aggregate Content

The mixes were cast and finished by the methods described in Chapter 3. Similarly, specimen testing was carried out using the standardised procedure, with the exception that both the left and centre slabs from the mould were tested for 3-body abrasion. The purpose of this was to establish statistically whether there was any difference in abrasion resistance between the left and centre slabs. There was a concern, raised during the earlier testing, that power finishing the relatively small area of the specimen may 'over-finish' the central area as the power-float passes over it more often. The results of this analysis are given in Appendix E, and show statistically that there was no difference in abrasion resistance between the centre and left slabs. The right slab was tested for wet abrasion as described in Chapter 3, Section 3.4.3.4.

Figure 6.15 illustrates two possible relationships between the 28 day cube strength and the proportion of C2 in the coarse aggregate, a linear relationship (solid line) and a quadratic relationship (dashed line). The linear relationship shows decreasing cube strength with increasing low-grade aggregate content. The quadratic relationship shows that the decrease in cube strength may occur in two stages. The first stage, zero to 50 per cent replacement, exhibits a reduction in cube strength of approximately 10 per cent. The second stage, at replacements above 50 per cent, exhibits a reduction in cube strength of approximately 20 per cent. It is clear from the accompanying statistical analysis that both relationships give a similar level of fit to the experimental data. While it is not apparent which is the most reliable, both demonstrate that increasing the proportion of low-grade aggregate reduced the cube strength. This clearly demonstrates the important role of aggregate strength in determining the strength of the resulting concrete.

Figure 6.16 also shows two possible relationships between the proportion of C2 and the 3-body abrasion depth, one linear and the other quadratic. The linear plot shows increasing abrasion depth as the proportion of C2 in the coarse aggregate was increased. The quadratic plot indicates that, initially, the abrasion depth increased proportionally with increasing proportion of C2, although the rate of increase reduced as the proportion neared 100 per cent. This graph clearly shows the influence of the coarse aggregate in developing abrasion resistance, although it is not the sole factor impacting on abrasion performance. The graph also shows that, up to a 50 per cent level of replacement, C2 can be used as part of the coarse aggregate and may still satisfy the limit (Concrete Society, 1994) of 0.40 mm associated with class AR3 concrete for floors in BS 8204: 1987. The relationships between wet abrasion depth and the proportion of C2 are illustrated in *Figure 6.17*. The linear plot shows gradually increasing wet abrasion depth as proportion of C2 increased. The quadratic plot shows that coarse aggregate replacement up to approximately 30 per cent may have a negligible effect on the wet abrasion resistance, but increasing the proportion above 50 per cent may significantly reduce the abrasion resistance. Testing of further specimens containing different proportions of C2 would be necessary to more clearly define the pattern of the quadratic relationship, although the statistical analysis and experimental data suggest that the quadratic relationship gives a marginally better fit. These results clearly demonstrate the sensitivity of the low-grade aggregate to the presence of water for, as well as fitting the quadratic relationship, the gradient of the graph increases rapidly as the proportion of C2 increases towards 100 per cent.

6.11.2 Variation of the Low-Grade Fine Aggregate Content

Due to restricted supplies of aggregate C2F it was only possible to cast two extra mixes, these being 33 per cent C2F and 67 per cent C2F respectively. For this reason no correlation coefficients have been calculated for this series of mixes. However, it is still possible to draw some interesting conclusions from the subsequent findings. *Figure 6.18* shows both linear and quadratic relationships between 28 day cube strength and the proportion of C2F in the fine aggregate. The linear plot shows that cube strength decreased as the proportion of C2F in the fine aggregate increased. The quadratic plot shows a quite different trend to that seen when C2 was used as the coarse aggregate. Up to approximately 70 per cent replacement of the fine aggregate the cube strength decreased proportionally with increasing proportion of C2F, whereas above this replacement there is only a negligible change in cube strength. This would seem to indicate that even quite small replacements of fine aggregate with crushed sandstone can result in significant reductions in cube strength, but this observation must be qualified by the limited data on which this is based. Furthermore the logic from the earlier experimental data does not suggest that such a trend would be supported by a more extensive data set.

The 3-body abrasion depths of the mixes are plotted against the proportion of C2F in the fine aggregate in *Figure 6.19*. The quadratic relationship shows that the 3-body abrasion depth steadily increased as the proportion of C2F increased, with the graph steepening slightly as the level of replacement approached 100 per cent. A linear plot is also shown for comparison. When the relationship is compared with that in *Figure 6.18*, it shows that although relatively small quantities of C2F appreciably reduced the cube strength, such proportions of C2F did not affect 3-body abrasion depth to the same extent. This suggests, as also observed in Section 6.8.1, that factors other than cube strength are influential in determining abrasion resistance. The role of cube strength is discussed further in Section 6.12.

From *Figure 6.20* it is clear that the wet abrasion depth increased very rapidly with an increasing proportion of C2F in the fine aggregate. The abrasion was so severe on the specimen containing 100 per cent C2F that the test had to be abandoned after only 5 minutes. Wet abrasion depth increased proportionally as the proportion of C2F increased, so even small proportions of C2F in the fine aggregate had a significant effect on the wet abrasion depth. This is different to the case when C2 was used as a coarse aggregate replacement, when replacements of up to 30 per cent appeared to have little effect on the wet abrasion depth. This reflects on the importance of the surface layer of the concrete, in particular the quality of the fine aggregate, and that even small quantities of low-grade fine aggregate can significantly influence wet abrasion resistance.

6.12 Relative Importance of the Main Factors Affecting Abrasion Resistance

6.12.1 Coarse Aggregate Mixes

In Section 6.2.1 significant relationships were presented which show correlations between the abrasion depth and cube strength, the free water-cement ratio, the percentage of coarse aggregate passing the 2.36 mm sieve and the Los Angeles Abrasion loss. It was also noted that there were good correlations between cube strength and the free water-cement ratio, the percentage passing the 2.36 mm sieve and the Los Angeles Abrasion loss. It is conceivable that, as correlations have been established between the cube strength and the free water-cement ratio, the percentage passing 2.36 mm and the Los Angeles Abrasion loss, these factors may also have influenced the relationship between the abrasion depth and cube strength.

In order to examine in more detail the correlation between abrasion depth and cube strength, it is necessary for the free water-cement ratio, the percentage passing 2.36 mm and the Los Angeles Abrasion loss to be constant. This can be achieved mathematically (Paradine and Rivett, 1964) by determining the *partial correlation coefficient* between abrasion depth and cube strength using the following equation:-

$$r_{xy.z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{\{1 - (r_{xz})^2\}}\sqrt{\{1 - (r_{yz})^2\}}} \qquad \textit{[Equation 6.1]}$$

Where:-

$r_{xy.z}$ is the correlation coefficient between abrasion depth and cube strength when free water-cement ratio is constant.

r_{xy} is the correlation coefficient between abrasion depth and cube strength.

r_{xz} is the correlation coefficient between abrasion depth and free water-cement ratio.

r_{yz} is the correlation coefficient between cube strength and free water-cement ratio.

The same equation can be used to determine the effect of the percentage passing 2.36 mm and Los Angeles Abrasion loss on the relationship between abrasion depth and cube strength. The values of r relating percentage passing 2.36 mm and Los Angeles Abrasion loss to abrasion depth and cube strength respectively are substituted for those of free water-cement ratio in the above equation. The relevant relationships and their correlation coefficients, taken from *Figures 6.3* to *6.13,* are tabulated in *Table 6.1* :-

Relationship	**Correlation Coefficient (r)**
3-Body Abrasion Depth/28 Day Cube Strength	0.77
3-Body Abrasion Depth/Free Water-Cement Ratio	0.82
28 Day Cube Strength/Free Water-Cement Ratio	0.76
3-Body Abrasion Depth/Percentage Passing 2.36 mm	0.90
28 Day Cube Strength/Percentage Passing 2.36 mm	0.85
Wet Abrasion Depth/28 Day Cube Strength	0.70
Wet Abrasion Depth/Free Water-Cement Ratio	0.75
28 Day Cube Strength/Free Water-Cement Ratio	0.76
28 Day Cube Strength/Los Angeles Abrasion Loss	0.82
3-Body Abrasion Depth/Los Angeles Abrasion Loss	0.68

Table 6.1. Table of Correlation Coefficients.

When *Equation 6.1* is applied using the relevant values of r from the above table, the correlation coefficient between abrasion depth and cube strength reduces to 0.39 when free water-cement ratio is kept constant, to 0.54 when the percentage passing the 2.36 mm sieve is kept constant, and to 0.51 when the Los Angeles Abrasion loss is kept constant. The first of these values is not statistically significant, whereas the other two values are statistically significant, but only at the 10 per cent level. This compares with a statistical significance at the 1 per cent level for each of the relationships before application of the partial correlation equation, *Equation 6.1.*

All the above results relate to 3-body abrasion test results, but the same procedure can be applied to wet abrasion results where there are correlations between abrasion depth and both cube strength and free water-cement ratio, and between cube strength and free water-cement ratio. Values of r for these relationships are given in *Table 6.1*. When these values are substituted into *Equation 6.1*, the partial correlation coefficient between wet abrasion depth and cube strength, when free water-cement ratio is kept constant, is calculated at 0.28. This result, together with that obtained from 3-body results and the fact that no relationship was found between 2-body abrasion depth and cube strength, would indicate that cube strength cannot be considered as the primary factor governing abrasion depth for mixes that contain low-grade coarse aggregates.

Using the same procedure as that described above, it is possible to examine the influence of aggregate properties on both cube strength and 3-body abrasion when free water-cement ratio is kept constant. *Table 6.2* shows the correlation coefficients for the various relationships both before and after the application of *Equation 6.1*.

Relationship	**r**	**r (constant w/c ratio)**
28 Day Cube Strength/Los Angeles Abrasion Loss	0.82	0.72
28 Day Cube Strength/Percentage Passing 2.36 mm	0.85	0.76
28 Day Cube Strength/Relative Density	0.78	0.75
28 Day Cube Strength/24 Hour Absorption	0.48	0.33
28 Day Cube Strength/Mohs' Hardness of Aggregate	0.24	0.17
3-Body Abrasion Depth/Los Angeles Abrasion Loss	0.68	0.45
3-Body Abrasion Depth/Percentage Passing 2.36 mm	0.90	0.89
3-Body Abrasion Depth/Relative Density	0.44	0.14
3-Body Abrasion Depth/24 Hour Absorption	0.22	0.15
3-Body Abrasion Depth/Mohs' Hardness of Aggregate	0.20	0.33

Table 6.2 Comparison of Correlation Coefficients.

These results indicate that at a constant free water-cement ratio the correlations between cube strength and Los Angeles Abrasion loss, percentage passing 2.36 mm and relative density do not reduce their level of significance (all 1 %). Similarly, the relationship between percentage passing 2.36 mm and 3-body abrasion depth does not reduce its level of significance (0.1 %) at a constant free water-cement ratio. The correlation between Los Angeles Abrasion loss is no longer significant at a constant free water-cement ratio, and appears to be a reflection on the fact that Los Angeles Abrasion loss has most influence at the later stages of abrasion when the coarse aggregate particles are encountered i.e. beneath the zone where free water-cement ratio is a dominant influence.

From the results presented earlier in Section 6.12.1 it is possible to predict graphically what level of abrasion resistance might be expected from specific combinations of free water-cement ratio and grading, and free water-cement ratio and Los Angeles Abrasion loss. These are shown in *Figures 6.21* and *6.22*, with the data points representing the mixes used during the current project. For reasons given in Chapter 4, Section 4.3.3, the Los Angeles Abrasion value of J9, (highlighted in *Figure 6.22*), is not considered as reliable as the other data points. It has only been used in this instance to help to locate an arbitrary category boundary. The diagrams have been sub-divided using the abrasion resistance categorisation of Kettle and Sadegzadeh (1987). The limit (Concrete Society, 1994) of 0.40 mm associated with class AR3 concrete for floors in BS 8204: 1987 coincides approximately with the maximum (average) limit of the 'average' category (solid line) specified in Kettle and Sadegzadeh (1987). The coarse aggregates producing concrete classified as 'poor' by Kettle and Sadegzadeh (1987) are C2 and J9, these are also outside current abrasion resistance specifications (Concrete Society, 1994). Those aggregates producing concrete within the 'average' category are C1, C3 and C4. Those producing concrete within the 'good' category are all of the Magnesian Limestones, the Jurassic Limestones J10, J11 and J12 and the control. The categories AR1 and AR2 have been omitted from the diagram because they would require a higher cement content than that used throughout the current work. It should be noted that the position of the category dividing lines are arbitrary, and do not necessarily mark the true boundaries. More data points would be required to establish the exact boundaries.

6.12.2 Fine Aggregate Mixes

As was the case with the coarse aggregate mixes described in Section 6.12.1, a significant correlation has been established between 28 day cube strength and free water-cement ratio, as shown in *Figure 6.14*. However, there was no correlation between 3-body abrasion depth and either the free water-cement ratio or the 28 day cube strength, and it is important to note that neither the 28 day cube strength or the abrasion depth as measured by all three test methods had significant correlations with the grading. Hardness of the fine aggregate though, shown in Chapter 5, *Figures 5.23*, *5.24 5.25*, *5.27* and *5.28*, has proved to be an important determining factor in both 2 and 3-body abrasion of the fine aggregate mixes, and to a lesser extent the wet abrasion depth. This would seem to indicate that the two principal factors governing abrasion resistance for the coarse aggregate mixes, i.e. free water-cement ratio and aggregate grading, are not the main factors controlling abrasion resistance for the fine aggregate mixes. Since the surface layer is predominantly fine aggregate and paste, the hardness/quality of these particles will clearly influence the rate of wear i.e. abrasion depth.

From the graphs of abrasion against time in Chapter 5, *Figures 5.2* to *5.21*, it is possible to see that in many cases the abrasion depth of the fine aggregate mixes measured after only 5 minutes was often similar to or even greater than those obtained during the coarse aggregate tests for the full 15 minute test period. It would seem probable therefore that, with the fine aggregate mixes, the surface of the concrete created by power finishing had been abraded during the first 5 minutes, this being indicated by the initial steepness of the abrasion/time graphs. This could account for the lack of correlation between abrasion depth and both the free water-cement ratio and grading, as both of these parameters have been shown to contribute significantly to the properties of the power finished surface of the concrete.

6.13 Abrasion Mechanisms

Although not a primary aim of the project, it was hoped from the outset that information would be gained from the testing programme to assist the understanding of the actual mechanisms involved during abrasion. From the initial phase of the work it was evident that the 3-body and 2-body testing produced abrasion depths of a broadly similar order, whereas wet abrasion testing produced appreciably greater abrasion depths. A detailed theoretical study of the failure mechanisms is outside the scope of this project, although some relevant experimental observations can be reported.

6.13.1 3-Body Abrasion

The 3-body abrasion tests were characterised by the progressive build up of wear debris around the periphery of the abrasion path, with only a limited amount of material remaining within the actual abrasion path. It appears that initially the 3-body tests were actually operating under 2-body conditions while the wear debris was accumulating within surface irregularities, described elsewhere as Abbot's Volumes (Godet, 1984). As the test continued these surface irregularities became filled and began to overspill, and it was at this point that 3-body conditions tended to prevail as the loose particles were able to move between the wheels and the concrete surface.

It appears that the first stages of surface breakdown involved crushing of the surface layer created by the power finishing process. Microcracks which are inevitably present within the paste, possibly due to shrinkage, can also contribute to the process of breakdown. Stresses induced in the cracks by the test apparatus were concentrated at the tips of the cracks (Griffiths, 1924) and as the test progressed the cracks extended. The cracks (may) eventually link up to create a network so that loose fragments were removed, possibly becoming abrasive particles. Abrasive particles that became trapped between the wheels and the concrete may momentarily increase stresses to a very high level as the loading of the machine was transferred not through the area of contact of the wheel, but through the much smaller contact area of the individual particles. This had the effect of dramatically increasing the stresses in the concrete directly beneath the particle, and thus concentrating the load of the apparatus in a very localised area. As the surface 'skin' was abraded more aggregate particles became exposed so that the load from the machine was increasingly applied to the bond between aggregate and paste and to individual exposed particles. It is possible that differences in elasticity between the paste and the aggregate may have resulted in differential movement between the two components, eventually leading to failure of the aggregate/paste bond. Sandstones typically have Modulus of Elasticity values 10 to 20 GPa below those of a flint sand mortar whereas quartz gravels can have values 10 to 20 GPa higher than flint sand mortar (Neville and Brooks, 1987). Observations during testing showed this interfacial zone to be an area of weakness, with the paste frequently breaking up and being removed from the periphery of aggregate particles. This illustrates the role of exposed aggregate particles, and is illustrated in *Plate 6.1,* which shows specimen slab J12FS1.

Microscopic analysis of the thin sections, prepared from cores cut through the abrasion path, showed no cracking to be visible below or around the abrasion path, either within the aggregate particles or at the aggregate/paste interface. This was the case for both the coarse and fine aggregate mixes. *Plate 6.2* shows the zone of concrete beneath the central section of the abrasion path for specimen J12FS1, which is typical of 3-body test specimens in that no cracking is visible. These results indicate that sub-surface breakdown (Avram,

1980) did not occur in this instance and that the breakdown occurred within the surface layer, probably due to localised impact and cyclic loading. Furthermore, during testing it was apparent that there was a minimal amount of sliding wear occurring at the interface between the wheels and the test surface, as the wheels were free to rotate on their axles rather than skid across the surface.

It is apparent from the results presented in earlier chapters that the two main factors affecting 3-body abrasion of concrete are the water-cement ratio together with the hardness/quality of the fine aggregate, with the durability of the coarse aggregate fraction becoming increasingly important as abrasion depths increase and contact with the coarse aggregate becomes progressively greater. Also significant is another factor, which generally affects concretes with lower quality coarse aggregates, this being the proportion of these aggregates finer than 5 mm. It is possible that this material will be brought to the surface during power finishing procedures, and subsequently reduce the overall quality of the surface layer. If the coarse aggregate is of good quality, or the proportion of the coarse aggregate finer than 5 mm is very small, the effect of this material on the surface layer is minimal. In a similar manner to *Figures 6.21* and *6.22* it is possible to predict the potential abrasion resistance from specific combinations of the hardness of the fine aggregate and the free water-cement ratio. *Figure 6.23* shows a plot of this data for both the coarse and fine aggregate mixes. The diagram shows that when fine aggregates of lower hardness are used, the water-cement ratio becomes subordinate in importance to the hardness/quality of the fine aggregates (lower area of diagram), and that the abrasion resistance of mixes containing harder fine aggregates is significantly affected by the free water-cement ratio (upper area of diagram). As with *Figures 6.21 and 6.22* the category divisions are arbitrary, and do not necessarily represent the true boundaries.

The apparently anomalous positions of data points representing J9 and M6F (highlighted on the diagram) may be due to their gradings - both have an excess of fine material when compared to the specifications in BS 882: 1992. It is possible that the excess of fines within these aggregates had a more significant effect on the properties of the surface layer than the other specimens, thus distorting their true position on the diagram. By comparing known aggregate and concrete properties of a particular mix with the three diagrams given in *Figures 6.21, 6.22* and *6.23*, it should be possible to determine the potential abrasion resistance of the concrete made with aggregates of this type. A multivariate analysis was considered as a mathematical means of analysing the data presented in *Figures 6.21, 6.22* and *6.23* and perhaps deriving an equation which could represent the various parameters, but it became apparent (Gauch, 1983) that at least 10 to 15 variables were required for this technique to be appropriate.

6.13.2 2-Body Abrasion

The method of surface breakdown during 2-body abrasion is essentially similar to that occurring in 3-body abrasion, with the exception that loose particles are removed from the surface before they may have an abrasive effect, although the effect of the abrasive has been shown to be minimal in many instances when no statistical differences were found between 3-body and 2-body abrasion. As found with the 3-body test specimens discussed earlier, the microscopic analyses of both coarse and fine aggregate specimens showed no cracking to be visible below or around the abrasion paths, shown in *Plates 6.3,* which shows specimen C3S1.

The main factors shown to affect 2-body abrasion are the water-cement ratio and the hardness/quality of the fine aggregates and, as with 3-body abrasion, the importance of the water-cement ratio is subordinate to the hardness/quality of the fine aggregates when low-grade fine aggregates are used. The effect of the finer fractions of the coarse aggregates on the surface layer during 3-body abrasion is not seen during 2-body abrasion. It is possible that these particles form part of the abrasive medium during 3-body abrasion, and are being removed by the vacuum cleaner during 2-body testing. Other abrasive particles also being removed by this process will be derived from the hydrated cement and the fine aggregate. In 60 per cent of the specimens tested there was no statistical difference between 3-body and 2-body abrasion depths, which suggests that the removal of the third body does not necessarily decrease abrasion. For mixes containing hard and durable fine aggregates a relationship has been established between the time elapsed before the commencement of power trowelling and a reduction in abrasion depth. This longer period of time between power floating and power trowelling may have allowed more bleed water to evaporate, thus having the effect of locally reducing the water-cement ratio, a factor which is known to increase the abrasion resistance. No single aggregate or concrete property could be found to account for the reduction in abrasion depth achieved by four of the mixes containing weaker fine aggregates, namely C2F, C3F, J10F and J11F. These reductions, however, could be attributed to two different factors. In the case of C2F and C3F high Los Angeles Abrasion losses enabled a considerable quantity of abrasive particles to be produced from these aggregates under 3-body conditions. Under 2-body conditions these particles were removed, and a statistically significant decrease in abrasion depth was the result. Specimens containing J10F and J11F had significantly lower free water-cement ratios than the other mixes containing crushed Jurassic Limestones, and it appears that these values were more influential in this case than the hardness/quality of the fine aggregate, which is similar for all the crushed Jurassic Limestones. As was evident with 3-body abrasion, the nature of the coarse aggregate became progressively more important as abrasion depth increased, and greater contact is made with these particles.

6.13.3 Wet Abrasion

One of the main factors, water-cement ratio, affecting both 2-body and 3-body abrasion has also been shown to influence wet abrasion although, as discussed in Section 6.13.1, it is of lesser importance when low-grade fine aggregates are used. As discussed earlier, however, the addition of water to the test surface had a profound effect on the abrasion resistance, with abrasion depths being up to 1000 per cent greater than those of the corresponding 3-body abrasion and the rates of abrasion also being much higher. It is evident that factors other than just water-cement ratio are having a profound effect during abrasion in the presence of water. It is thought that this may be attributed principally to three possible mechanisms. During the test the water tended to pond within the abrasion path, thus retaining more of the test debris within the abrasion path, leading to a more rapid increase in the rate of abrasion. Debris did not generally adhere to the wheels during the wet test. Secondly, locally high hydraulic pressures could be developed between the wheels and the concrete. As the wheels pass over an area of concrete covered with water, the water becomes compressed and exerts extreme pressures, especially within any cracks and irregularities. These pressures could accelerate failure by the mechanisms already described in Section 6.13.1. Finally, as seen particularly in mixes containing crushed rock fines, the abrasion depth increase with time is linear, even though the low-grade fines are in combination with a good quality coarse aggregate. It is possible in this instance that the relatively weak mortar was being abraded around the better quality particles. Eventually these particles became loosened and may be removed or fragmented, the result being a rapid increase in abrasion depth. Microscopic analysis of the thin sections has shown small-scale cracking to be visible on some wet test specimens, an example of which is illustrated in *Plate 6.4.* which shows specimen C4FS1. The cracks tended to be sub-parallel to the outer surface of the specimens, and pass predominantly through the paste and around aggregate particles. The severity of wet abrasion is highlighted in the abrasion/time graphs in Chapter 5, which not only show greater abrasion depths at the end of the test, they also show a faster rate of abrasion from the outset.

6.14 Summary

It has become evident from the current project that the abrasion of concrete, under any of the test conditions employed, involves the complex interplay of many different parameters. It has been shown that for different aggregates under different modes of wear, the various parameters have a varying degree of influence, with free water-cement ratio and the hardness/quality of the fine aggregate being particularly influential. Many of these parameters have been examined in fulfilling the aims of this project, but it has only 'scratched the surface' in gaining an understanding of the mechanisms involved in the abrasion of concrete. Section 6.13 has shown how a knowledge of specific concrete and aggregate properties can be used to determine potential abrasion resistance of concrete containing low-grade aggregates.

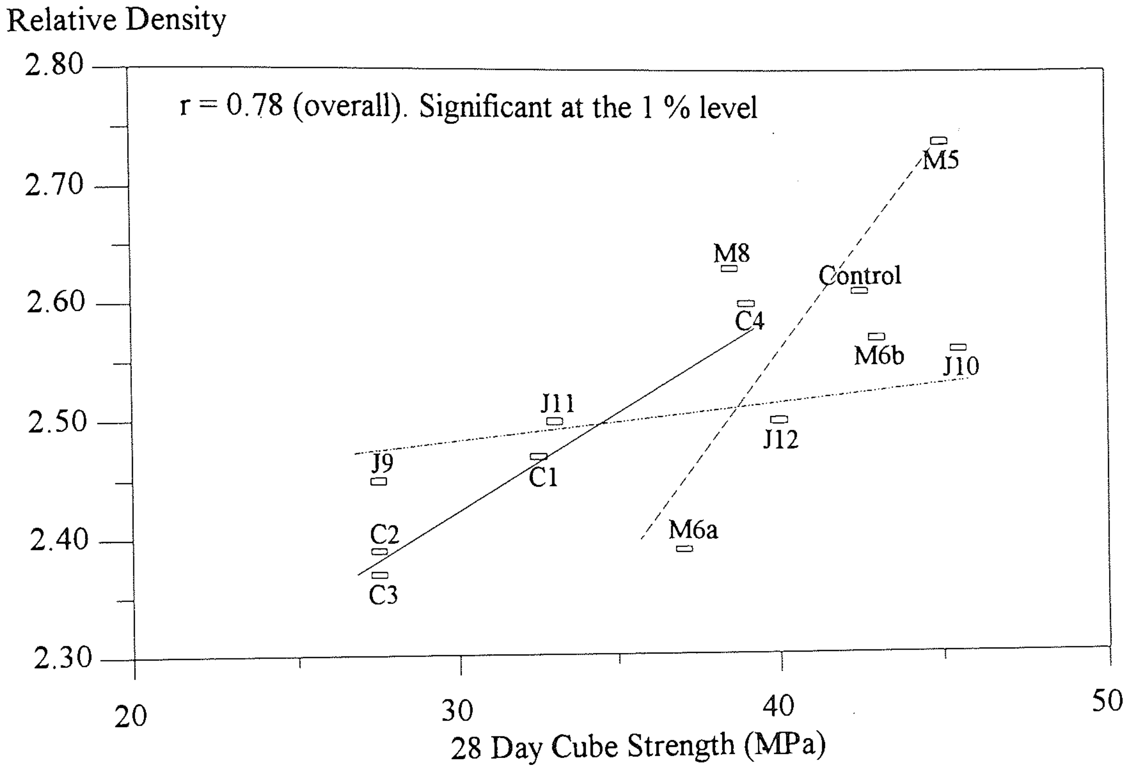

Figure 6.1 Relationships between relative density of the coarse aggregates and the 28-day cube strengths of the concretes containing them.

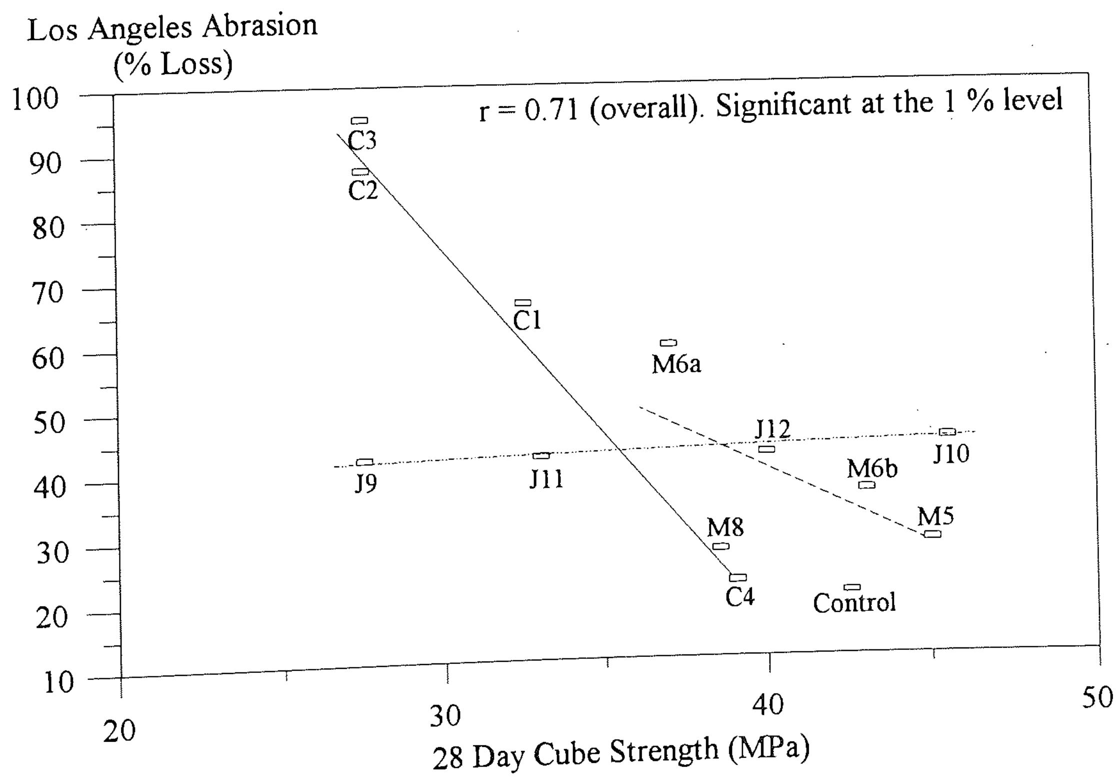

Figure 6.2 Relationships between Los Angeles Abrasion loss of the coarse aggregates and the 28-day cube strengths of the concretes containing them.

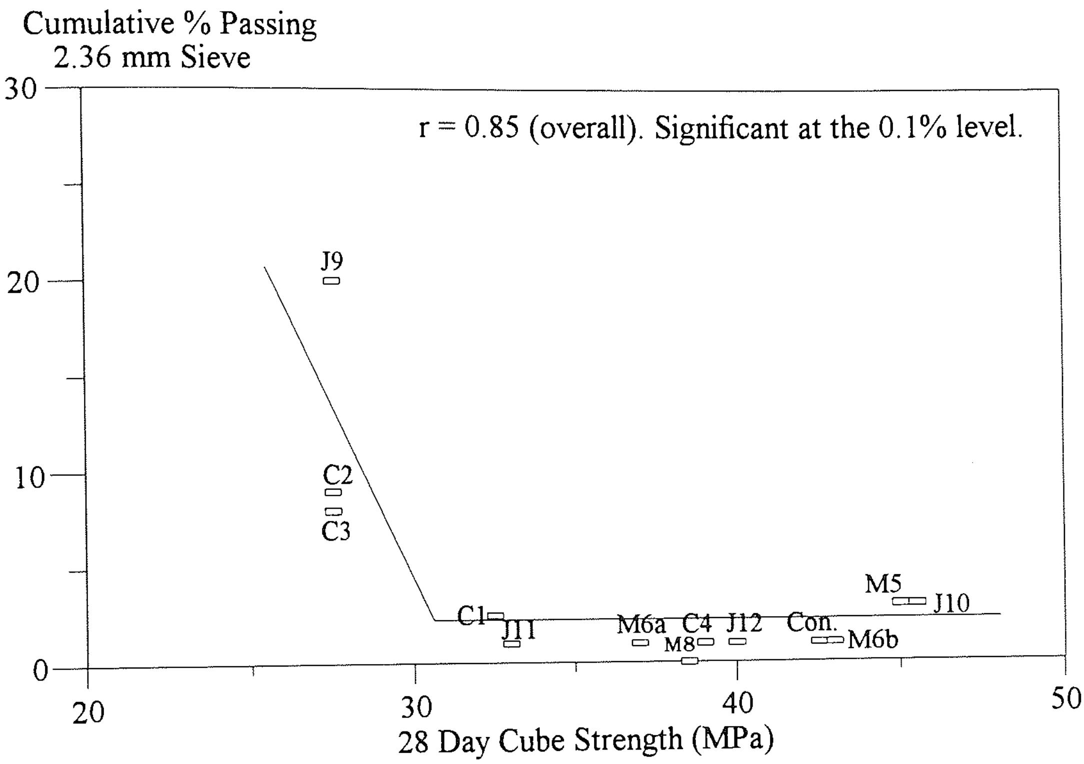

Figure 6.3 Relationship between percentage passing 2.36 mm sieve for the coarse aggregates and the 28-day cube strength of the concrete containing them.

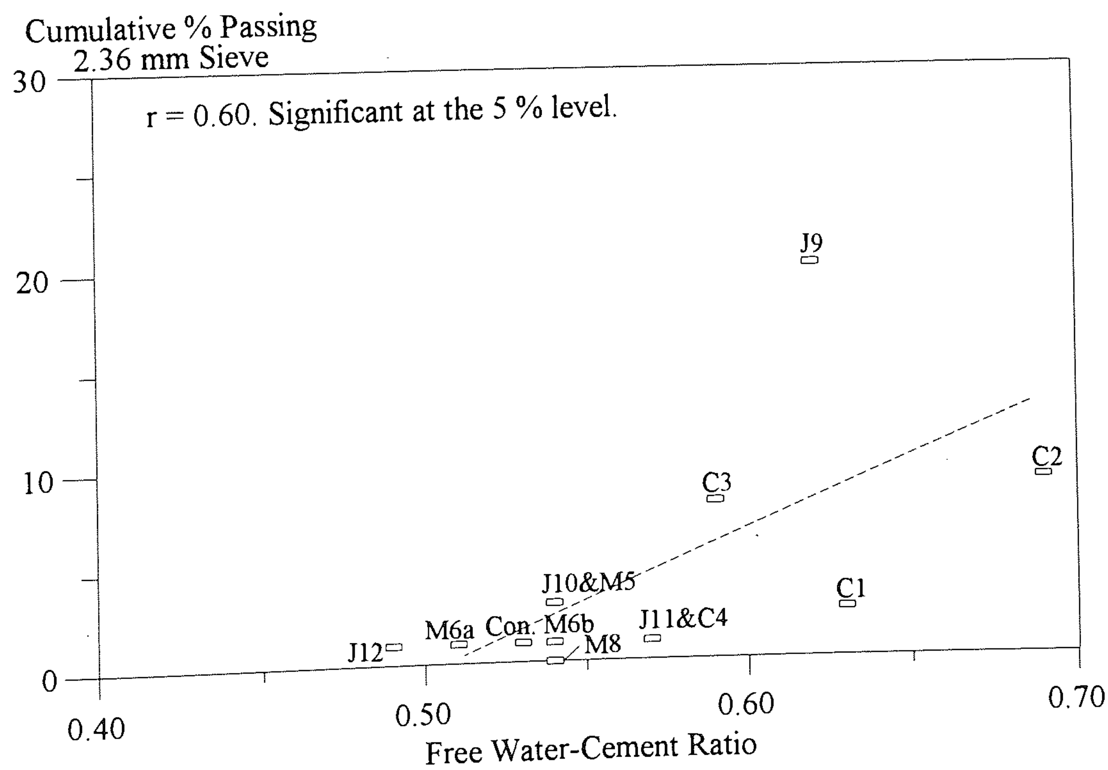

Figure 6.4. Relationship between percentage passing 2.36 mm sieve and free water-cement ratio.

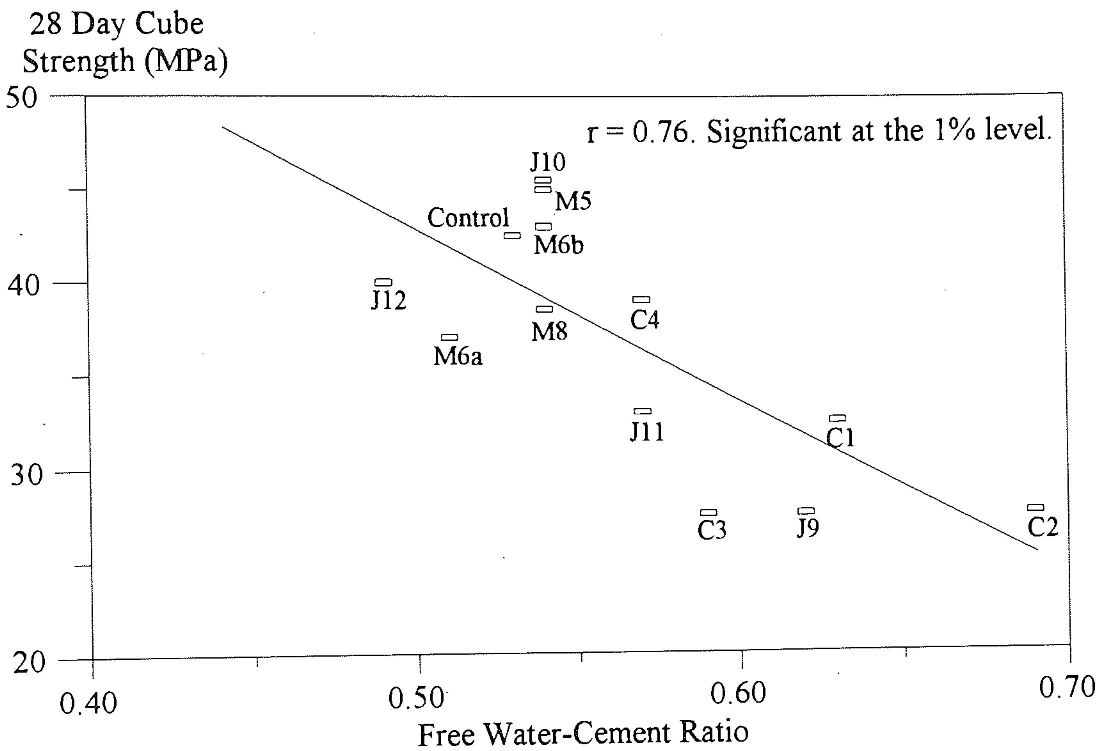

Figure 6.5 Relationship between free water-cement ratio and 28-day cube strength.

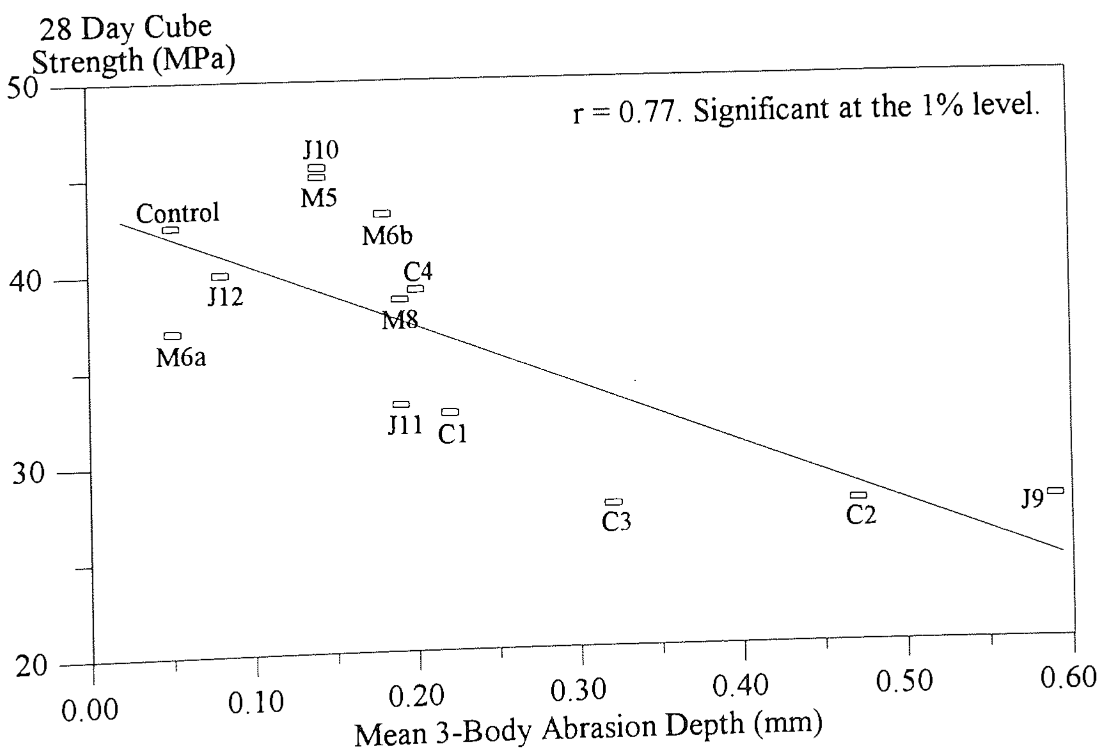

Figure 6.6 Relationship between 28 day cube strength and 3-body abrasion depth.

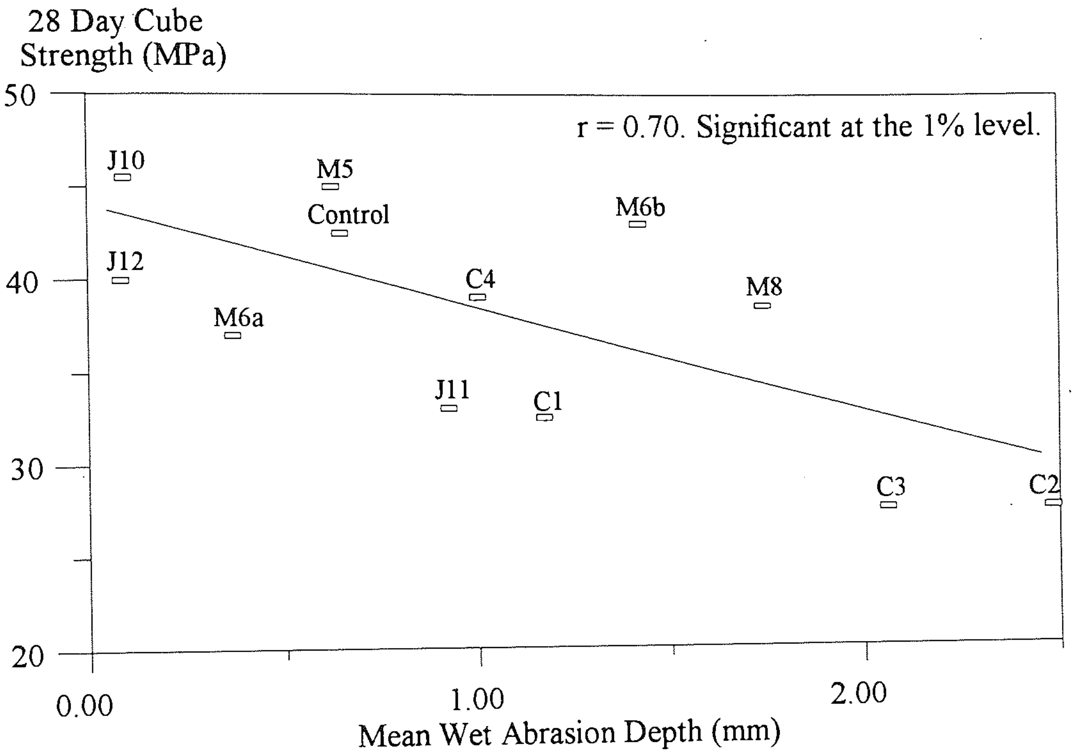

Figure 6.7 Relationship between 28 day cube strength and wet abrasion depth.

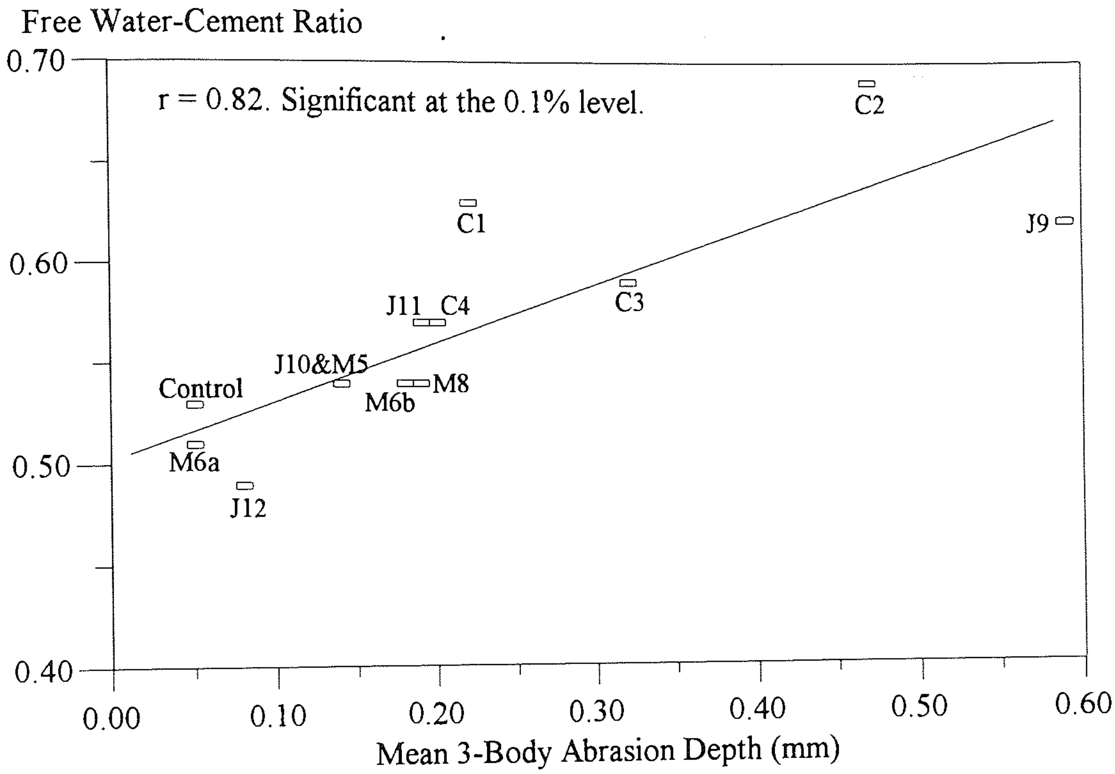

Figure 6.8 Relationship between free water-cement ratio and 3-body abrasion depth.

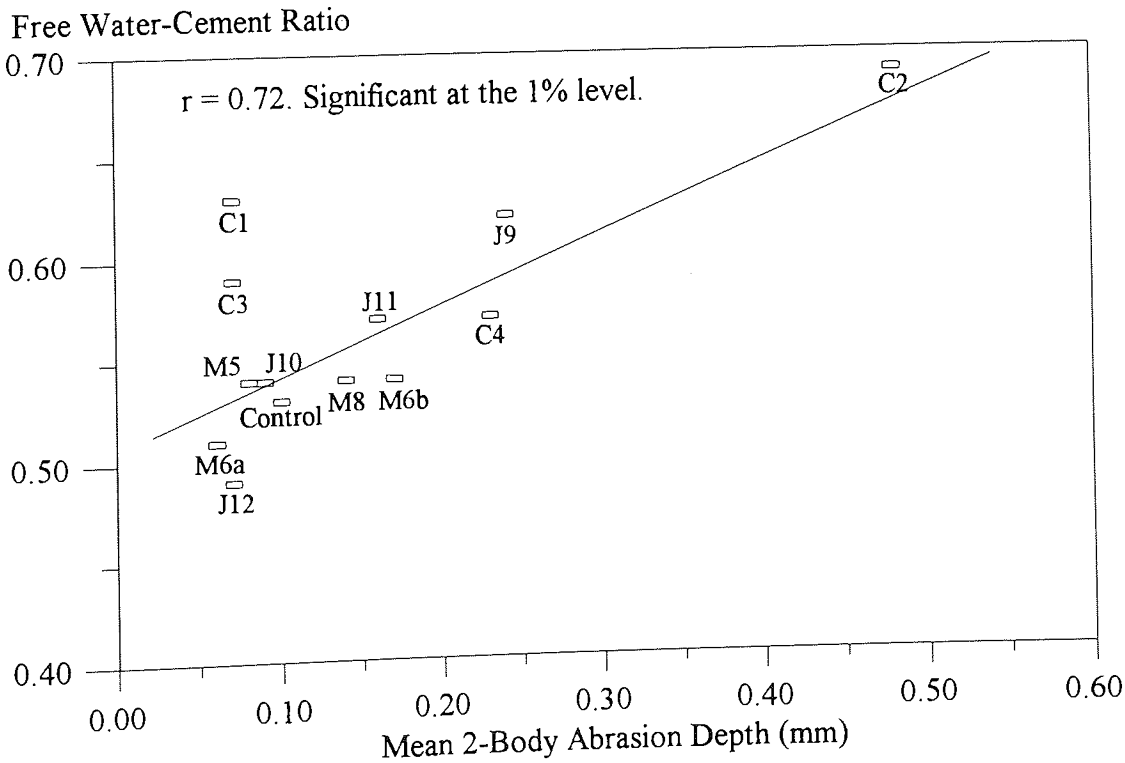

Figure 6.9 Relationship between free water-cement ratio and 2-body abrasion depth.

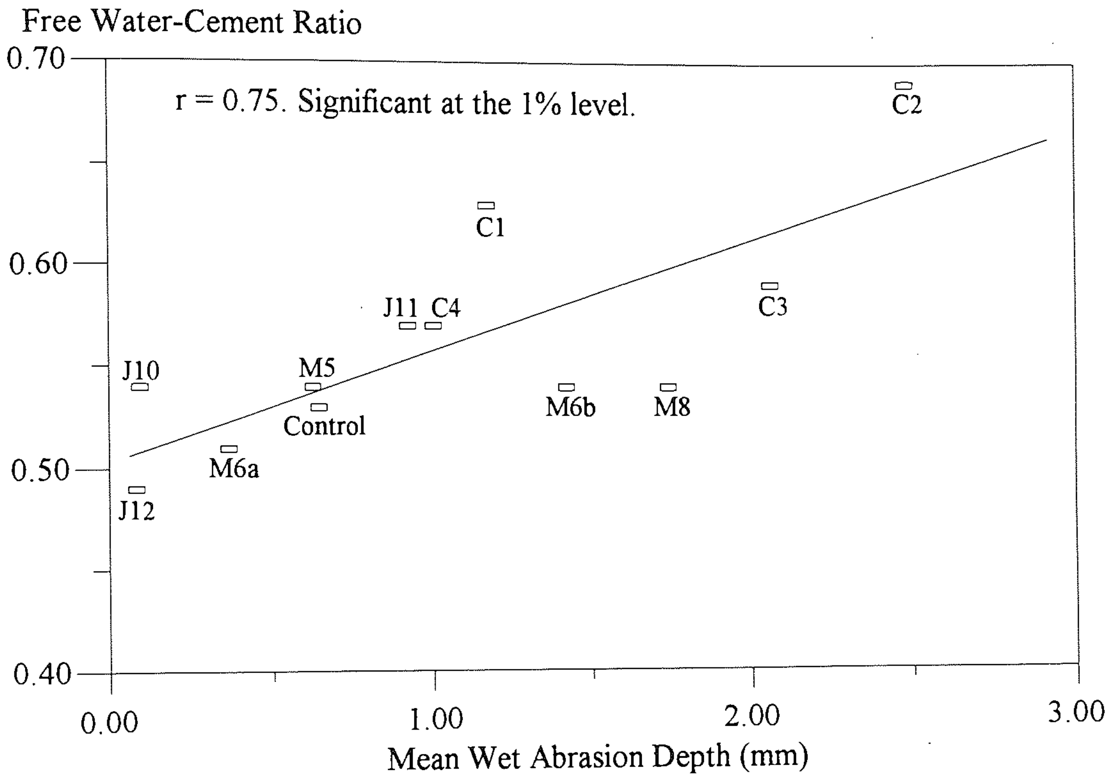

Figure 6.10 Relationship between free water-cement ratio and wet abrasion depth.

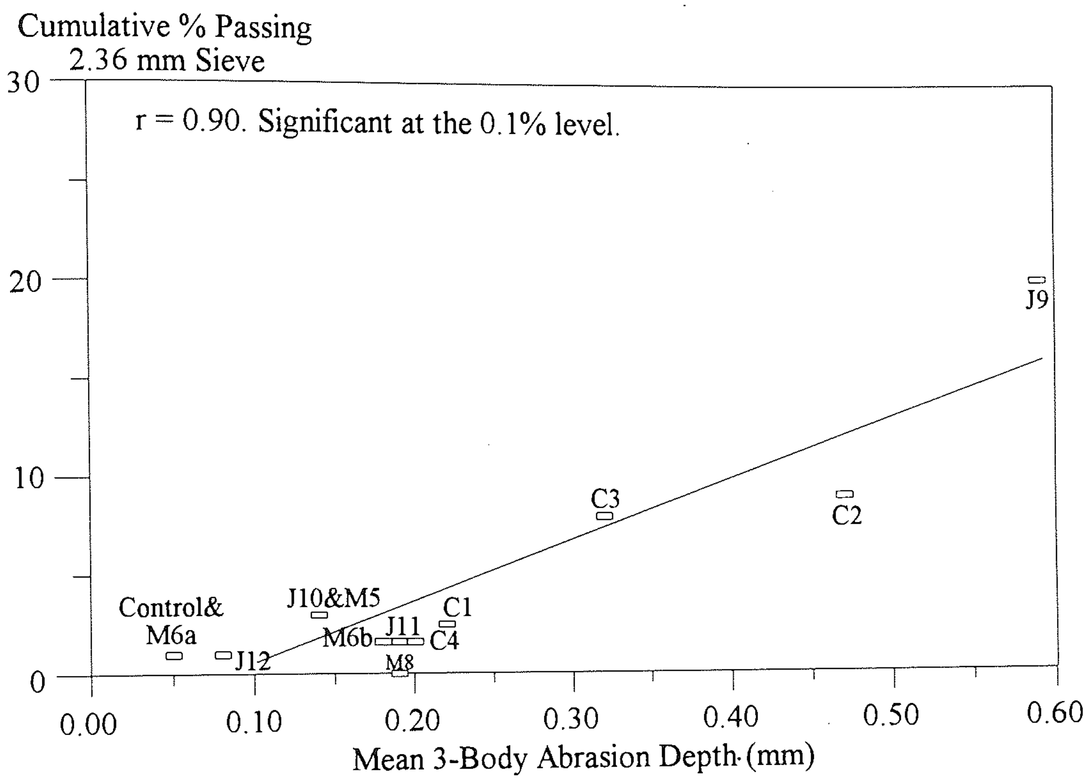

Figure 6.11. Relationship between cumulative percentage passing 2.36 mm and 3-body abrasion depth.

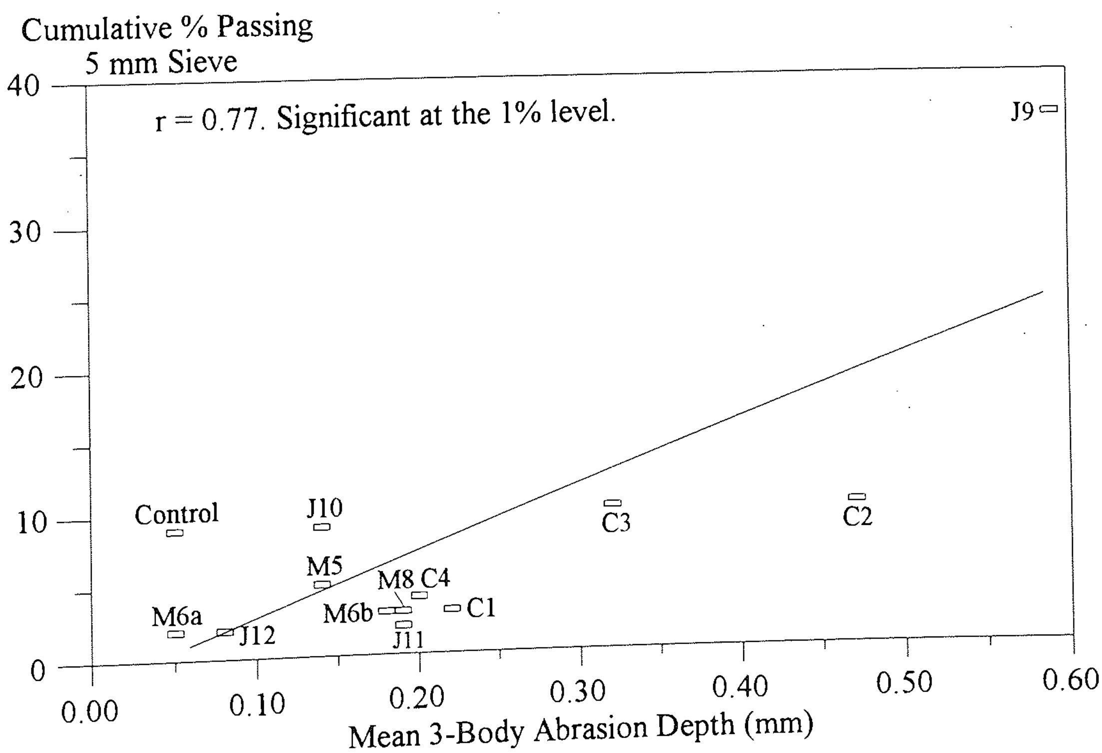

Figure 6.12. Relationship between cumulative percentage passing 5 mm and 3-body abrasion depth.

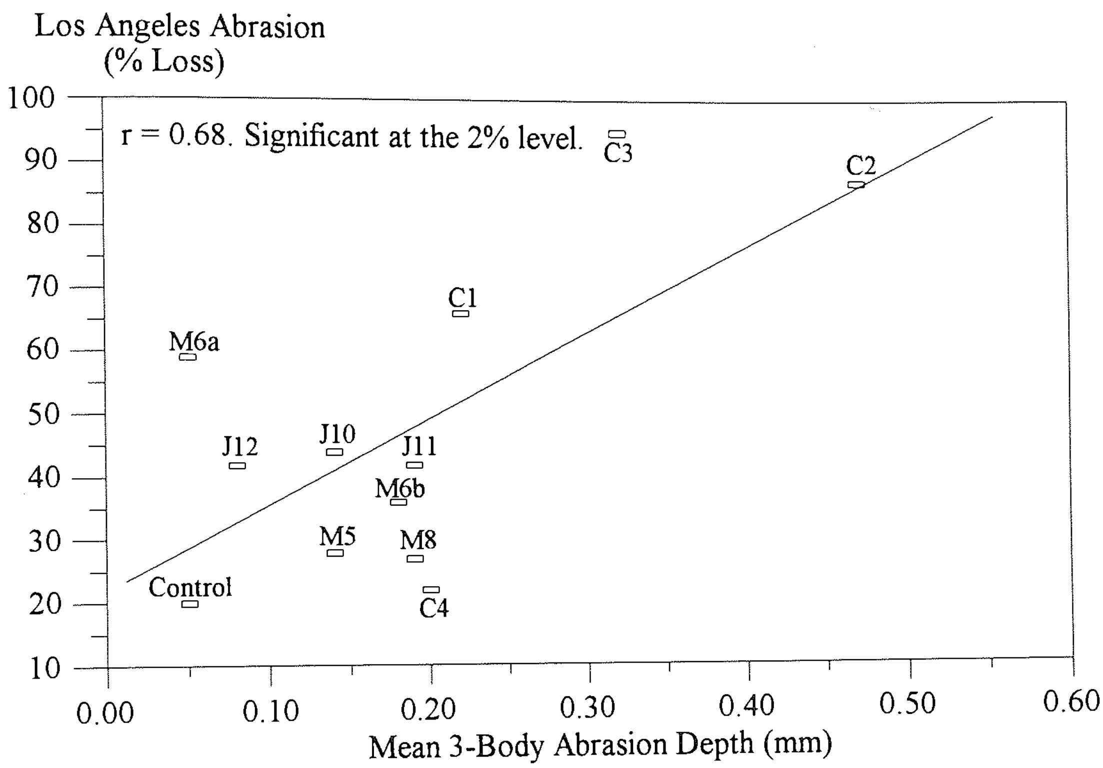

Figure 6.13. Relationship between Los Angeles Abrasion loss and 3-body abrasion depth.

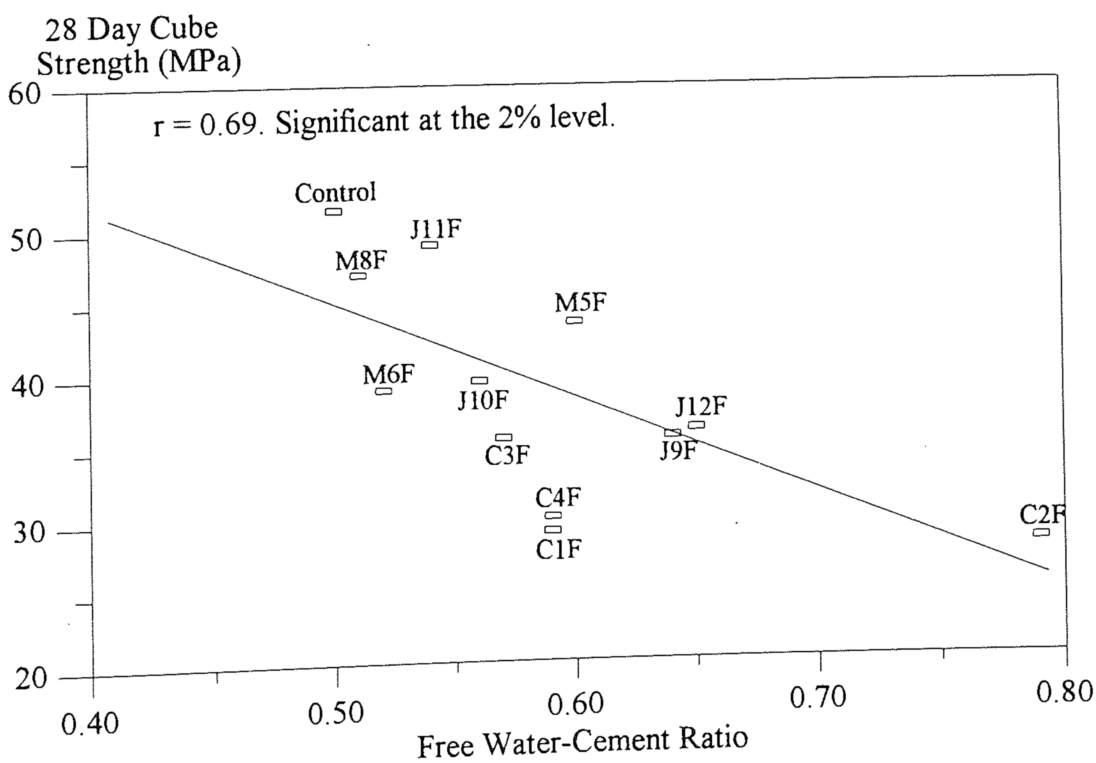

Figure 6.14. Relationship between free water-cement ratio and 28 day cube strength for mixes containing crushed fines.

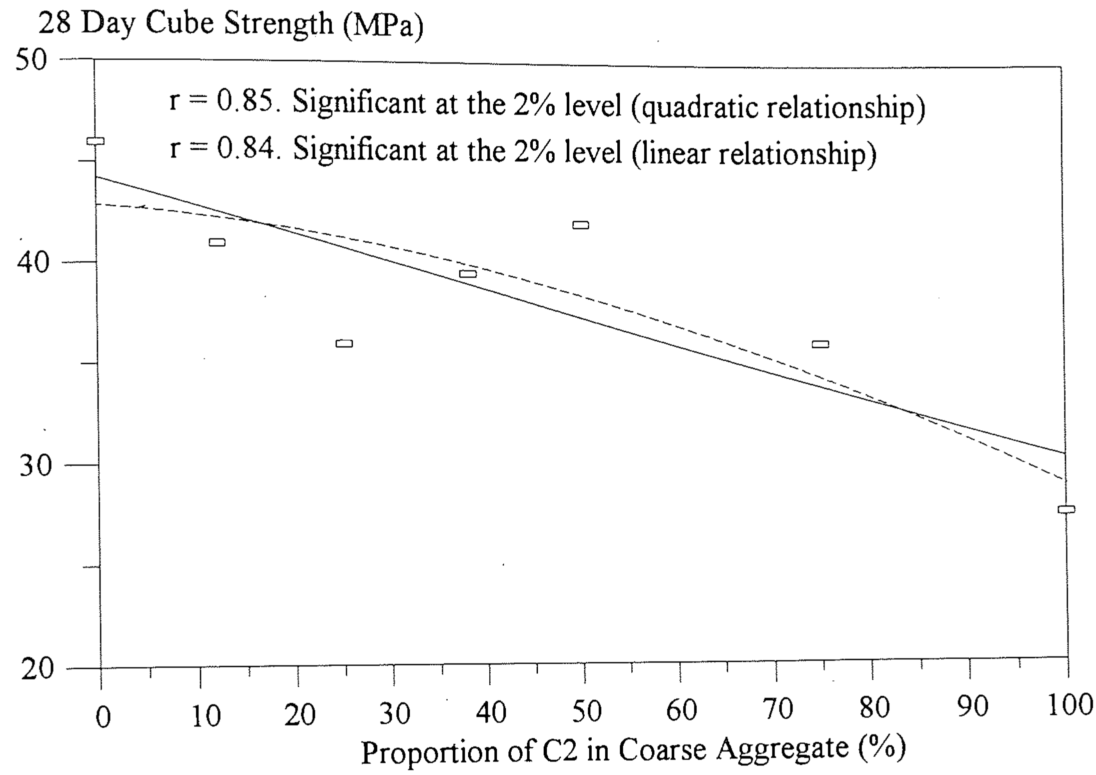

Figure 6.15. Possible relationships between proportion of C2 and 28 day cube strength.

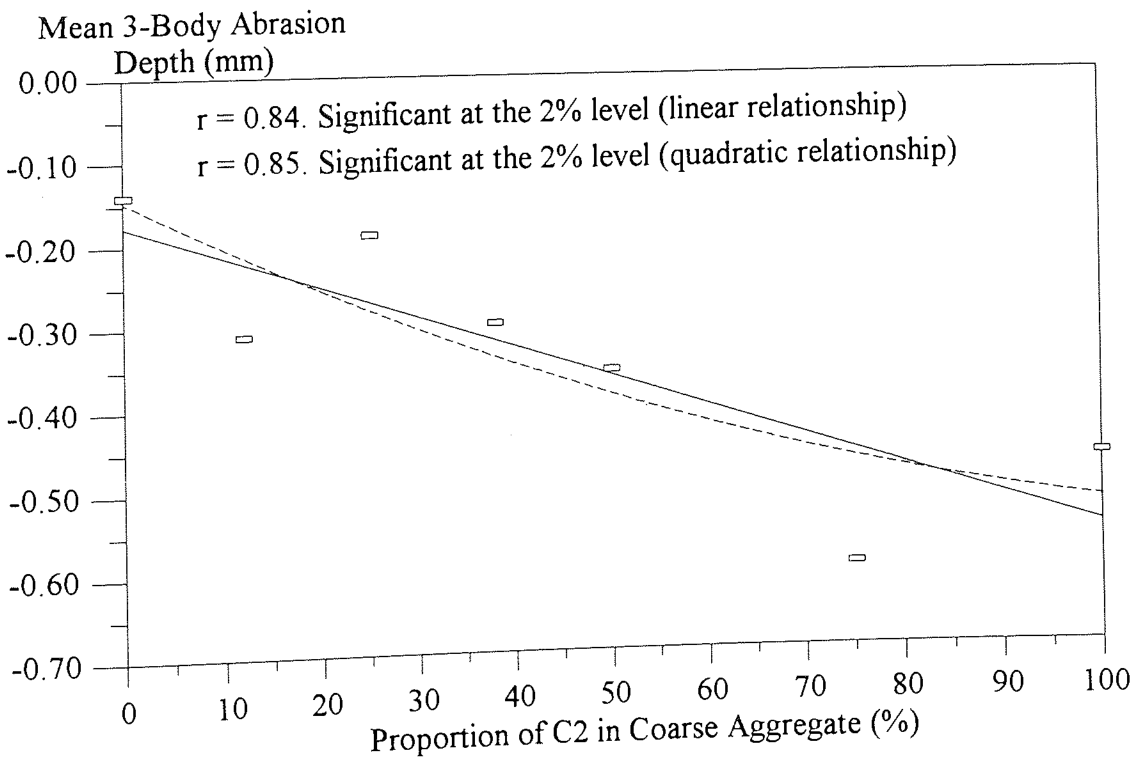

Figure 6.16. Possible relationships between proportion of C2 and 3-body abrasion depth.

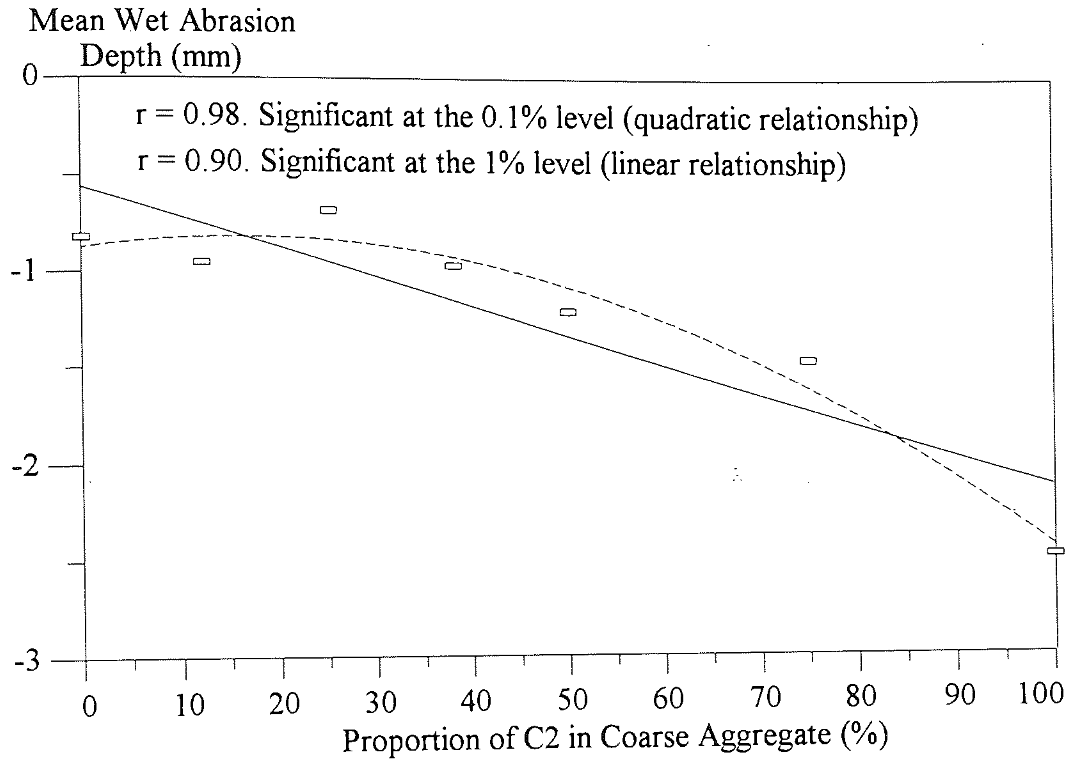

Figure 6.17. Possible relationships between proportion of C2 and wet abrasion depth.

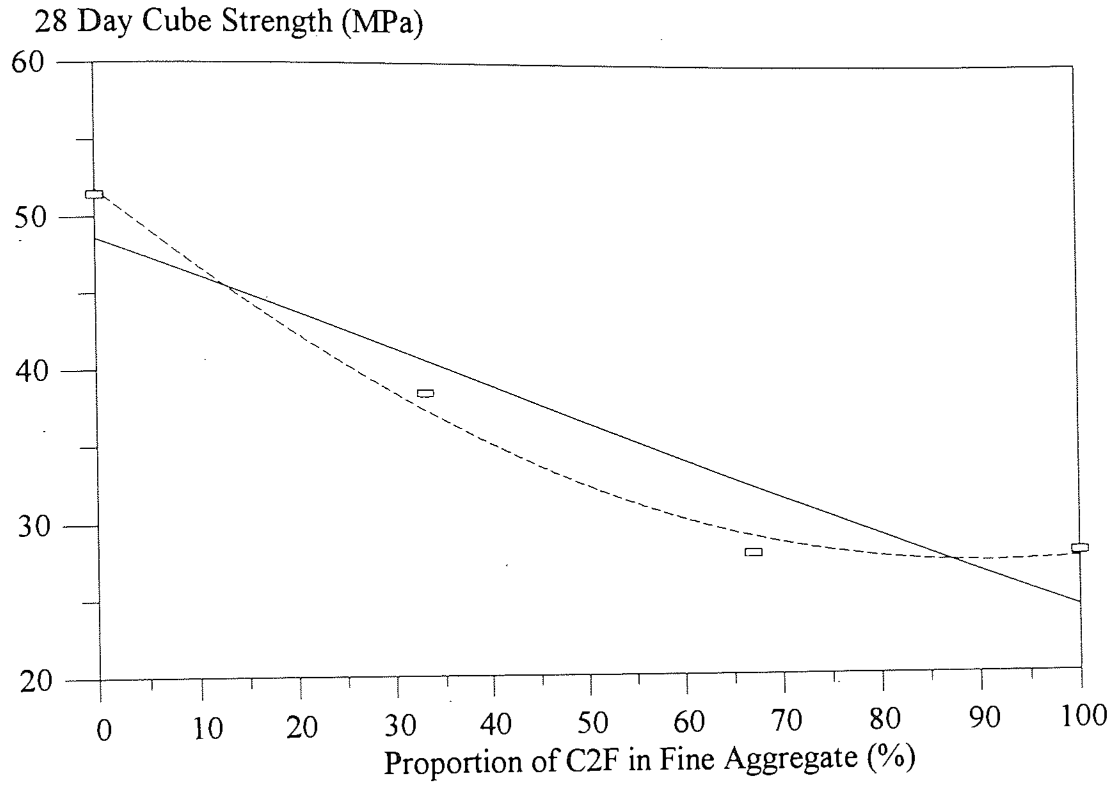

Figure 6.18. Possible relationships between proportion of C2F and 28 day cube strength.

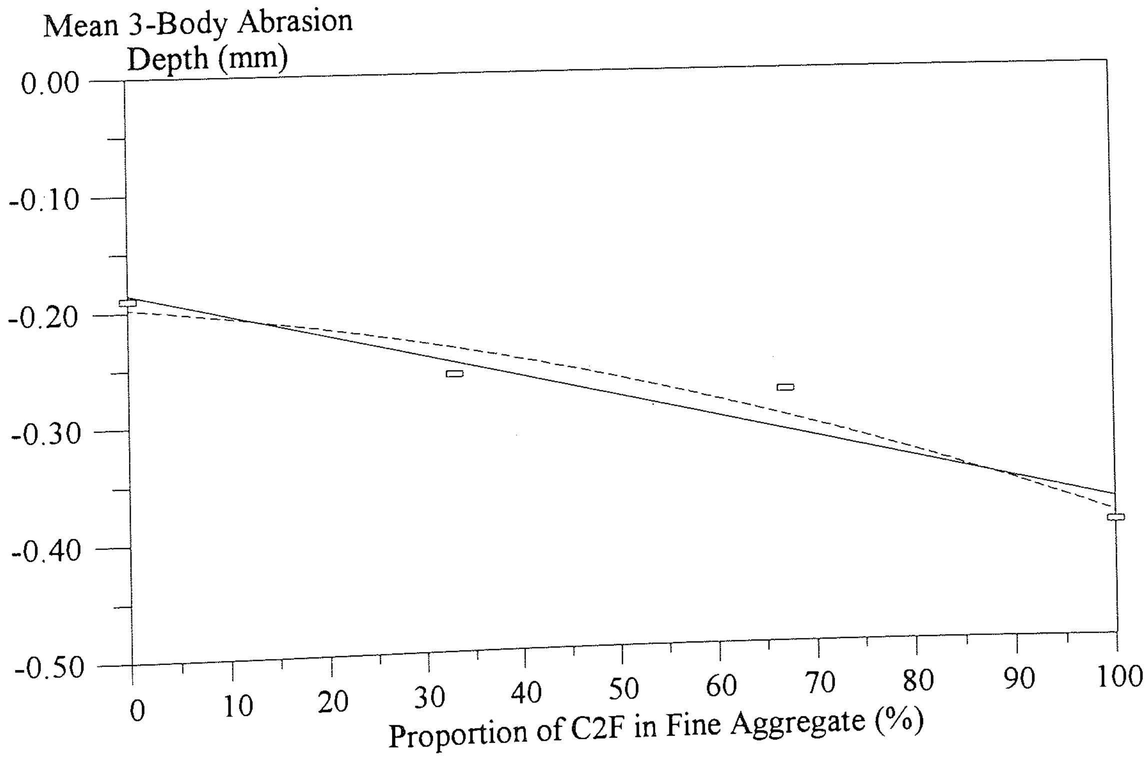

Figure 6.19. Possible relationships between proportion of C2F and 3-body abrasion depth.

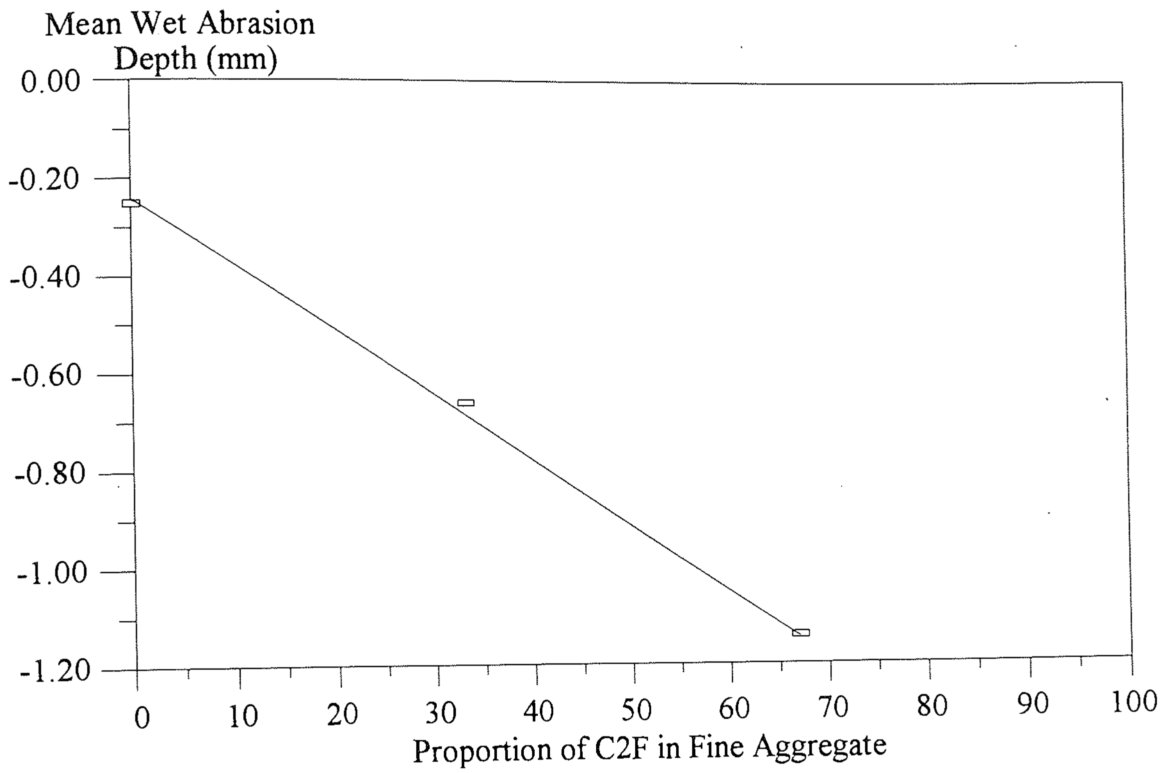

Figure 6.20. Relationship between proportion of C2F and wet abrasion depth.

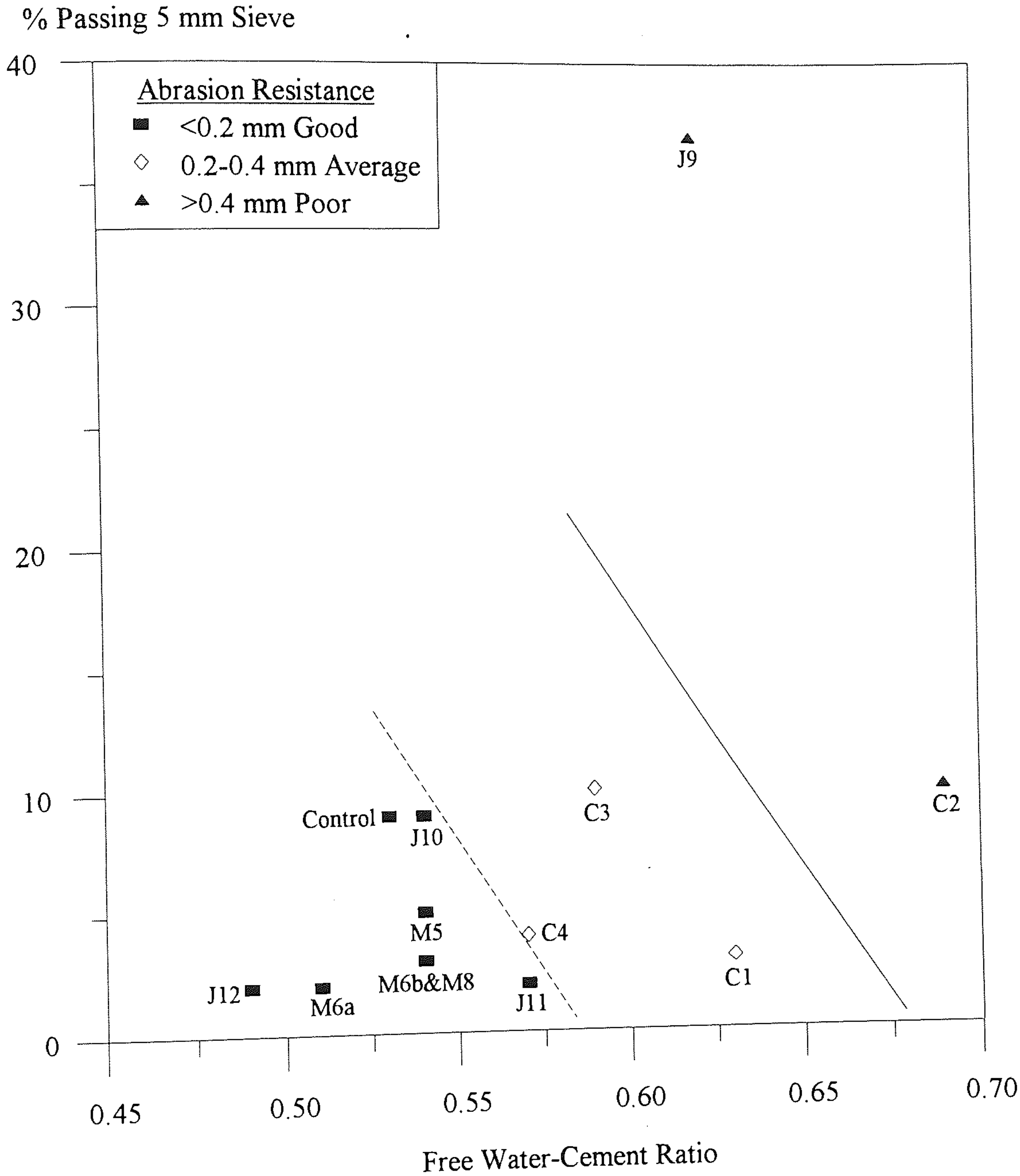

Figure 6.21. Determination of potential abrasion resistance from the free water-cement ratio and the grading of the coarse aggregates. The solid line marks the maximum (average) depth recommended for class AR3 concrete in Concrete Society Technical Report TR 34 (1994).

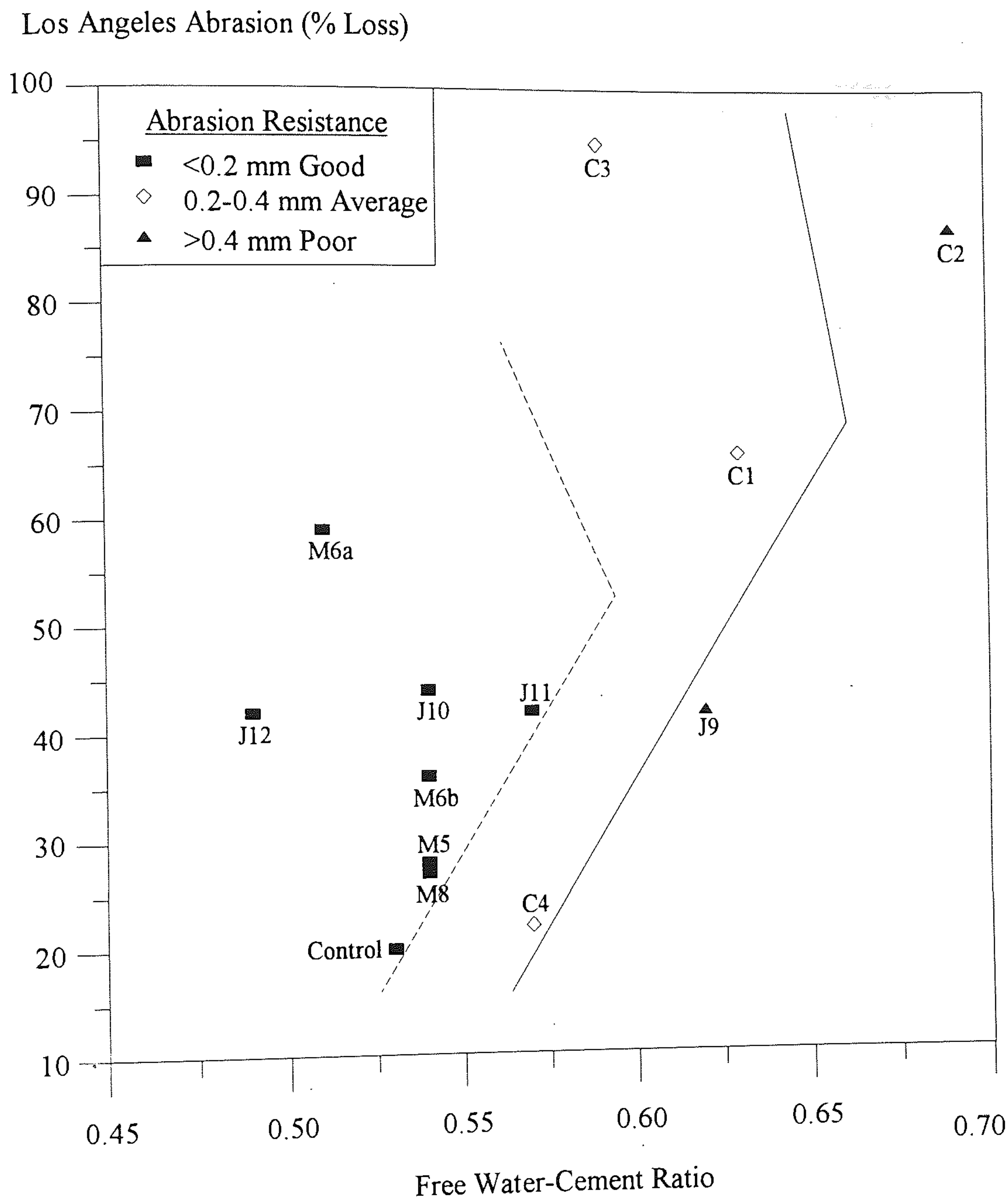

Figure 6.22. Determination of potential abrasion resistance from the free water-cement ratio and the Los Angeles Abrasion loss of the coarse aggregates. The solid line marks the maximum (average) depth recommended for class AR3 concrete in Concrete Society Technical Report TR 34 (1994).

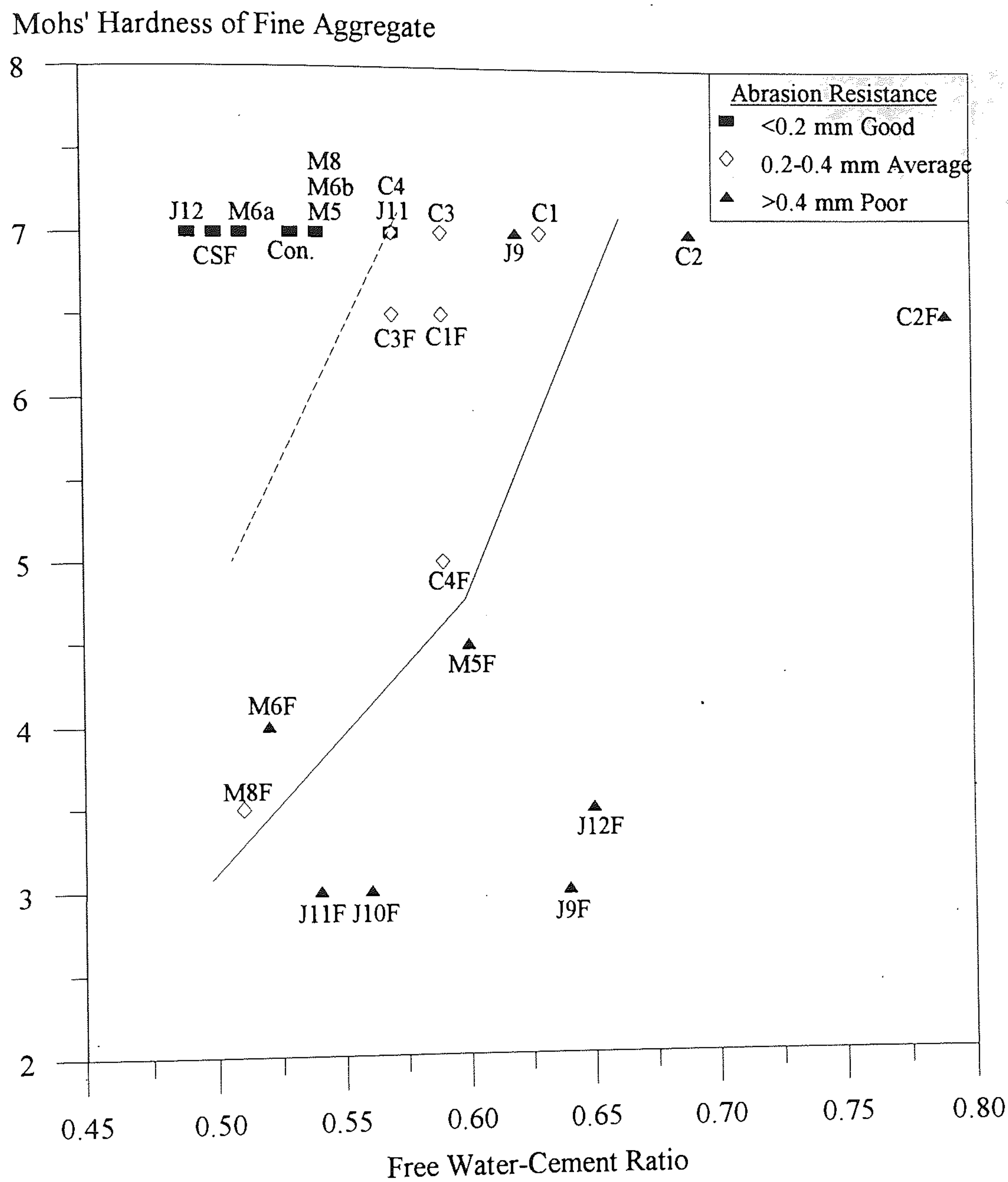

Figure 6.23. Determination of potential abrasion resistance from the free water-cement ratio and the hardness of the fine aggregates. The solid line marks the maximum (average) depth recommended for class AR3 concrete in Concrete Society Technical Report TR 34 (1994).

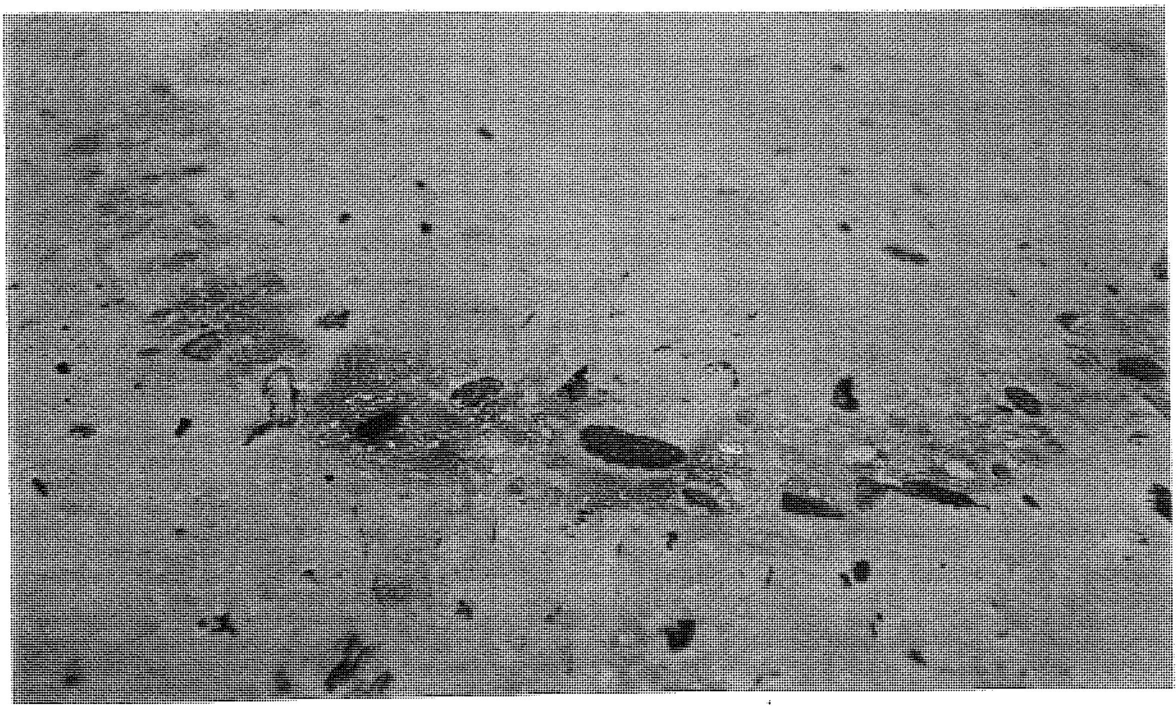

Plate 6.1. Breaking up of the paste around the periphery of coarse aggregate particles within specimen slab J12FS1.

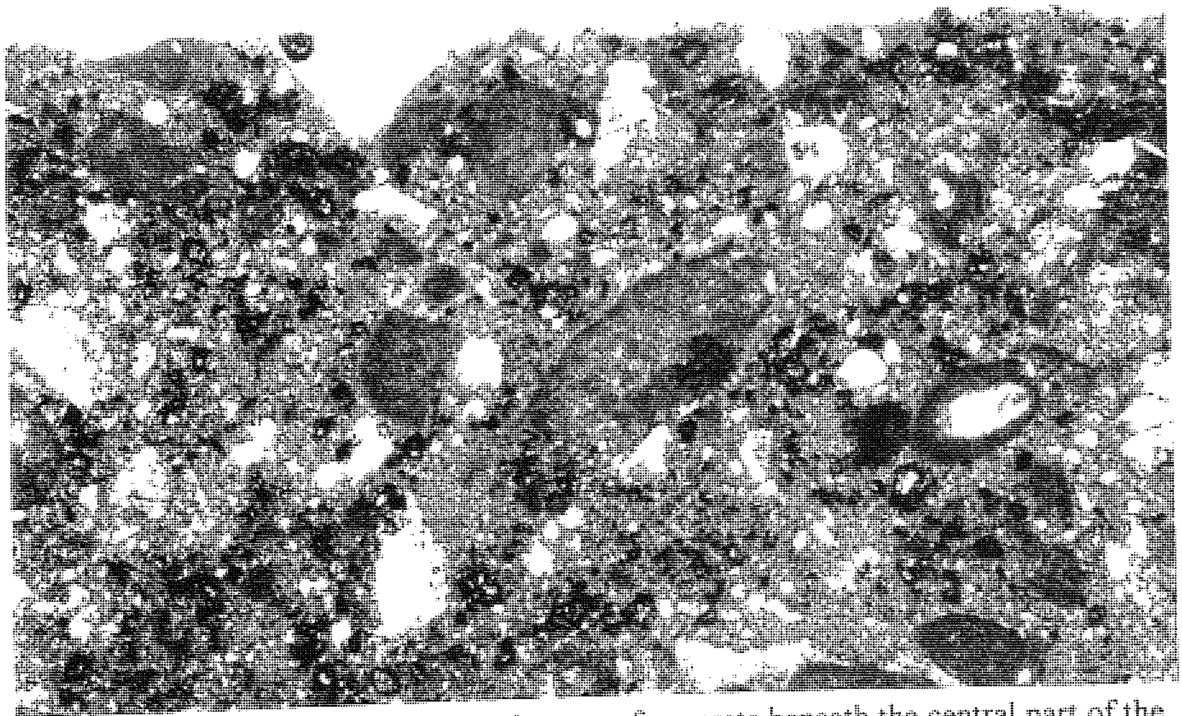

Plate 6.2 Photomicrograph showing the area of concrete beneath the central part of the abrasion path of specimen J12FS1 after 3-body abrasion testing (x40).

Chapter 7 Conclusions

7.1 Introduction

The test results obtained from the current project have been reported and discussed in the preceding chapters. This chapter presents a summary of the findings and conclusions drawn from these chapters.

7.2 Aggregate Properties

1. The aggregates used during this project generally gave poorer performance in the standard aggregate tests than the normal concrete aggregate. The relative densities were lower, the 24 hour absorptions higher and the Los Angeles Abrasion losses greater.

2. The highest Los Angeles Abrasion losses were obtained by the Carboniferous Sandstone aggregates, with the lowest losses obtained by the Magnesian Limestones. This was due to the granular, poorly cemented nature of the Carboniferous rocks. The Magnesian Limestones had a well-crystallised fabric.

3. A good correlation was found between the 24 hour absorption values of the coarse aggregates and those of the crushed fines from the same source. No correlation was found between the equivalent relative density values. This is thought to be due to the crushing process removing the larger pore spaces.

4. Total pore volume has been shown during the current research to be an indicator of potential durability of the Carboniferous Sandstone aggregates.

5. A good correlation was found between the Mohs' Hardness of the aggregates and Vickers Hardness Number.

7.3 General Concrete Properties

1. The low-grade aggregates used throughout the project required more water than normal concrete aggregates to achieve a satisfactory level of workability.

2. For a given free water-cement ratio, lower cube strengths were obtained when using low-grade aggregates rather than normal concrete aggregates.

3. The standard power finishing techniques can be used with concrete containing low-grade aggregates, although finishing times varied widely.

7.3.1 Properties of the Coarse Aggregate Mixes

1. The relative density, Los Angeles Abrasion loss and grading of the coarse aggregates, together with the free water-cement ratio all have significant influences on the cube strength of concrete containing lower-grade coarse aggregates.

2. The cube strength of concrete containing Carboniferous Sandstone aggregates was generally lower than those containing Magnesian or Jurassic Limestones.

3. A 50 per cent replacement of coarse aggregate with Carboniferous Sandstone aggregate produced an estimated 10 per cent reduction in cube strength.

7.3.2 Properties of the Fine Aggregate Mixes

1. The free water-cement ratio of concretes containing low-grade fine aggregates had a significant influence on the resultant cube strength. No single fine aggregate property had a significant direct influence on cube strength.

2. Concrete containing low-grade crushed fines exhibited a proportional decrease in cube strength up to an estimated replacement of 70 per cent. Above this value the rate of decrease reduced.

7.4 Abrasion Resistance

1. Using many of the aggregates examined in this project it was possible to make concrete that satisfied the requirements of Concrete Society Technical Report No. 34 (Concrete Society, 1994) associated with class AR3 direct finished concrete for floors in BS 8204: 1987.

2. Abrasion under 2-body and 3-body conditions showed statistically similar results.

3. The addition of water to the test surface greatly decreased the abrasion resistance.

4. The abrasion resistance has been shown to be influenced by the water-cement ratio and cube strength of the concrete, the grading and Los Angeles Abrasion losses of the coarse aggregate and the hardness/quality of the fine aggregate.

5. An increased cube strength did not necessarily increase abrasion resistance.

6. No single relationship was found between the cube strength and the abrasion resistance for mixes containing low-grade fine aggregates.

7. The relationship between the cube strength and the abrasion resistance of concrete containing low-grade coarse aggregates has been shown to be a measure of the influence of water-cement ratio on cube strength, rather than the dependence of abrasion resistance on cube strength.

8. The 3-body abrasion resistance was primarily dependent upon the free water-cement ratio and the hardness/quality of the fine aggregate, with the quality of the coarse aggregate only becoming more influential at increased depths. The proportion of fine material within the coarse fraction was also important; if this is considerable it can have a significant effect on the overall quality of the fine aggregate fraction. When low-grade fines were present, the free water-cement ratio became subordinate in importance to the hardness/quality of the fine aggregate.

9. The 2-body abrasion resistance was significantly influenced by the free water-cement ratio and hardness/quality of the fine aggregate, and, when the fine aggregate was of good quality, by the time elapsed before the commencement of power trowelling.

10. The free water-cement ratio has been shown to influence the wet abrasion resistance, but the action of the water retaining debris in the abrasion path and hydraulic pressures are thought to be the principal factors in producing the significantly greater depths associated with wet abrasion.

11. Concrete with up to 50 per cent replacement of the coarse aggregate with Carboniferous Sandstone could satisfy the AR3 specification for the abrasion resistance of direct finished concrete quoted in Concrete Society Technical Report TR 34 (Concrete Society, 1994).

12. Tests on concrete containing low-grade sandstone coarse aggregates showed that a negligible increase in wet abrasion depth may be achieved for replacements of up to 50 per cent.

13. The breakdown of concrete during abrasion is primarily caused by crushing and the extension of cracks due to cyclical stressing.

14. The damage to concrete due to abrasion using the rolling wheel apparatus was restricted to the area of contact of the wheels.

15. Generally, the Magnesian Limestones produced concrete with the best abrasion resistance, and the Carboniferous Sandstones the worst. Two Jurassic Limestones had significantly better wet abrasion resistance than all of the other aggregates.

16. Three graphs have been plotted from which it is possible to predict the potential abrasion resistance for concrete containing low-grade aggregates. These graphs are free water-cement ratio against percentage of the coarse aggregate passing the 5 mm sieve, free water-cement ratio against Los Angeles Abrasion loss of the coarse aggregate and free water-cement ratio against Mohs' Hardness of the fine aggregate.

7.5 Concluding Remarks

This chapter has summarised the conclusions from the current study, and it has become apparent throughout this work that these aggregates can be used quite satisfactorily in concrete floor slabs, and that they are capable of producing abrasion resistances within current specifications. The significant effect of water on abrasion has also been highlighted. The main aggregate and concrete properties which affect abrasion have been determined, and a graphical method has been devised which enables abrasion resistance to be determined from free water-cement ratio and various low-grade aggregate properties.

Chapter 8 Recommendations for Further Work

8.1 Introduction

Throughout the current study it has become apparent that there are several aspects of the work that would benefit from further investigation. These are summarised in the following sections.

8.2 Test Method and Procedures

1. Consideration should be given to adapting the test apparatus so that the test duration is measured by a specified number of revolutions, possibly incorporating an automatic switch which would provide increased accuracy of the test duration.

2. For further investigation of 2-body abrasion a more uniform method of test debris removal is probably required. This could take the form of a hood which encloses the whole apparatus, to which the vacuum cleaner is attached. This method would remove debris from the whole test area at a constant rate.

3. Develop a standard test to permit a precise assessment of the stiffness of the fresh concrete. Not only would this enable assessment of the suitability of concrete for power finishing, it would make comparison of the finishing times for different low-grade mixes more accurate.

4. Examine in detail the statistical analysis of the raw data to determine the exact nature of the sample distribution and whether or not it is skewed. This would help to establish the importance (or otherwise) of outlying data points and how they can be accounted for in calculating mean abrasion values.

8.3 Abrasion Resistance

1. A series of mixes should be prepared which include water-reducing agents. These agents would significantly reduce the free water-cement ratios of mixes containing low-grade aggregates, a factor shown during this study to significantly influence abrasion resistance. It would also be necessary to assess the consequences of using such agents on the cost of the concrete.

2. A full series of mixes should be prepared which varies the proportion of low-grade aggregates, both coarse and fine, from zero to 100 per cent. This could follow on from work carried out during the present study, and pinpoint aggregate proportions which indicate changes in abrasion resistance.

3. Mixes should be prepared to enable the zones of predicted abrasion resistance (Chapter 6, *Figures 6.21, 6.22* and *6.23*) to be accurately defined. These mixes would need to consist of specific combinations of free water-cement ratio with coarse aggregate grading, fine aggregate hardness and Los Angeles Abrasion loss.

4. Following on from the graphical prediction of abrasion resistance, it may be possible to analyse the data mathematically, and derive an equation which could represent the variables shown to be influential upon abrasion resistance.

5. Due to the unexpectedly good performance of aggregate M6a, which had a high clay content, a series of mixes could be prepared which would contain varying proportions of clay minerals. If other factors are kept constant, the role of the clay minerals on abrasion resistance could be investigated and quantified.

6. The practicality of using low-grade aggregates for flooring situations could be explored fully if an opportunity could be found to use them in the construction of a (large) ground floor slab. This would yield, in time, important performance results which could advance the use of these aggregates.

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Appendix A

Mix Details

Specimen	Cement (kg)	Coarse (kg)	Water within coarse agg. (kg)	Fines (kg)	Added Water (kg)
CS2	59.4	205.4	0	129.6	36.5
C1S1	59.4	200.9	4.5	129.6	39.5
C2S1	59.4	198.8	6.6	129.6	42.7
C3S1	59.4	198.6	6.8	129.6	40.5
C4S1	59.4	202.7	2.7	129.6	37.7
M5S1	59.4	205.0	0.4	129.6	37.5
M6aS1	59.4	191.8	13.6	129.6	37.0
M6bS1	59.4	196.6	8.8	129.6	36.0
M8S1	59.4	202.3	3.1	129.6	36.0
J9S1	59.4	191.2	14.2	129.6	37.5
J10S1	59.4	197.0	8.4	129.6	33.0
J11S1	59.4	199.4	6.0	129.6	38.0
J12S1	59.4	204.2	1.2	129.6	39.0

Table A.1. Details of the coarse aggregate mix proportions.

Specimen	Cement (kg)	Fines (kg)	Water within Fine agg. (kg)	Coarse (kg)	Added Water (kg)
CSF1	59.4	140.4	0	205.4	32.0
C1FS1	59.4	130.2	10.2	205.4	27.5
C2FS1	59.4	130.6	9.8	205.4	38.5
C3FS1	59.4	130.4	10.0	205.4	30.5
C4FS1	59.4	136.5	4.0	205.4	39.0
M5FS1	59.4	134.9	5.5	205.4	33.0
M6FS1	59.4	125.7	14.7	205.4	31.5
M8FS1	59.4	133.1	7.3	205.4	27.0
J9FS1	59.4	126.2	14.2	205.4	33.0
J10FS1	59.4	133.2	7.2	205.4	33.0
J11FS1	59.4	132.0	8.4	205.4	28.2
J12FS1	59.4	132.3	8.1	205.4	37.5

Table A.2. Details of the fine aggregate mix proportions.

Appendix B

Aggregate Details

Sample Reference:-	C1 and C1F
Quarry Details:-	Montcliffe Quarry Georges Lane Horwich Bolton, Greater Manchester
Grid Reference:-	SD656122
Owner:-	ARC Northern Ltd Round 'O' Quarry, Cobbs Brow Lane Latham, Lancashire
Geological Horizon:-	Ousel Nest Grit, Lower Coal Measures
Coarse Aggregate Details:-	Supplied as 20-5 mm graded
Fine Aggregate Details:-	C1F, supplied crushed, 5 mm down

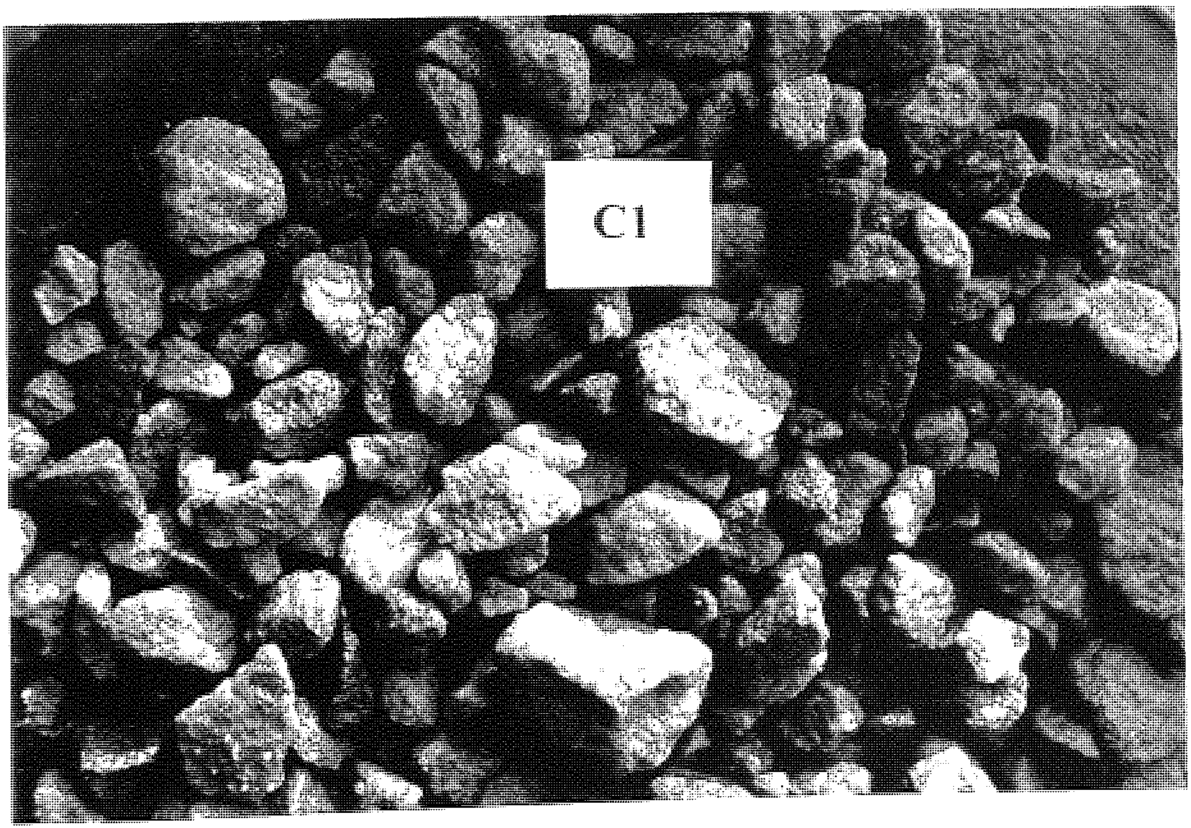

Plate B.1 A typical sample of aggregate C1.

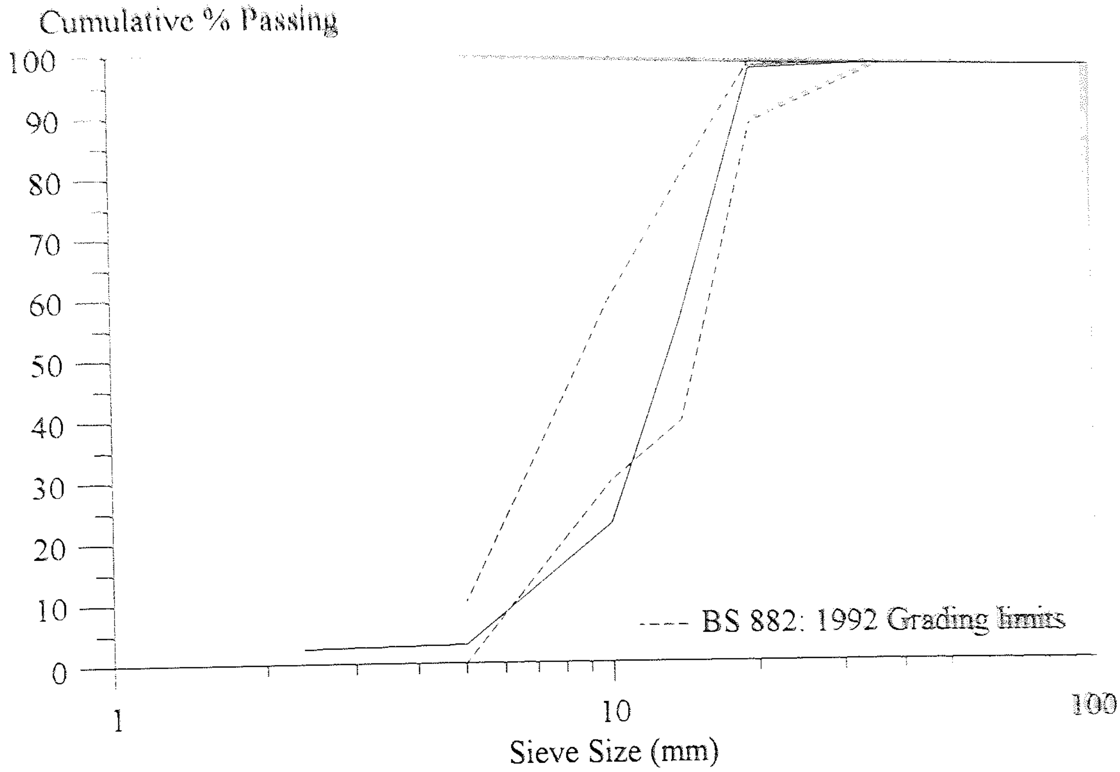

Figure B.1. Particle size distribution of sample C1.

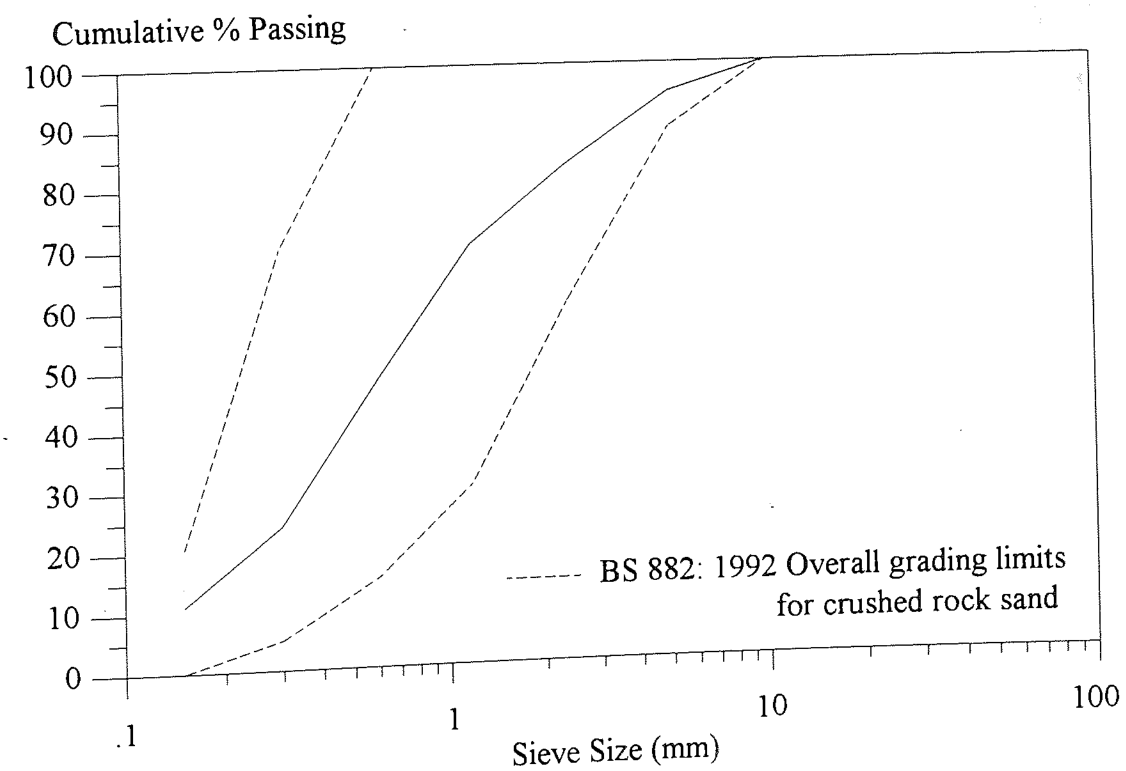

Figure B.2. Particle size distribution of sample C1F.

Sample Reference:- C2 and C2F

Quarry Details:- Little Quarry
Whittle-Le-Woods
Chorley
Lancashire

Grid Reference:- SD584219

Owner:- J. and J. Ashcroft
Little Quarries, Hill Top Lane
Whittle-Le-Woods, Lancashire

Geological Horizon:- Revidge Grit, Millstone Grit Series

Coarse Aggregate Details:- Supplied as 20-5 mm graded

Fine Aggregate Details:- C2F, supplied crushed, 5 mm down

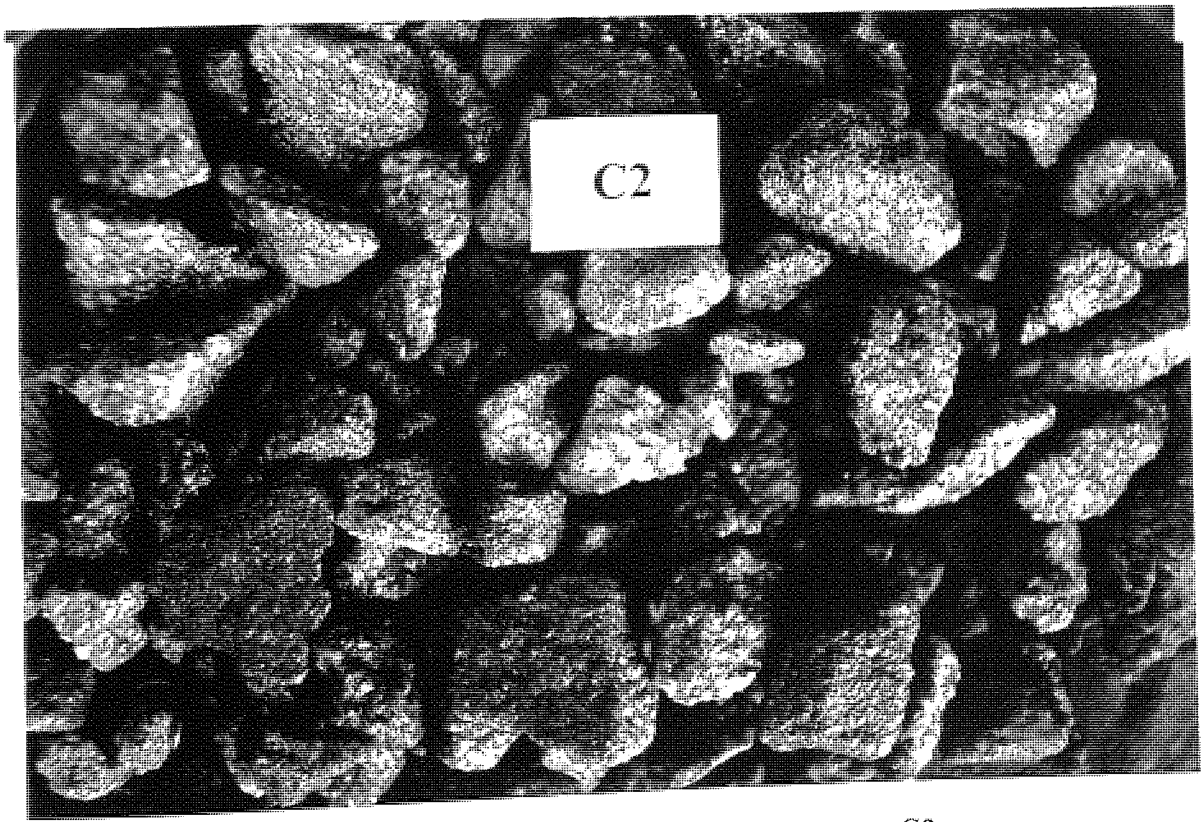

Plate B.2 A typical sample of aggregate C2.

Sample Reference:- C3 and C3F

Quarry Details:- Waddington Fell Quarry
Slaidburn Road
Waddington
Clitheroe, Lancashire

Grid Reference:- SD718477

Owner:- Waddington Fell Quarries Ltd
Slaidburn Road, Waddington
Clitheroe, Lancashire

Geological Horizon:- Warley Wise Gritstone, Millstone Grit Series

Coarse Aggregate Details:- Supplied as 20-5 mm graded

Fine Aggregate Details:- C3F, supplied crushed and washed, 5 mm down

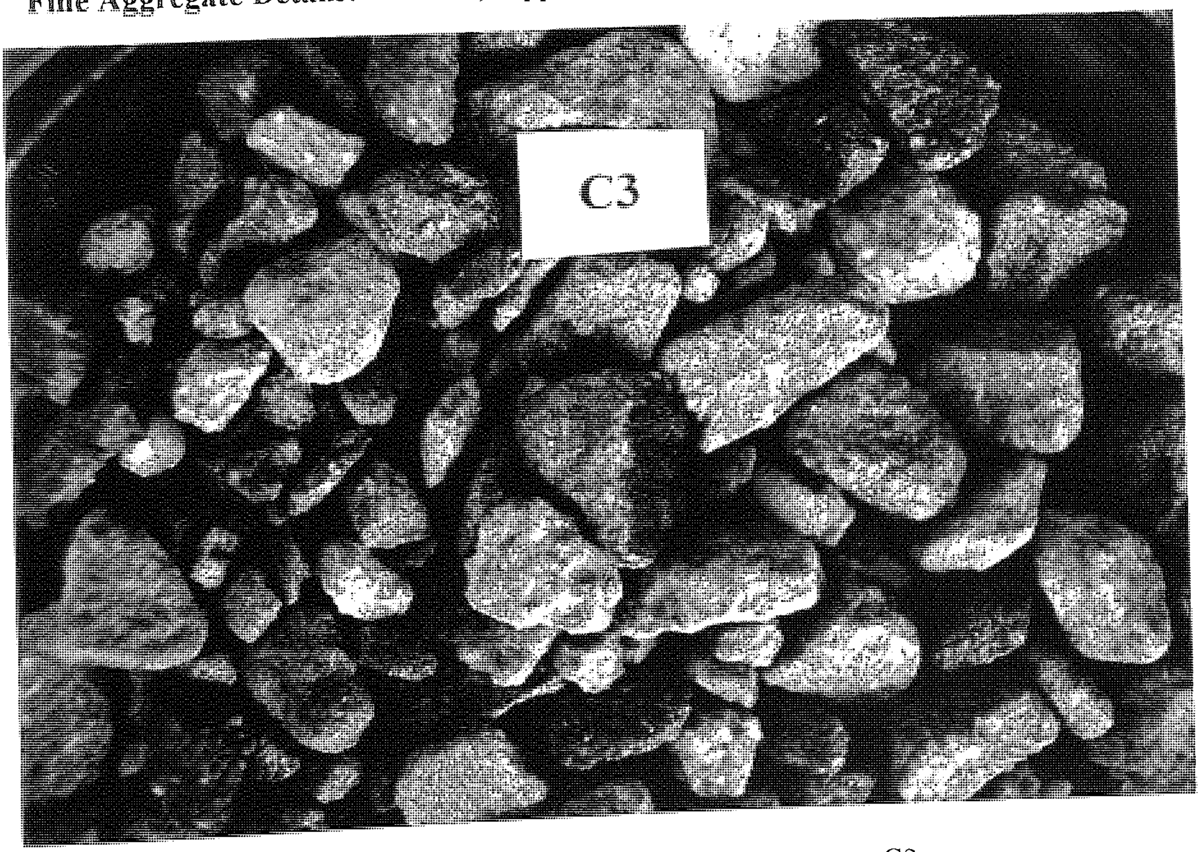

Plate B.3 A typical sample of aggregate C3.

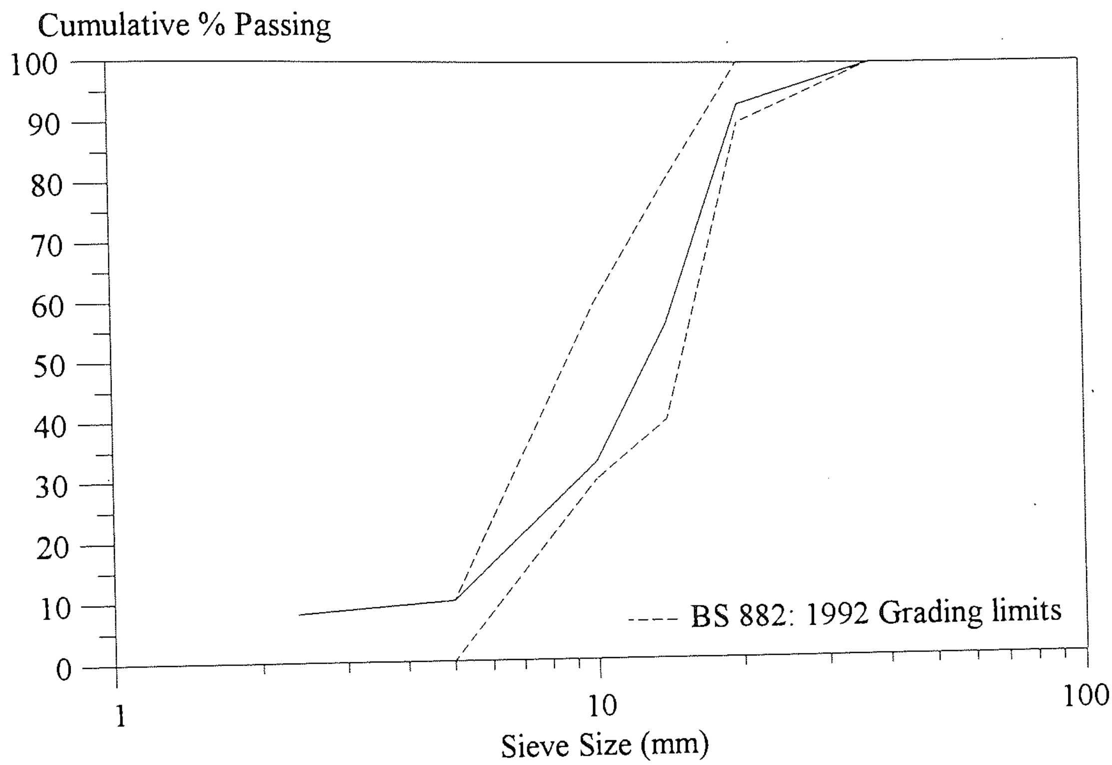

Figure B.5. Particle size distribution of sample C3.

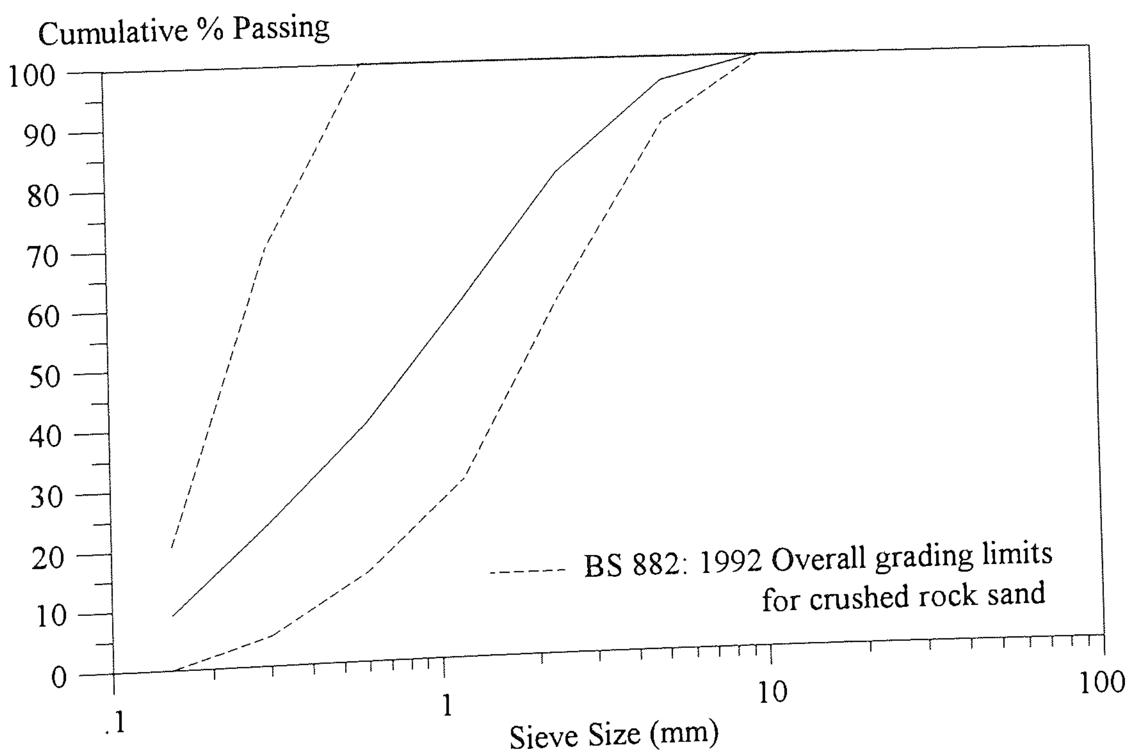

Figure B.6. Particle size distribution of sample C3F.

Sample Reference:- C4 and C4F

Quarry Details:- Whitworth Quarry
Tong Lane
Whitworth
Rochdale, Lancashire

Grid Reference:- SD872303

Owner:- Bardon Roadstone Ltd
Stoneleigh, Park End Road
Workington, Cumbria

Geological Horizon:- Upper Haslingden Flags, Millstone Grit Series

Coarse Aggregate Details:- Supplied as 20 mm, 14 mm, 10 mm and 6 mm single sizes

Fine Aggregate Details:- C4F, supplied crushed, 6 mm to dust

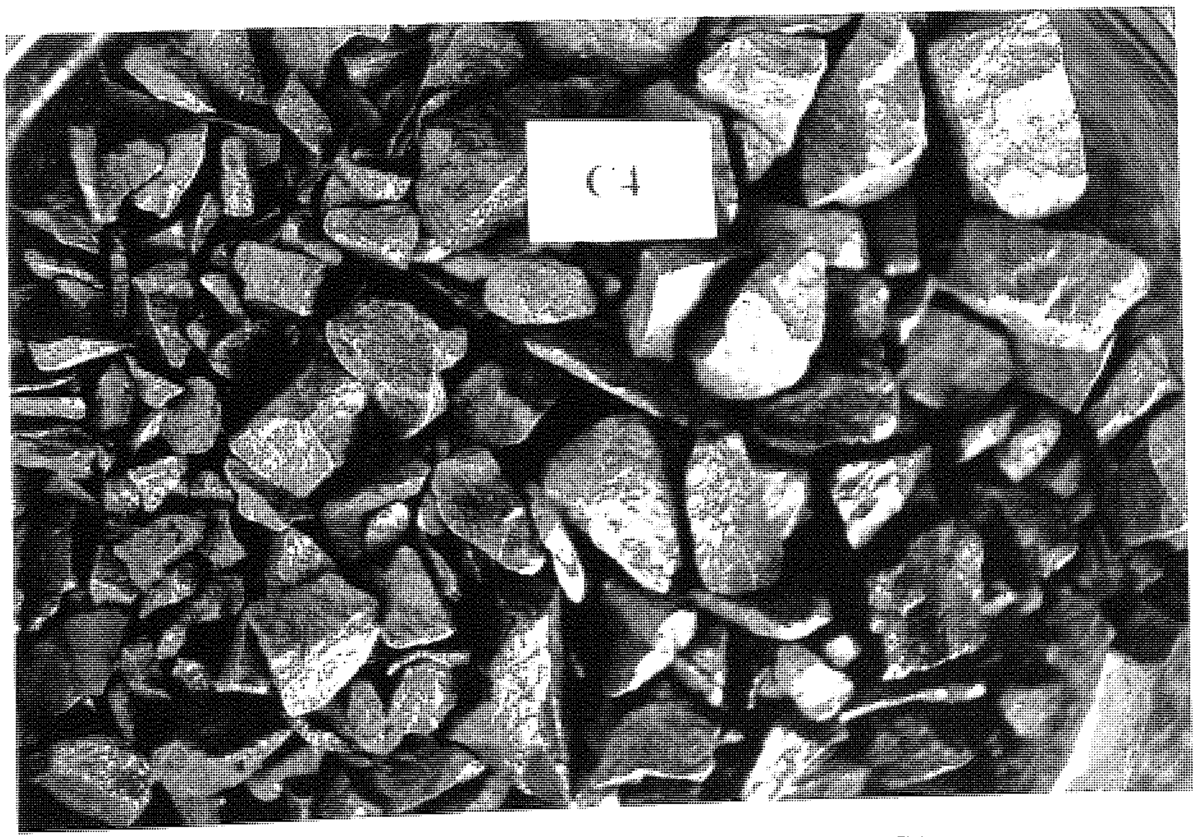

Plate B.4 A typical sample of aggregate C4.

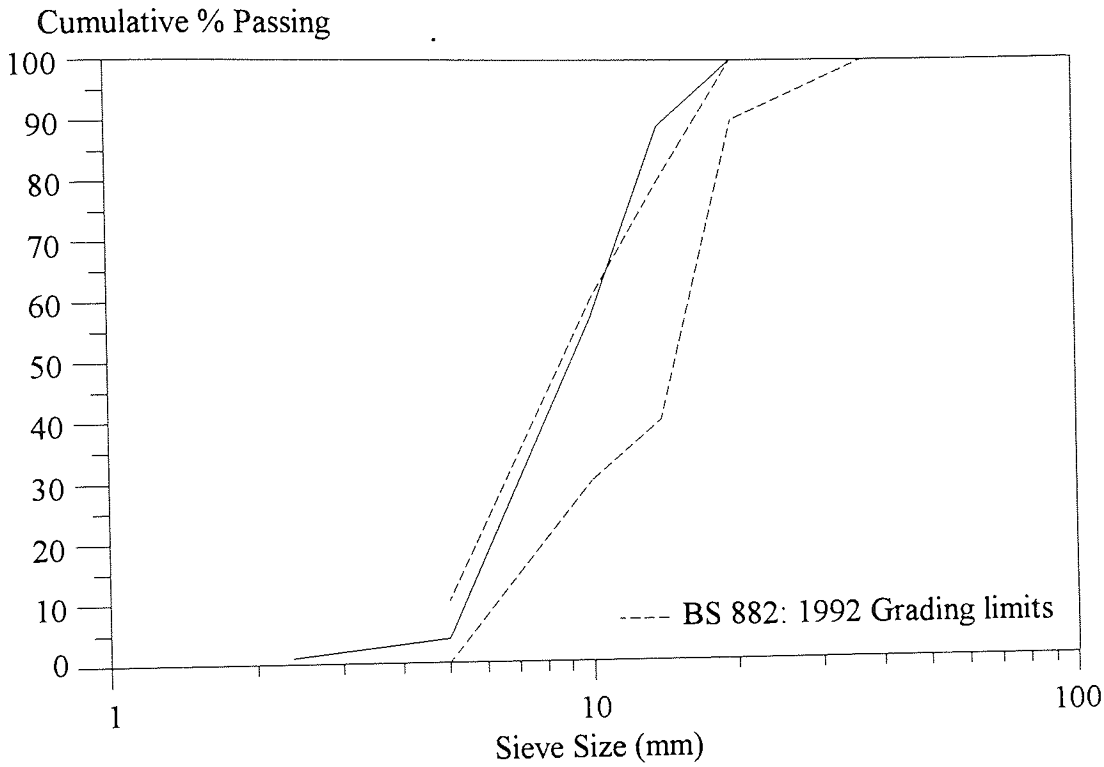

Figure B.7. Particle size distribution of sample C4.

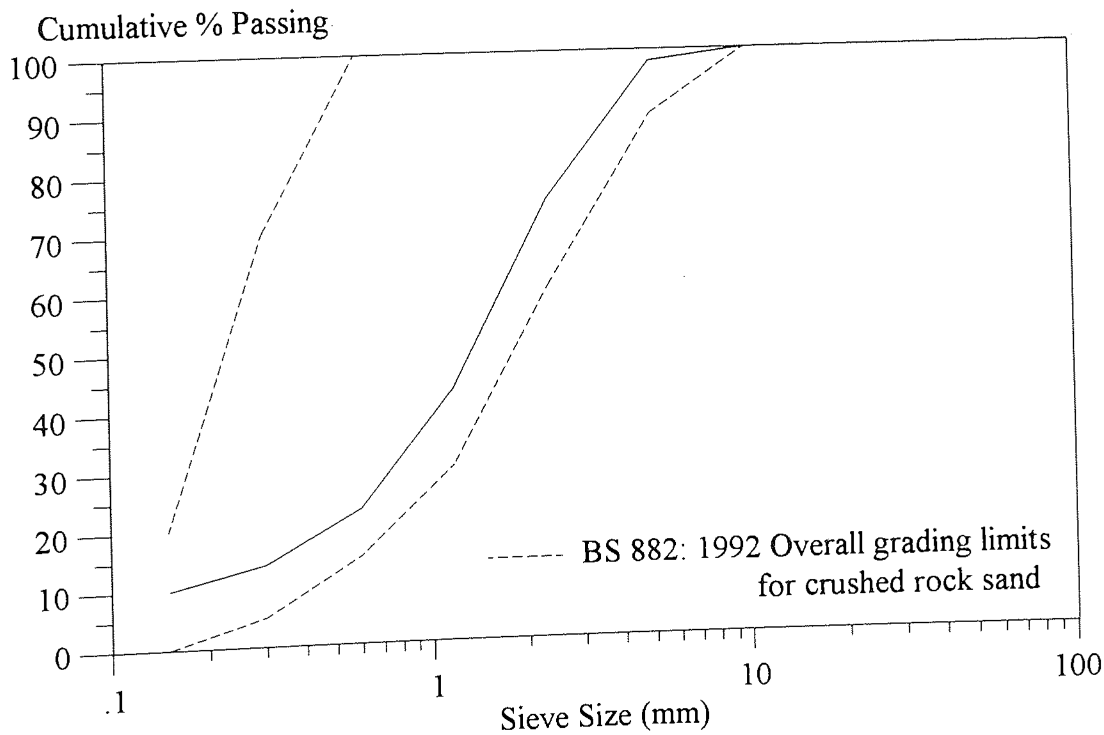

Figure B.8. Particle size distribution of sample C4F.

Sample Reference:- M5 and M5F

Quarry Details:- Whitwell Quarry
Southfield Lane
Whitwell
Worksop, Nottinghamshire

Grid Reference:- SK530753

Owner:- Redland Aggregates Ltd
Whitwell works, Southfield Lane
Whitwell, Nottinghamshire

Geological Horizon:- Lower Magnesian Limestone

Coarse Aggregate Details:- Supplied as 20-5 mm graded

Fine Aggregate Details:- M5F,supplied crushed, 5 mm down

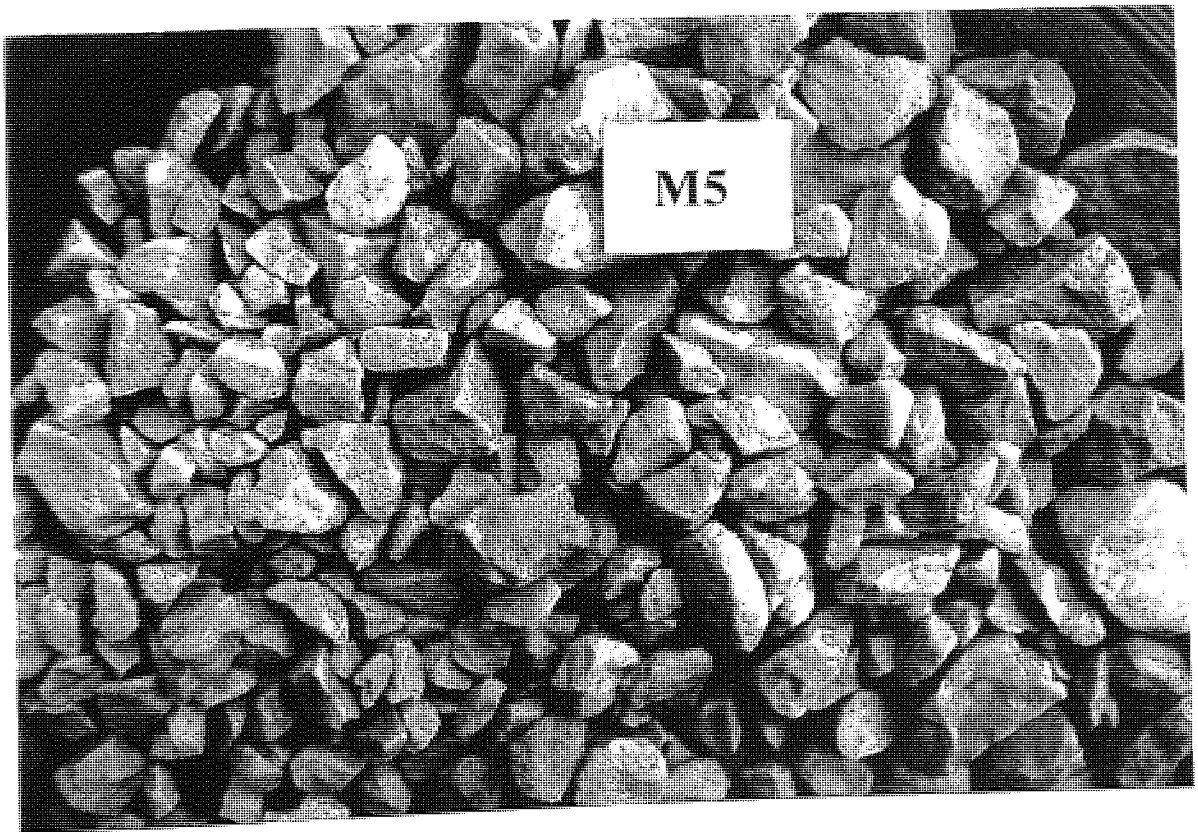

Plate B.5 A typical sample of aggregate M5.

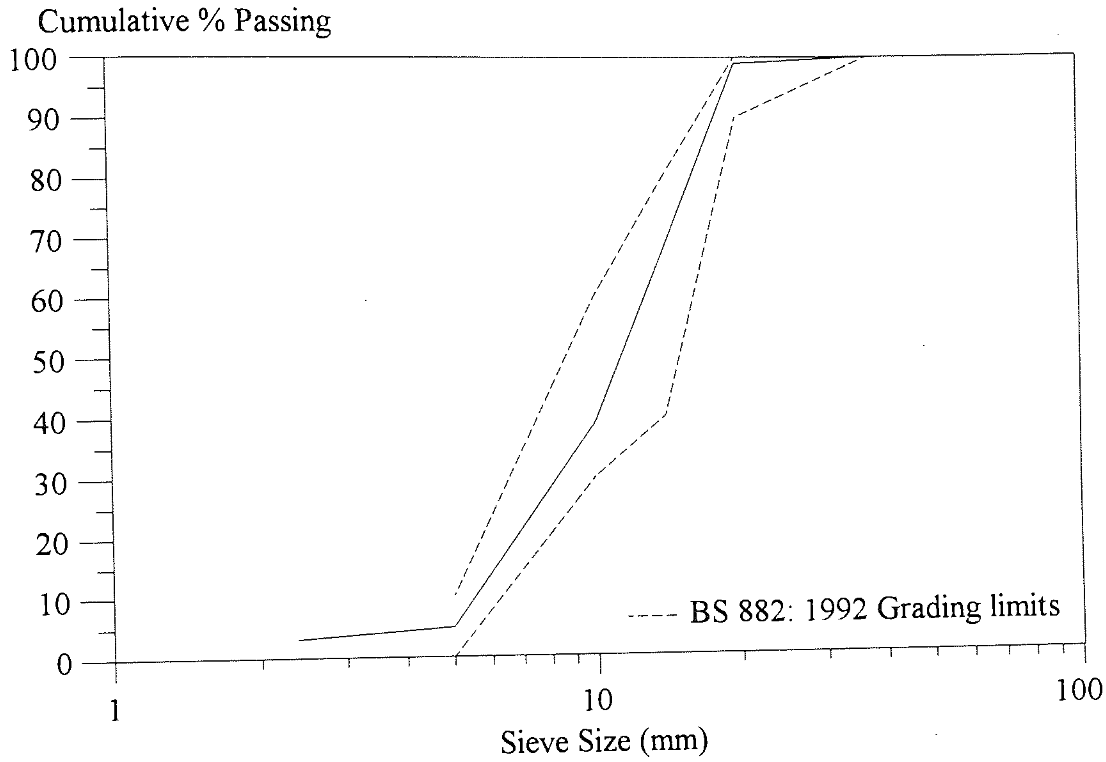

Figure B.9. Particle size distribution of sample M5.

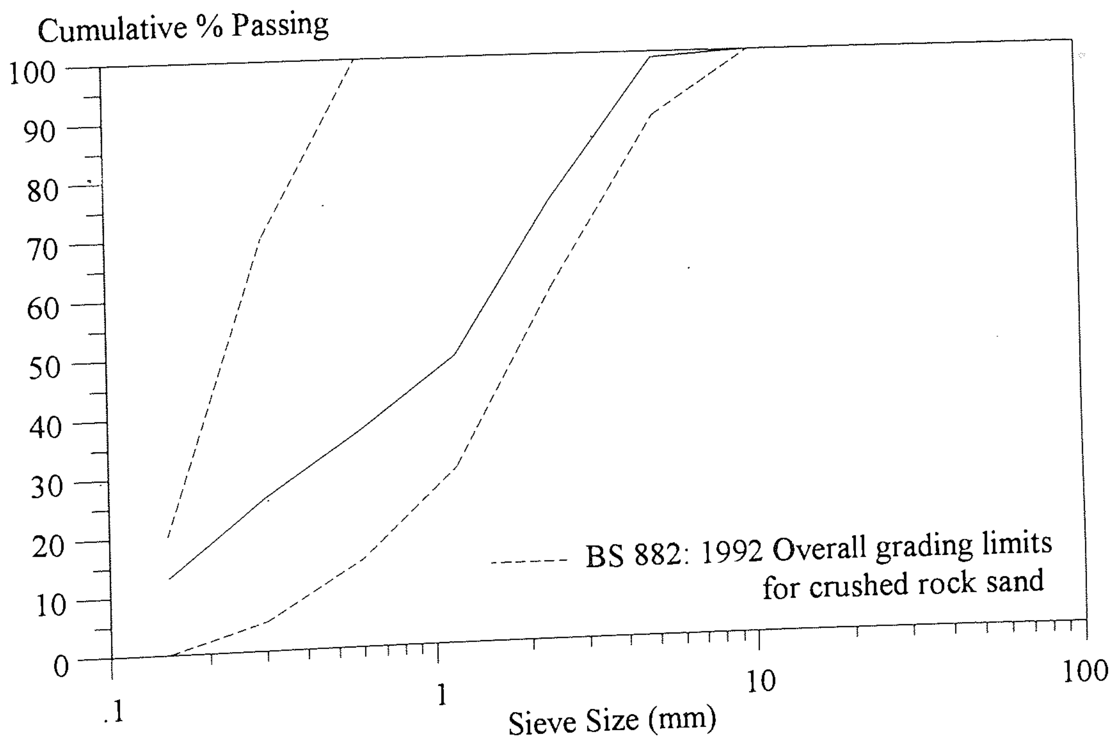

Figure B.10. Particle size distribution of sample M5F.

Sample Reference:- M6a, M6b and M6F

Quarry Details:- Cadeby works
Garden Lane, Cadeby
Conisborough
Doncaster, South Yorkshire

Grid Reference:- SE523005

Owner:- Redland Aggregates Ltd
Whitwell works, Southfield Lane
Whitwell, Nottinghamshire

Geological Horizon:- Lower Magnesian Limestone

Coarse Aggregate Details:- M6a, 20-10 mm and 10-5 mm crushed once
M6b, 20-10 mm and 10-5 mm crushed twice

Fine Aggregate Details:- M6F, supplied crushed, 5 mm down

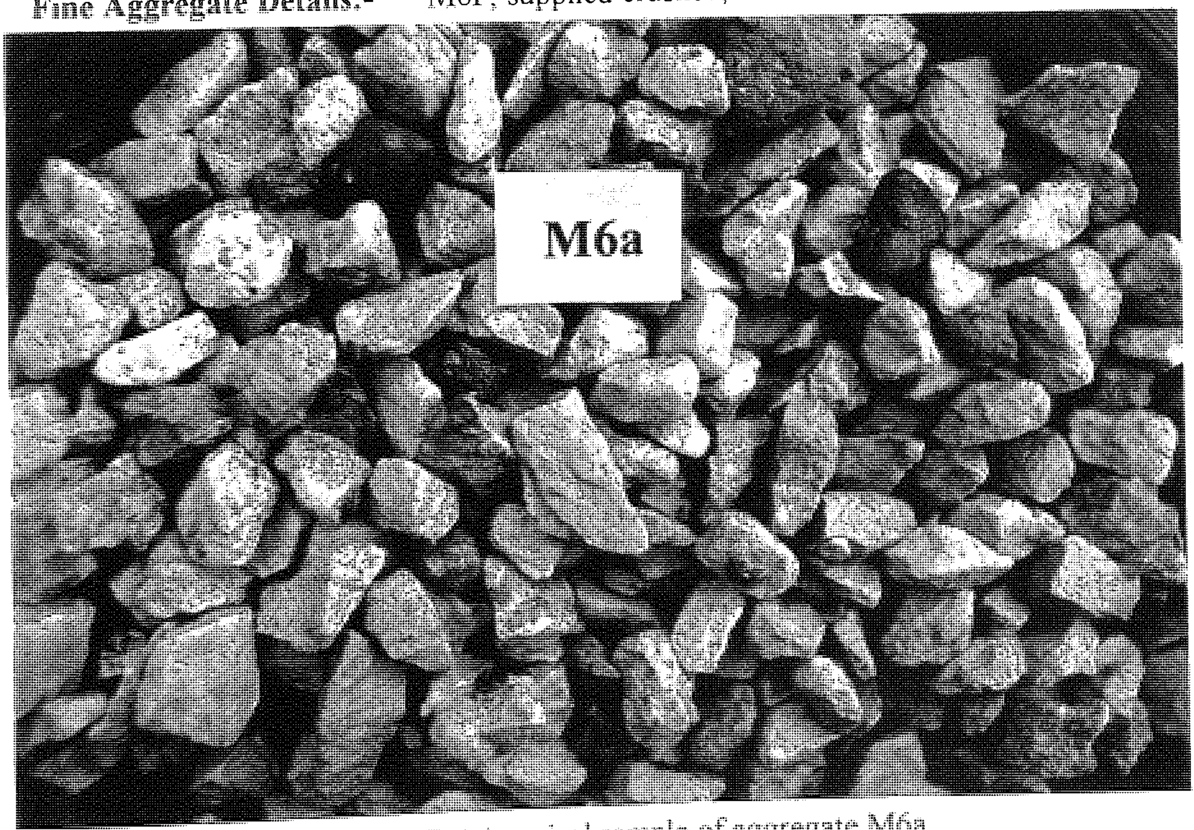

Plate B.6 A typical sample of aggregate M6a.

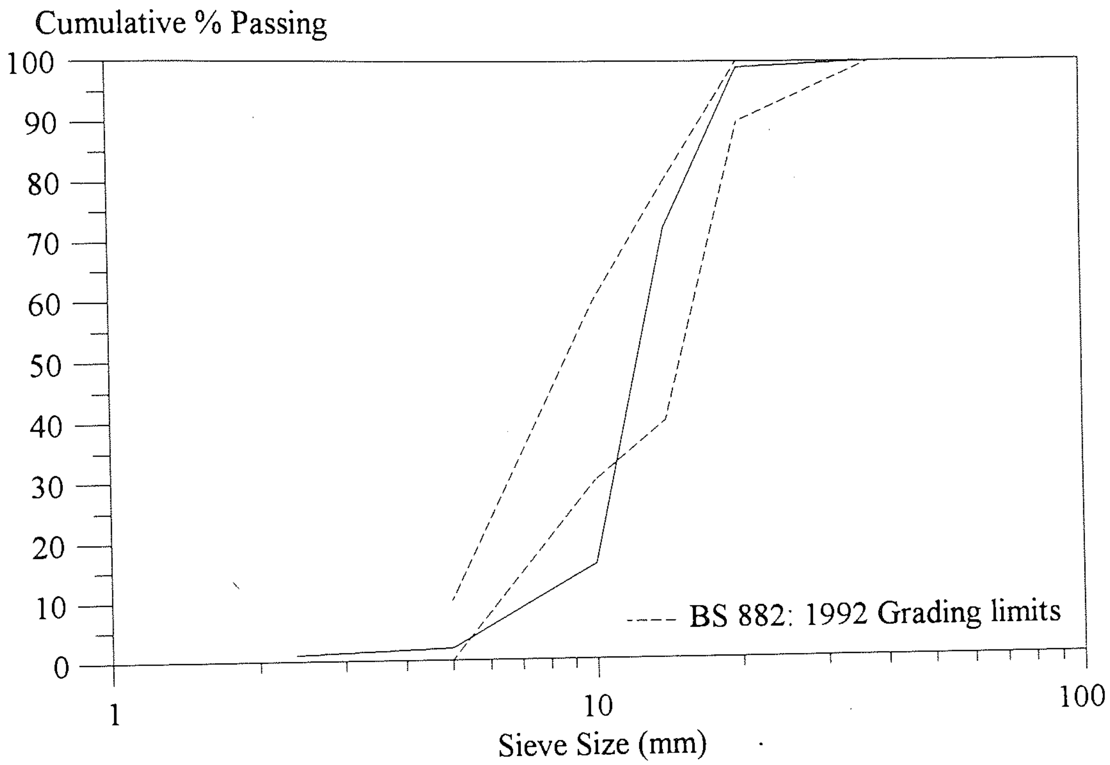

Figure B.11. Particle size distribution of sample M6a.

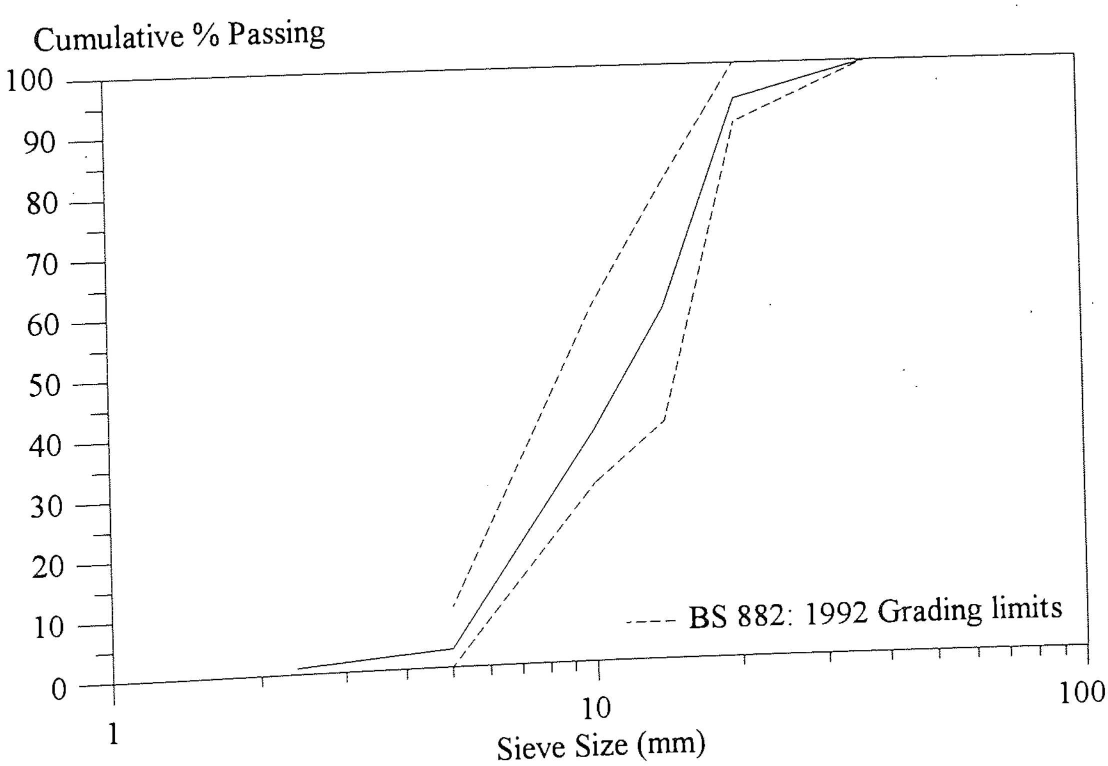

Figure B.12. Particle size distribution of sample M6b.

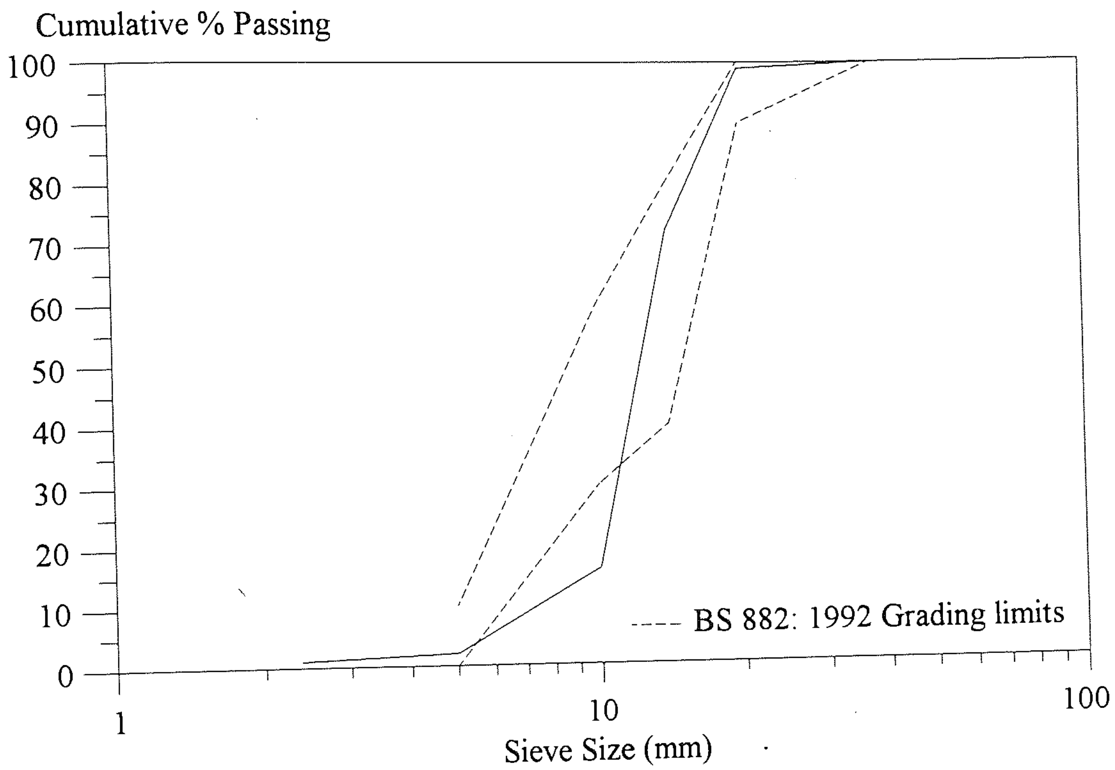

Figure B.11. Particle size distribution of sample M6a.

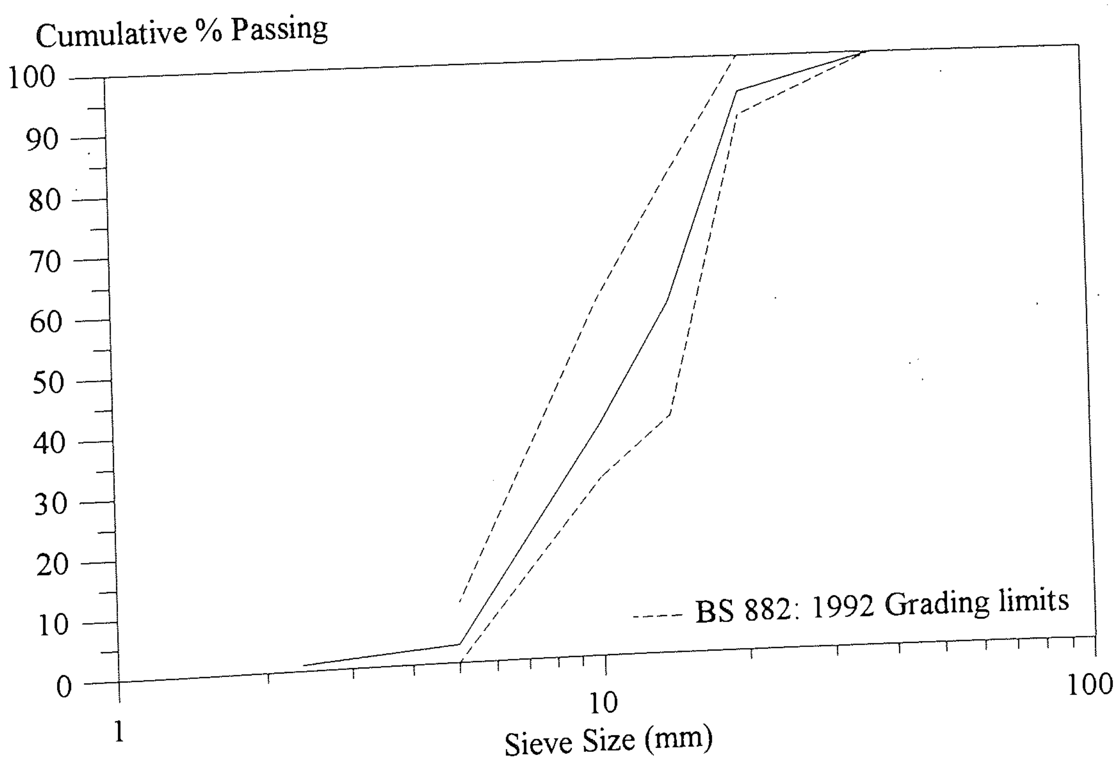

Figure B.12. Particle size distribution of sample M6b.

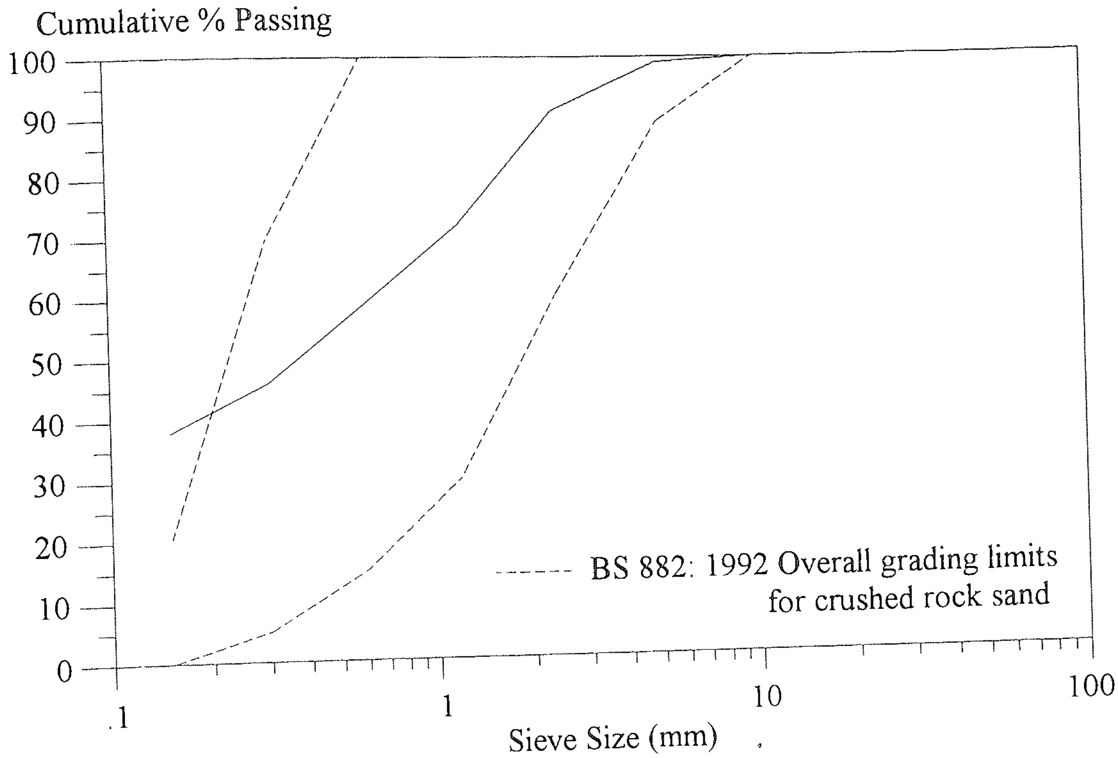

Figure B.13. Particle size distribution of sample M6F.

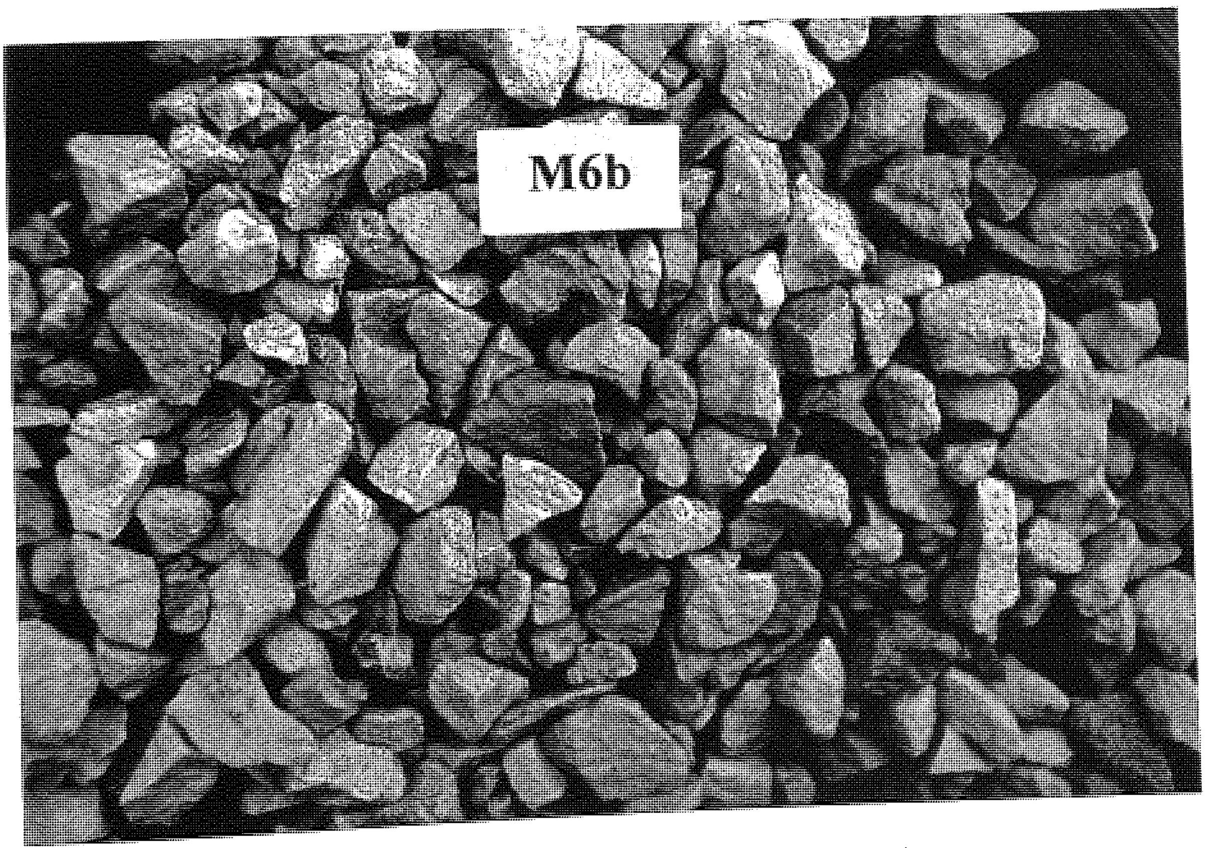

Plate B.7 A typical sample of aggregate M6b.

Sample Reference:-	M8 and M8F
Quarry Details:-	Spring Lodge Quarry Womersley Doncaster South Yorkshire
Grid Reference:-	SE522202
Owner:-	Tilcon Quarry Products Fell Bank, Birtley Chester-Le-Street, County Durham
Geological Horizon:-	Upper Magnesian Limestone
Coarse Aggregate Details:-	Supplied as 20-5 mm graded
Fine Aggregate Details:-	M8F, supplied as 5 mm down

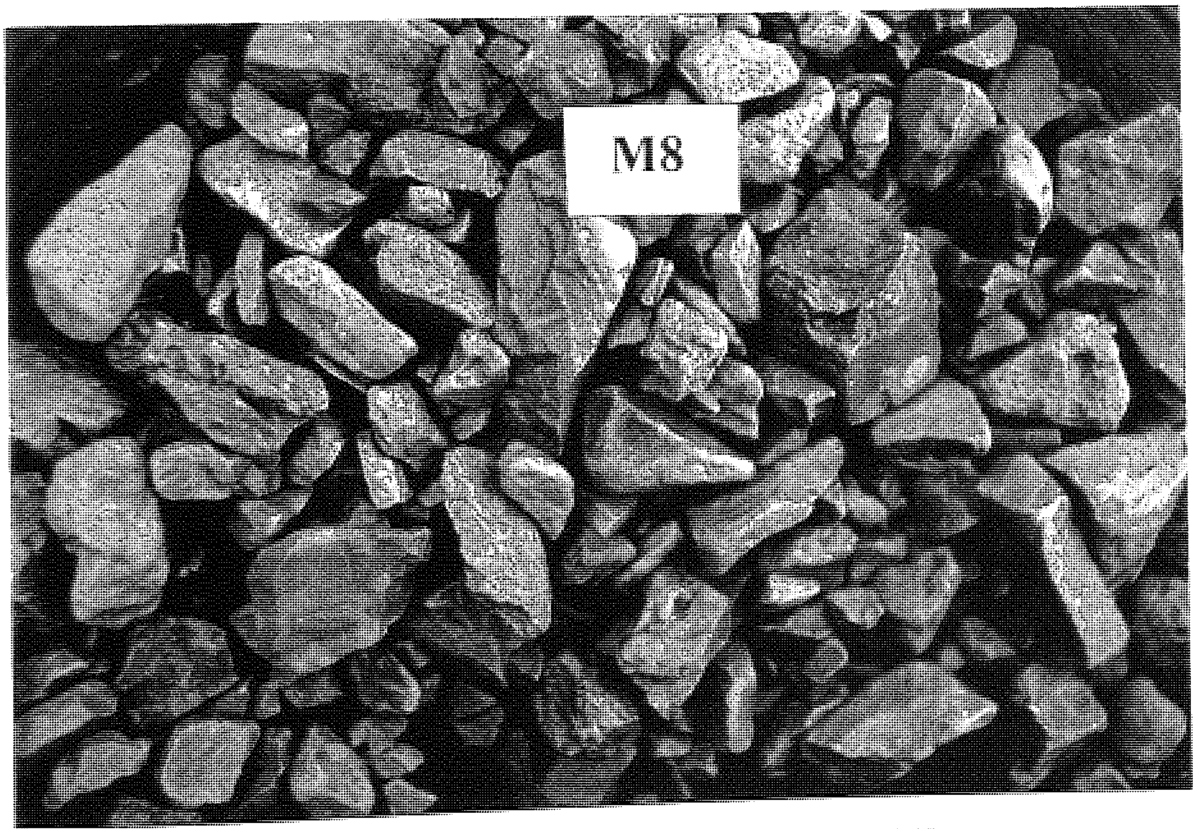

Plate B.8 A typical sample of aggregate M8.

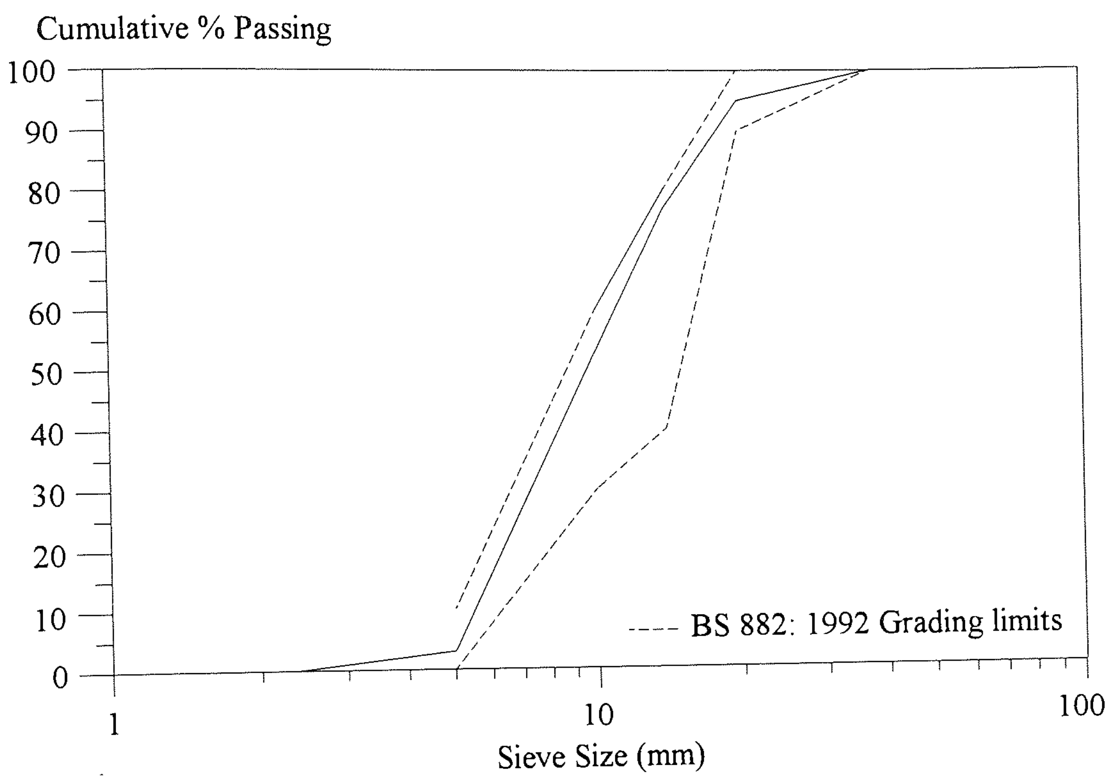

Figure B.14. Particle size distribution of sample M8.

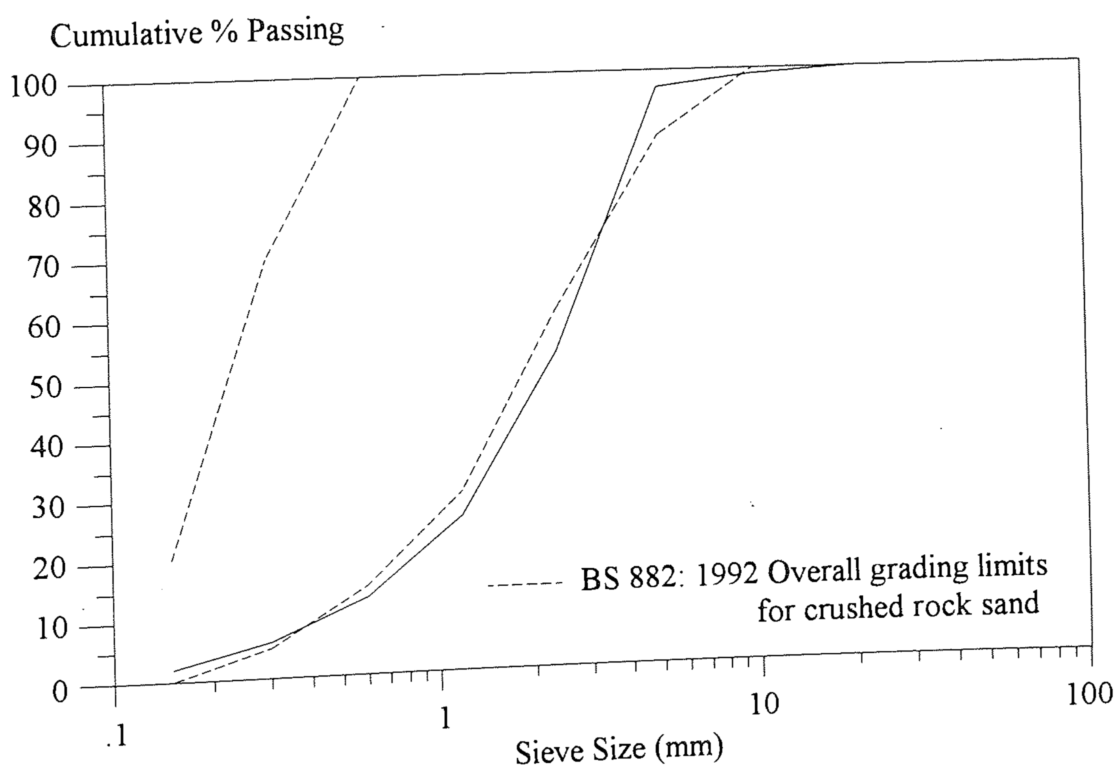

Figure B.15. Particle size distribution of sample M8F.

Sample Reference:-	J9 and J9F
Quarry Details:-	Town Quarry Ditchley Road Charlbury Oxfordshire
Grid Reference:-	SP364198
Owner:-	J. Curtis and Sons Ltd Thrupp Lane, Radley Abingdon, Oxfordshire
Geological Horizon:-	Clypeus Grit, Inferior Oolite
Coarse Aggregate Details:-	Supplied as 20 mm down
Fine Aggregate Details:-	J9F, supplied as 5 mm down

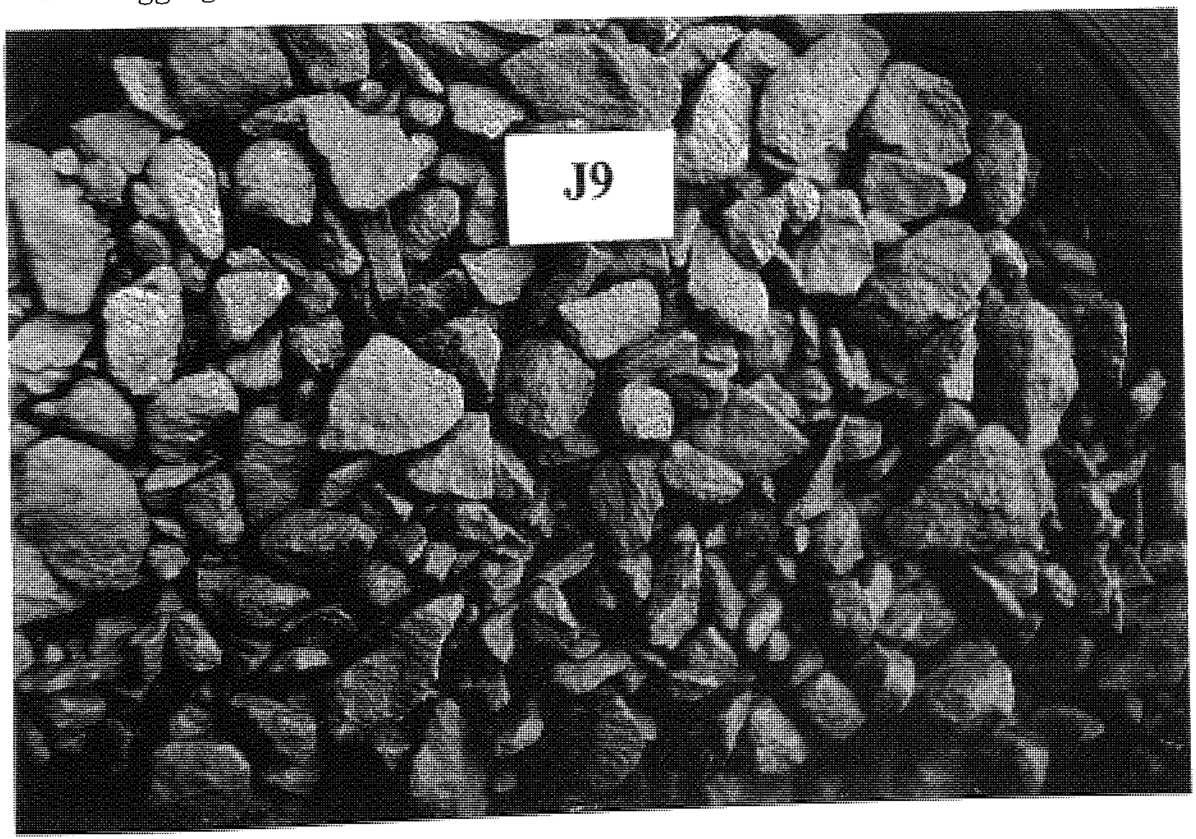

Plate B.9 A typical sample of aggregate J9.

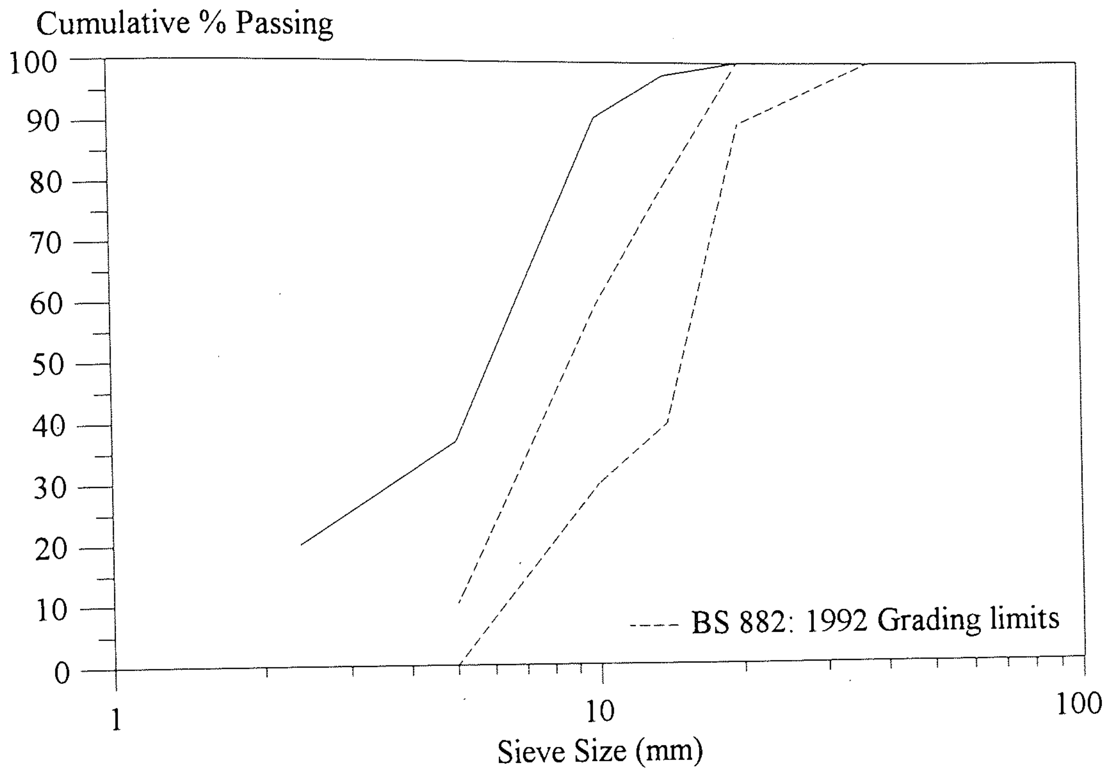

Figure B.16. Particle size distribution of sample J9.

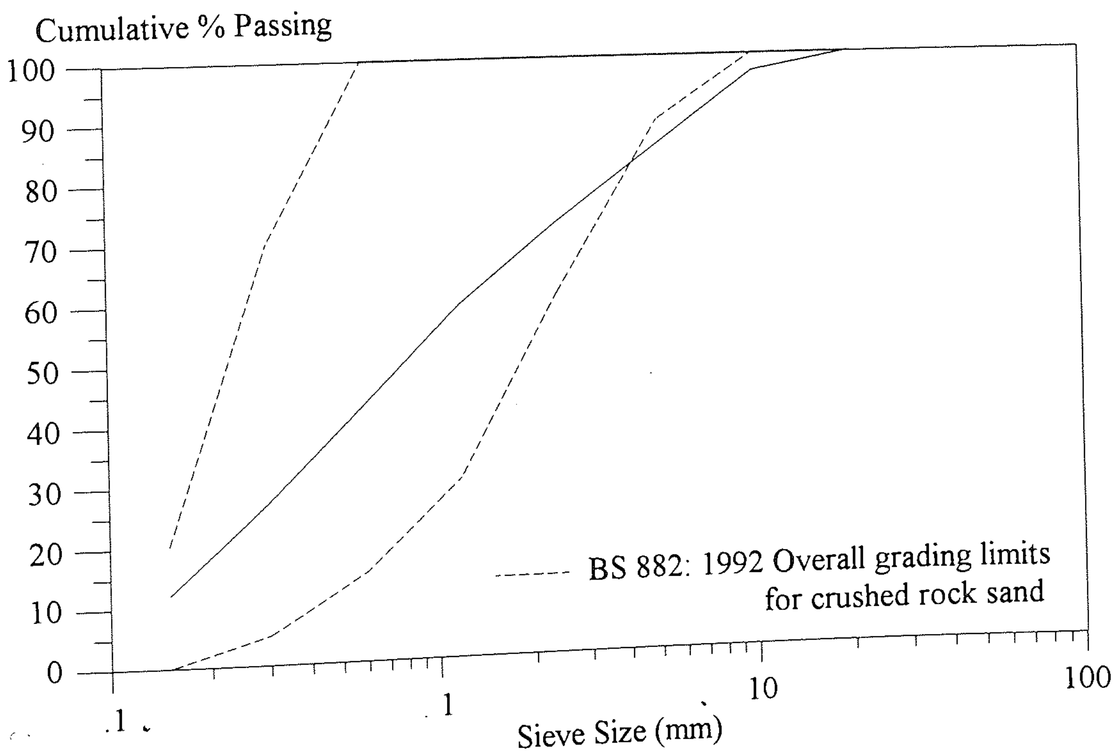

Figure B.17. Particle size distribution of sample J9F.

Sample Reference:- J10 and J10F

Quarry Details:- Swellwold Quarry
Nr. Temple Guiting
Cheltenham
Gloucestershire

Grid Reference:- SP149270

Owner:- Cotswold Stone Quarries Ltd
Brockhill Quarry, Naunton
Cheltenham, Gloucestershire

Geological Horizon:- Chipping Norton Limestone

Coarse Aggregate Details:- Supplied as 20-14 mm and 14-4 mm

Fine Aggregate Details:- J10F, supplied as 4 mm down

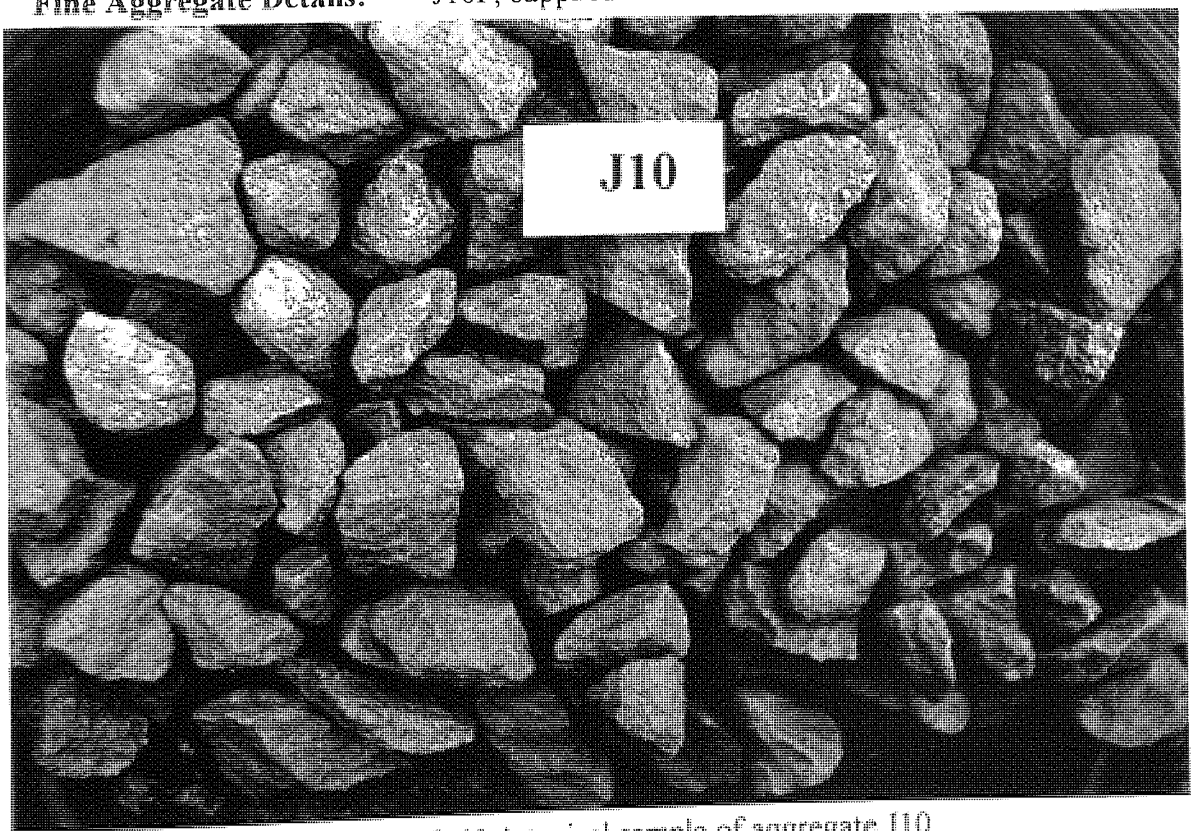

Plate B.10 A typical sample of aggregate J10.

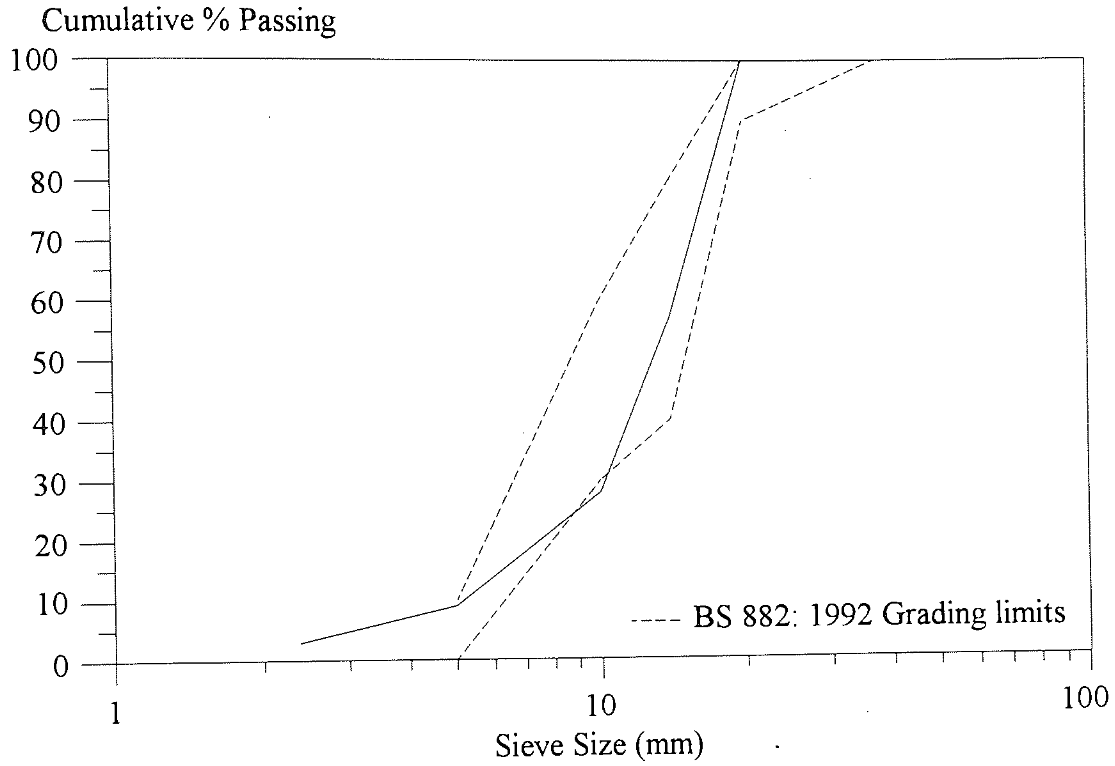

Figure B.18. Particle size distribution of sample J10.

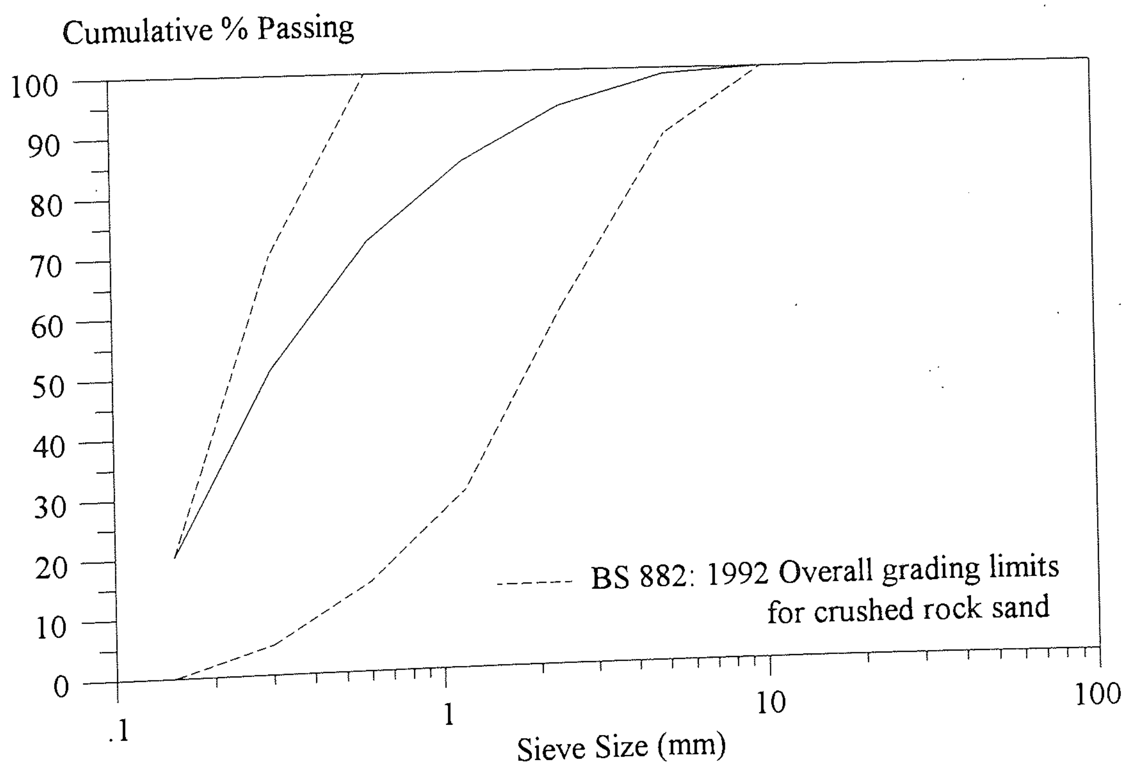

Figure B.19. Particle size distribution of sample J10F.

Sample Reference:- J11 and J11F

Quarry Details:- Huntsman Quarry
Naunton
Cheltenham
Gloucestershire

Grid Reference:- SP124254

Owner:- Huntsmans Quarries Ltd
The Old School, Naunton
Cheltenham, Gloucestershire

Geological Horizon:- Stonesfield Slate, Great Oolite

Coarse Aggregate Details:- Supplied as 20-5 mm graded

Fine Aggregate Details:- J11F, supplied crushed, 5 mm down

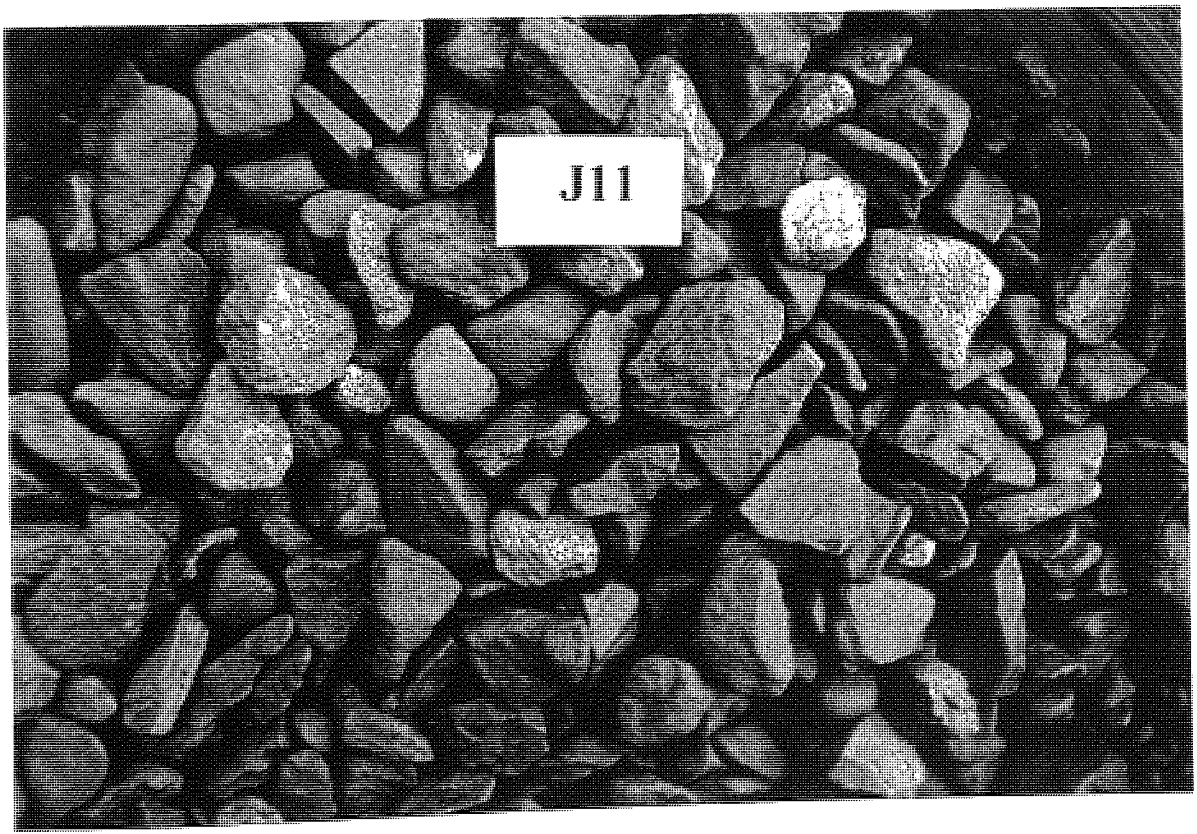

Plate B.11 A typical sample of aggregate J11.

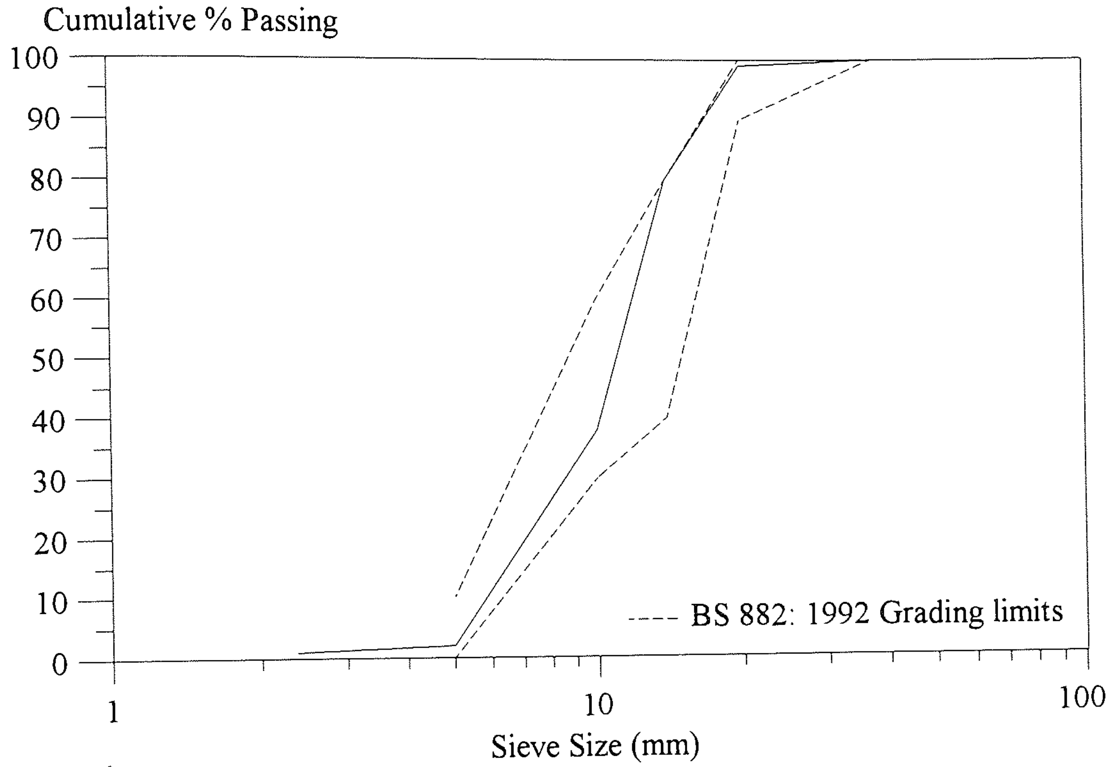

Figure B.20. Particle size distribution of sample J11.

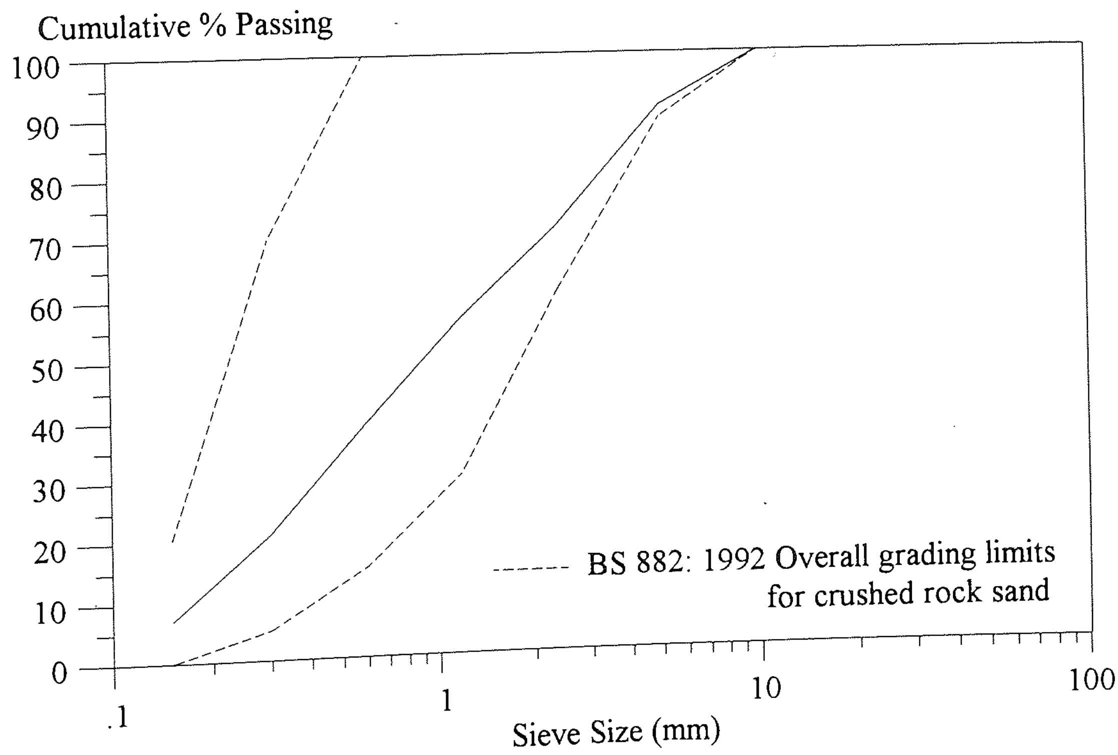

Figure B.21. Particle size distribution of sample J11F.

Sample Reference:-	J12 and J12F
Quarry Details:-	Daglingworth Quarry Gloucester Road Cirencester Gloucestershire
Grid Reference:-	SP001060
Owner:-	ARC Southern Ltd Stoneleigh House Frome, Somerset
Geological Horizon:-	White Limestone, Great Oolite
Coarse Aggregate Details:-	Supplied as 20-5 mm graded
Fine Aggregate Details:-	J12F, supplied crushed, 5 mm down

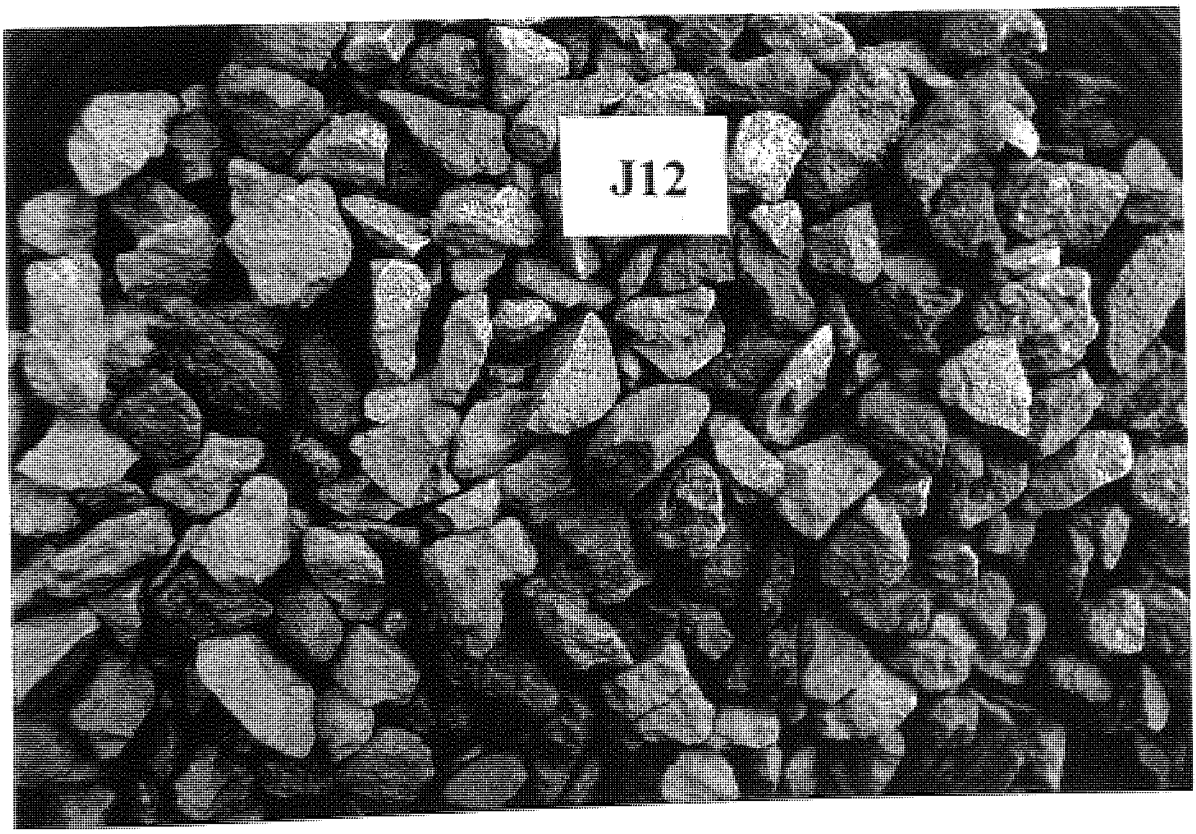

Plate B.12 A typical sample of aggregate J12.

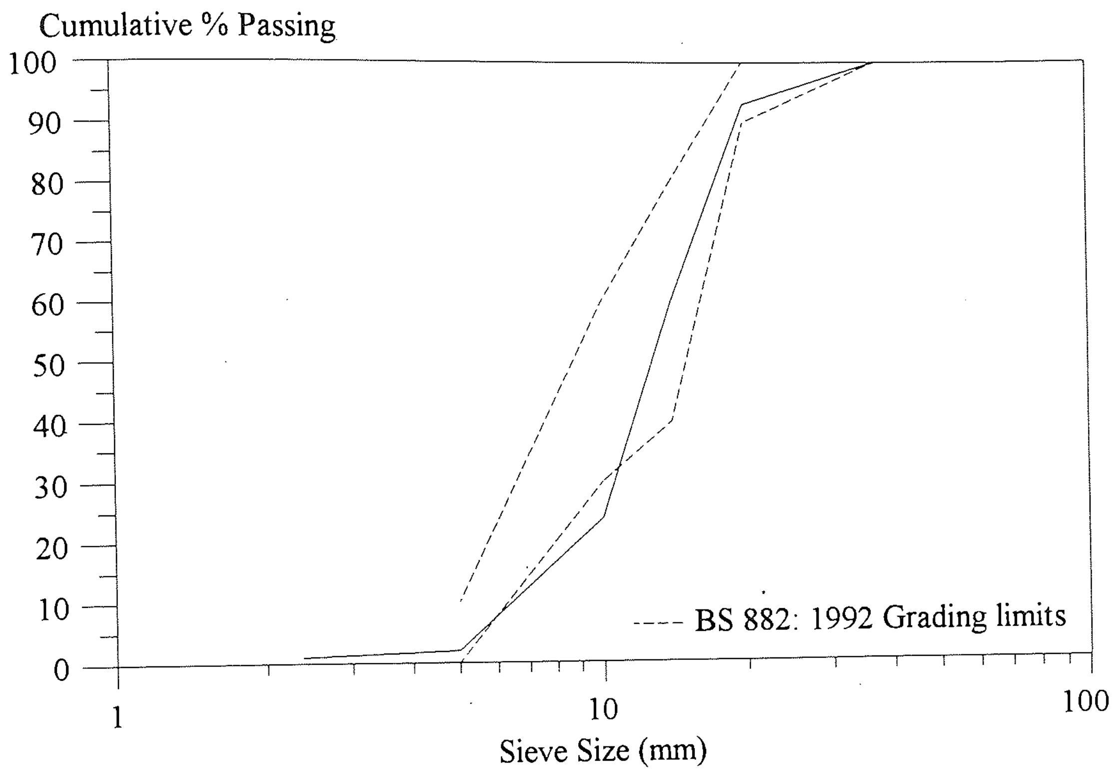

Figure B.22. Particle size distribution of sample J12.

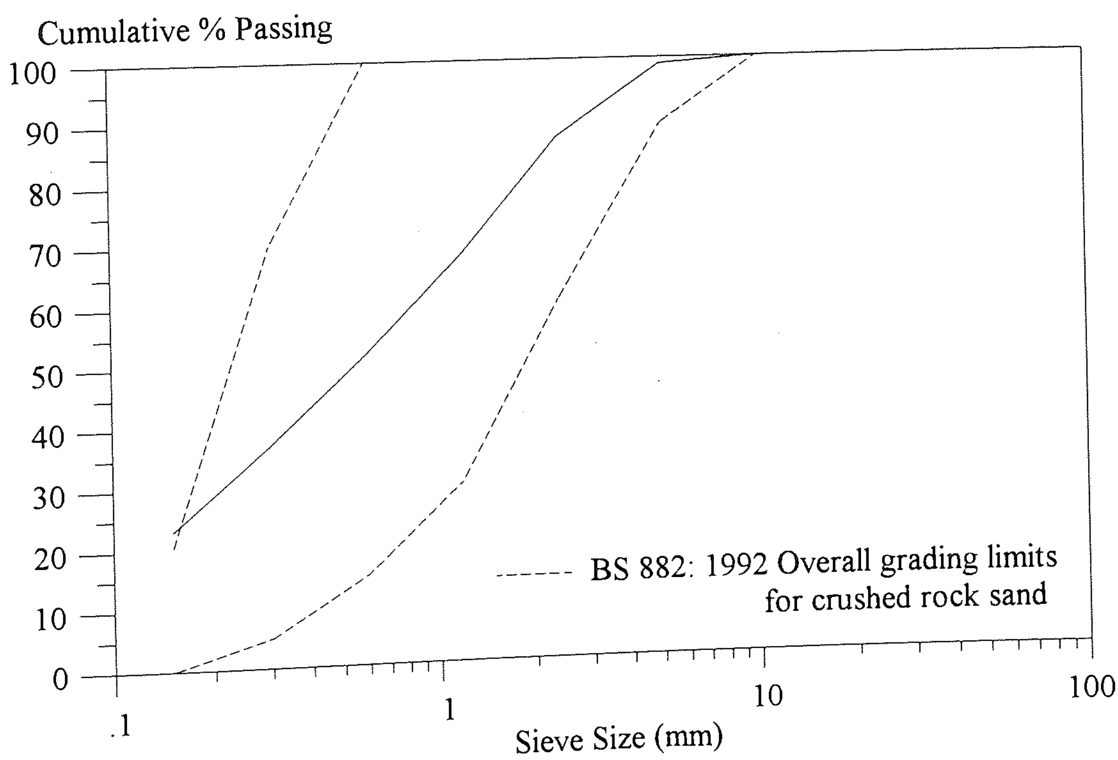

Figure B.23. Particle size distribution of sample J12F.

Sample Reference:- Coarse and Fine aggregate control (CS and CSF)

Quarry Details:- Weeford Quarry
Canwell
Sutton Coldfield
Staffordshire

Grid Reference:- SK133020

Owner:- ARC Central Ltd
Ashby Road East, Shepshed
Loughborough, Leicestershire

Geological Horizon:- Bunter Pebble Beds, Permo-Trias

Coarse Aggregate Details:- Supplied as 20-10 mm and 10-5 mm graded, and combined in the proportion 2:1

Fine Aggregate Details:- Supplied as 5 mm down

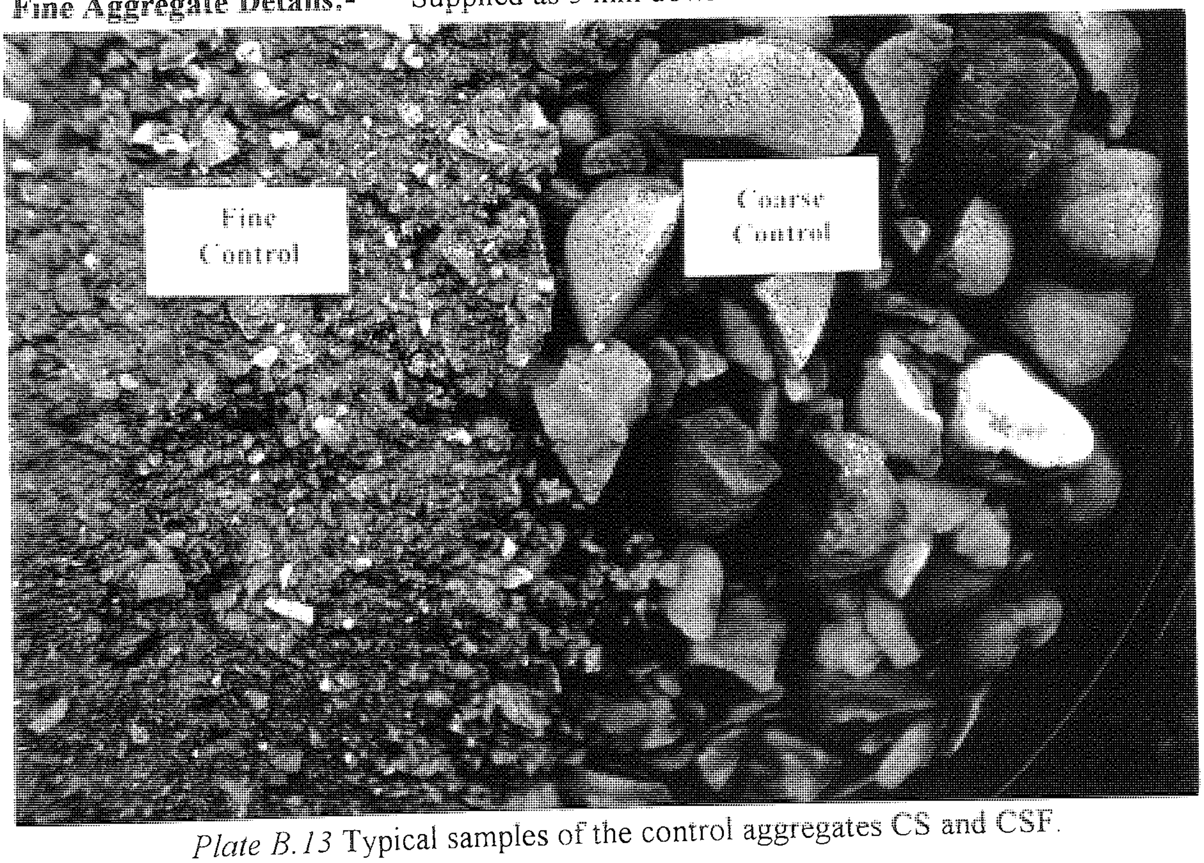

Plate B.13 Typical samples of the control aggregates CS and CSF.

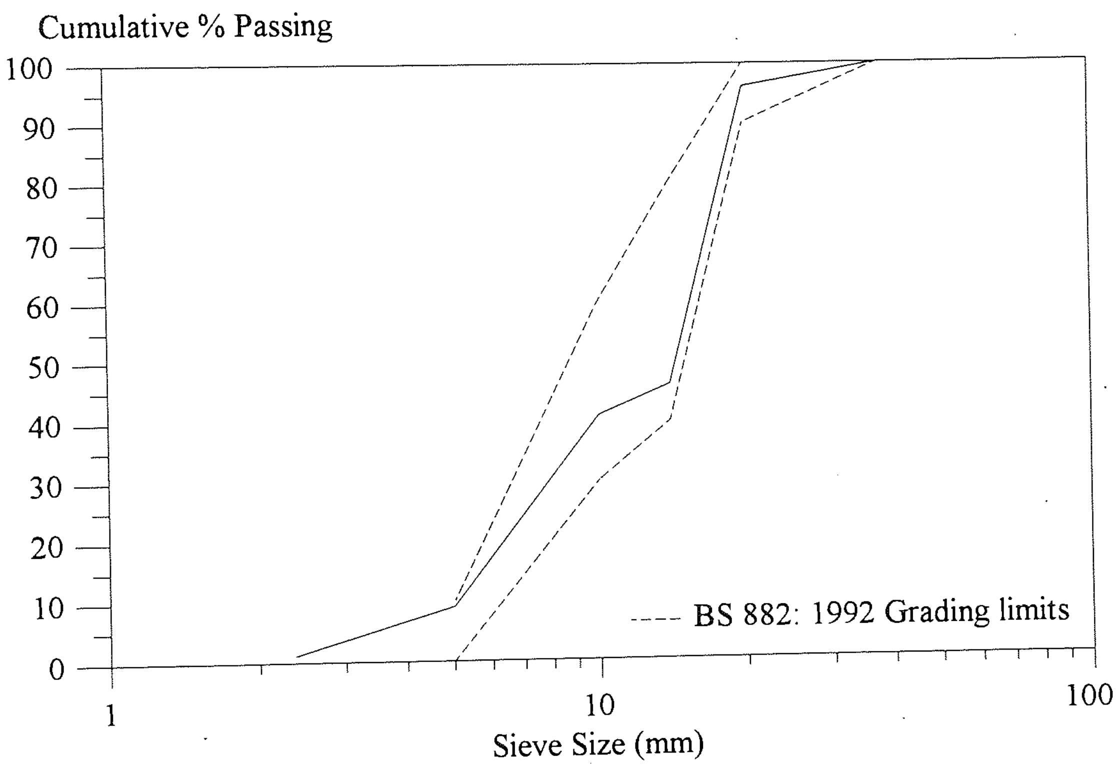

Figure B.24. Particle size distribution of the coarse aggregate control.

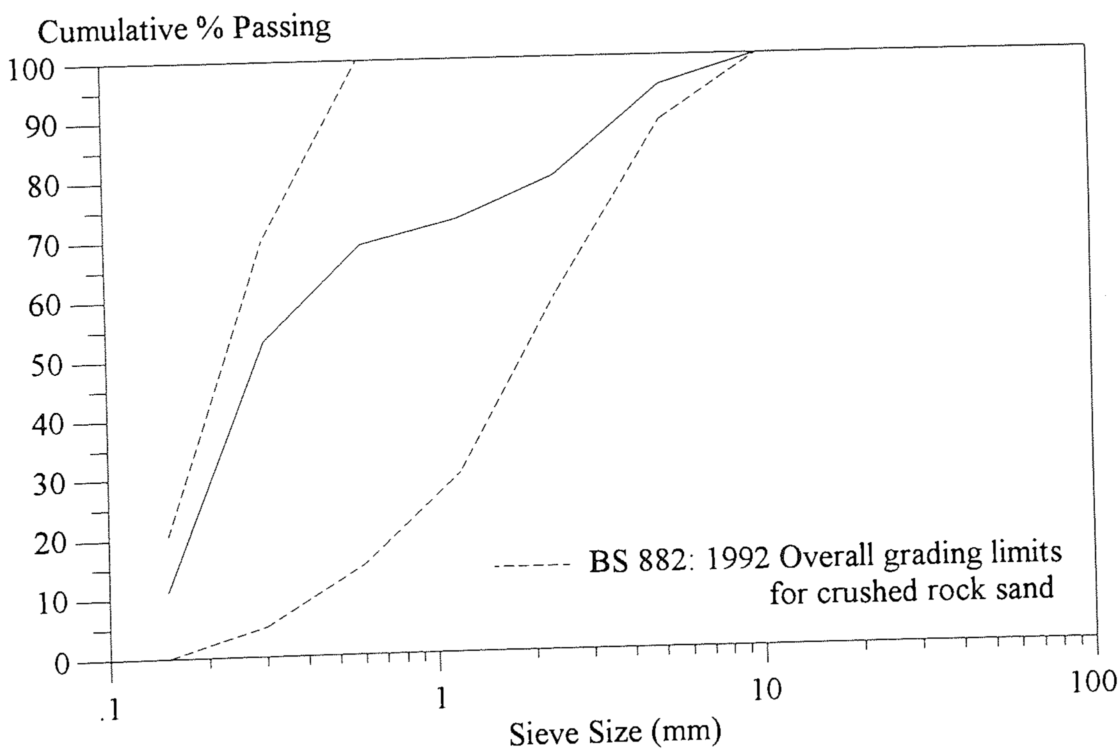

Figure B.25. Particle size distribution of the fine aggregate control. For natural sands the upper limit on material passing 150 μm is reduced from 20 % to 15 %.

Appendix C

Abrasion Test Results for Coarse Aggregate Mixes

Specimen	C1S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	-	-	-
2	-	-	-
3	0.01	0.01	0.02
4	0.02	0.18	0.18
5	0.16	0.16	0.23
6	0.15	0.21	0.26
7	0.07	0.13	0.26
8	0.02	0.04	0.07
9	0.07	0.24	0.37
10	0.17	0.27	0.32
11	0.12	0.13	0.15
12	0.05	0.04	0.04
13	0.06	0.07	0.08
14	0.04	0.10	0.18
15	0.04	0.19	0.35
16	0.14	0.27	0.33
17	0.12	0.24	0.38
18	0.18	0.25	0.34
19	0.14	0.32	0.45
20	0.12	0.20	0.29
21	0	0.05	0.07
22	0.01	0.02	0.06
23	0.02	0.03	0.03
24	0.07	0.14	0.30
Mean (x_{ave})	0.08	0.15	0.22
SD (σ)	0.06	0.09	0.13
Coeff. of Var. (%)	75	60	59
$\frac{X_{max} - X_{ave}}{\sigma}$	1.7	1.9	1.8
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.6	1.5
Corrected Mean	**0.08**	**0.15**	**0.22**
Corrected SD	**0.06**	**0.09**	**0.13**

Table C.1. 3-body abrasion results for specimen C1S1.

Specimen	C2S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0	0	0.02
2	-	-	-
3	0.09	0.39	0.49
4	0.30	0.30	0.29
5	0.28	0.30	0.31
6	0.34	0.69	1.04
7	0.63	1.07	1.35
8	0.23	0.40	0.80
9	0.48	0.65	0.75
10	0.19	0.38	0.50
11	0.08	0.17	0.45
12	0.24	0.40	0.48
13	0.05	0.08	0.12
14	0.14	0.17	0.21
15	0.03	0.14	0.26
16	0.29	0.77	0.93
17	0.18	0.28	0.45
18	-	-	-
19	0	0.09	0.28
20	0.26	0.38	0.45
21	0.16	0.37	0.50
22	0.17	0.29	0.48
23	0.08	0.22	0.42
24	0.21	0.34	0.37
Mean (X_{ave})	0.20	0.36	0.50
SD (σ)	0.15	0.25	0.31
Coeff. of Var. (%)	75	69	62
$\frac{X_{max} - X_{ave}}{\sigma}$	2.9	2.8	2.7
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.4	1.6
Corrected Mean	**0.19**	**0.33**	**0.47**
Corrected SD	**0.12**	**0.20**	**0.25**

Table C.2. 3-body abrasion results for specimen C2S1.

Specimen	C3S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.01	0.11	0.18
2	0	0.09	0.21
3	0.01	0.03	0.08
4	0.03	0.03	0.03
5	0.01	0.22	0.39
6	0.03	0.04	0.14
7	0.05	0.59	0.97
8	0.22	0.51	0.69
9	0.15	0.36	0.62
10	0.14	0.49	0.84
11	0.03	0.20	0.60
12	0.08	0.20	0.26
13	0.04	0.15	0.32
14	0	0.02	0.04
15	0.01	0.01	0.01
16	0.08	0.24	0.43
17	0.05	0.16	0.37
18	0.09	0.18	0.43
19	0.01	0.02	0.06
20	0	0	0.02
21	-	-	-
22	0.04	0.12	0.43
23	0.05	0.13	0.33
24	0.08	0.30	0.53
Mean (x_{ave})	0.05	0.18	0.35
SD (σ)	0.06	0.17	0.27
Coeff. of Var. (%)	120	94	77
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.4	2.3
$\frac{X_{ave} - X_{min}}{\sigma}$	0.8	1.1	1.3
Corrected Mean	**0.05**	**0.16**	**0.32**
Corrected SD	**0.04**	**0.15**	**0.24**

Table C.4. 3-body abrasion results for specimen C3S1.

Specimen	C4S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0	0.01	0.08
2	0.03	0.06	0.08
3	0	0.05	0.08
4	0.10	0.16	0.31
5	0.04	0.08	0.21
6	0.05	0.13	0.30
7	0.06	0.09	0.17
8	0.05	0.09	0.15
9	-	-	-
10	0.09	0.29	0.58
11	0.04	0.14	0.19
12	0.05	0.10	0.27
13	0.02	0.12	0.37
14	0.05	0.08	0.11
15	-	-	-
16	-	-	-
17	0.03	0.05	0.14
18	0.10	0.15	0.16
19	0.10	0.15	0.15
20	0.01	0.01	0.02
21	0.11	0.35	0.50
22	0.16	0.40	0.50
23	0.09	0.18	0.22
24	0	0.02	0.05
Mean (x_{ave})	0.06	0.13	0.22
SD (σ)	0.04	0.10	0.16
Coeff. of Var. (%)	67	77	73
$\frac{X_{max} - X_{ave}}{\sigma}$	2.5	2.7	2.3
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	1.2	1.3
Corrected Mean	**0.05**	**0.10**	**0.20**
Corrected SD	**0.04**	**0.07**	**0.14**

Table C.4. 3-body abrasion results for specimen C4S1.

Specimen	M5S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.02	0.02	0.02
2	0.03	0.08	0.18
3	0.12	0.26	0.48
4	0.06	0.15	0.28
5	0.07	0.14	0.40
6	0.10	0.18	0.34
7	0.05	0.06	0.09
8	0	0.02	0.05
9	0.02	0.03	0.03
10	0.01	0.01	0.01
11	-	-	-
12	0.01	0.01	0.02
13	0.05	0.07	0.07
14	0	0.01	0.04
15	-	-	-
16	0.05	0.07	0.14
17	0	0	0.05
18	-	-	-
19	0.03	0.03	0.09
20	-	-	-
21	-	-	-
22	0.02	0.06	0.18
23	0.16	0.28	0.41
24	0.06	0.09	0.20
Mean (x_{ave})	0.05	0.08	0.16
SD (σ)	0.04	0.08	0.15
Coeff. of Var. (%)	80	100	94
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.5	2.1
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.0	1.0
Corrected Mean	**0.04**	**0.06**	**0.14**
Corrected SD	**0.03**	**0.05**	**0.13**

Table C.5. 3-body abrasion results for specimen M5S1.

Specimen	M6aS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0	0.01	0.02
2	0.03	0.05	0.06
3	0.11	0.14	0.15
4	0	0.02	0.03
5	0.01	0.02	0.03
6	-	-	-
7	0.05	0.10	0.12
8	0.07	0.09	0.11
9	0.03	0.03	0.03
10	0.06	0.06	0.07
11	-	-	-
12	0.01	0.01	0.01
13	0.03	0.03	0.03
14	0	0	0.03
15	0	0.01	0.01
16	0	0	0
17	0.06	0.06	0.10
18	0.02	0.04	0.07
19	-	-	-
20	-	-	-
21	0.02	0.05	0.07
22	0.05	0.05	0.07
23	0.08	0.09	0.11
24	0.01	0.02	0.03
Mean (x_{ave})	0.03	0.04	0.06
SD (σ)	0.03	0.04	0.04
Coeff. of Var. (%)	100	100	67
$\frac{X_{max} - X_{ave}}{\sigma}$	2.7	2.5	2.3
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.0	1.5
Corrected Mean	**0.03**	**0.04**	**0.05**
Corrected SD	**0.03**	**0.03**	**0.04**

Table C.6. 3-body abrasion results for specimen M6aS1.

Specimen	M6bS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.07	0.10	0.12
2	0.22	0.30	0.38
3	0.14	0.14	0.24
4	0.07	0.08	0.08
5	0.19	0.18	0.18
6	0.03	0.06	0.06
7	0.17	0.18	0.24
8	0.14	0.14	0.14
9	0.14	0.14	0.18
10	0.04	0.09	0.15
11	0.18	0.35	0.50
12	0.21	0.24	0.38
13	0.03	0.08	0.12
14	0.01	0.01	0.03
15	0.05	0.10	0.20
16	0.06	0.11	0.13
17	0.11	0.16	0.28
18	0.12	0.21	0.26
19	0.17	0.18	0.25
20	0.02	0.07	0.09
21	0.02	0.06	0.06
22	0.13	0.15	0.20
23	0.10	0.12	0.17
24	0.02	0.06	0.11
Mean (x_{ave})	0.10	0.14	0.19
SD (σ)	0.07	0.08	0.11
Coeff. of Var. (%)	70	57	58
$\frac{X_{max} - X_{ave}}{\sigma}$	1.7	2.6	2.8
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.6	1.5
Corrected Mean	**0.10**	**0.12**	**0.18**
Corrected SD	**0.07**	**0.06**	**0.09**

Table C.7. 3-body abrasion results for specimen M6bS1.

Specimen	M8S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.13	0.13	0.16
2	0.01	0.04	0.06
3	0.13	0.19	0.24
4	0.10	0.26	0.36
5	0.08	0.12	0.12
6	0.11	0.11	0.11
7	0.02	0.03	0.06
8	0.22	0.25	0.26
9	0.15	0.20	0.25
10	-	-	-
11	0	0	0
12	0.20	0.32	0.57
13	0.27	0.37	0.43
14	0.11	0.14	0.14
15	0.08	0.07	0.11
16	0.12	0.12	0.23
17	0.04	0.08	0.11
18	0.23	0.28	0.35
19	0.11	0.15	0.27
20	0.05	0.06	0.15
21	0.04	0.15	0.18
22	0.20	0.31	0.40
23	0.03	0.05	0.04
24	0.12	0.11	0.13
Mean (x_{ave})	0.11	0.15	0.21
SD (σ)	0.07	0.10	0.14
Coeff. of Var. (%)	64	67	67
$\frac{x_{max} - x_{ave}}{\sigma}$	2.3	2.2	2.6
$\frac{x_{ave} - x_{min}}{\sigma}$	1.6	1.5	1.5
Corrected Mean	**0.10**	**0.14**	**0.19**
Corrected SD	**0.07**	**0.09**	**0.12**

Table C.8. 3-body abrasion results for specimen M8S1.

Specimen	J9S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.07	0.19	0.79
2	0.09	0.46	0.66
3	0.34	0.53	0.53
4	-	-	-
5	0	0.03	0.13
6	0.18	0.28	0.87
7	0.50	0.85	0.98
8	0.08	0.12	0.60
9	0.15	0.53	0.70
10	0.11	0.14	0.20
11	0.05	0.09	0.28
12	0.44	0.82	0.98
13	0.16	0.22	0.78
14	0	0.02	0.02
15	-	-	-
16	0.21	0.63	0.84
17	0.09	0.44	0.75
18	0.26	0.48	0.62
19	0.23	0.23	0.34
20	-	-	-
21	-	-	-
22	0.36	0.71	0.83
23	0.24	0.41	0.75
24	0.03	0.06	0.17
Mean (x_{ave})	0.18	0.36	0.59
SD (σ)	0.14	0.26	0.30
Coeff. of Var. (%)	78	72	51
$\frac{x_{max} - x_{ave}}{\sigma}$	2.3	1.9	1.3
$\frac{x_{ave} - x_{min}}{\sigma}$	1.3	1.3	1.9
Corrected Mean	**0.16**	**0.36**	**0.59**
Corrected SD	**0.13**	**0.26**	**0.30**

Table C.9. 3-body abrasion results for specimen J9S1.

Specimen	J10S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.08	0.10	0.20
2	0.13	0.16	0.35
3	0.12	0.18	0.26
4	0.05	0.10	0.21
5	0.05	0.10	0.10
6	0.07	0.09	0.14
7	0.13	0.17	0.26
8	0.16	0.21	0.27
9	0.03	0.06	0.08
10	0.01	0.01	0.05
11	0.06	0.10	0.14
12	0.11	0.16	0.22
13	0.04	0.06	0.09
14	0.01	0.01	0.07
15	0.02	0.05	0.08
16	0.02	0.03	0.05
17	0.04	0.06	0.08
18	0.09	0.14	0.22
19	0.07	0.10	0.13
20	0.06	0.07	0.13
21	0.02	0.05	0.06
22	0.04	0.06	0.06
23	0.04	0.06	0.09
24	0.08	0.14	0.17
Mean (x_{ave})	0.06	0.09	0.15
SD (σ)	0.04	0.05	0.08
Coeff. of Var. (%)	67	56	53
$\frac{x_{max} - x_{ave}}{\sigma}$	2.5	2.4	2.5
$\frac{x_{ave} - x_{min}}{\sigma}$	1.3	1.6	1.3
Corrected Mean	**0.06**	**0.09**	**0.14**
Corrected SD	**0.04**	**0.05**	**0.07**

Table C.10. 3-body abrasion results for specimen J10S1.

Specimen	J11S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.05	0.06	0.18
2	0.09	0.15	0.23
3	0.10	0.12	0.17
4	0.12	0.15	0.26
5	0.15	0.20	0.24
6	0.22	0.32	0.37
7	0.11	0.16	0.27
8	0.12	0.16	0.18
9	0.15	0.22	0.23
10	0.17	0.24	0.24
11	-	-	-
12	0.08	0.13	0.15
13	0.07	0.11	0.11
14	0.04	0.08	0.08
15	0.15	0.15	0.15
16	0.11	0.12	0.14
17	0.07	0.09	0.14
18	0.08	0.10	0.13
19	0.06	0.11	0.18
20	0.01	0.02	0.09
21	0.11	0.15	0.27
22	0.24	0.33	0.46
23	0.12	0.15	0.17
24	0.08	0.10	0.13
Mean (x_{ave})	0.11	0.15	0.20
SD (σ)	0.05	0.07	0.09
Coeff. of Var. (%)	45	47	45
$\frac{X_{max} - X_{ave}}{\sigma}$	2.6	2.6	2.9
$\frac{X_{ave} - X_{min}}{\sigma}$	2.0	1.9	1.3
Corrected Mean	**0.10**	**0.13**	**0.19**
Corrected SD	**0.04**	**0.05**	**0.07**

Table C.11. 3-body abrasion results for specimen J11S1.

Specimen	J12S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.02	0.10	0.10
2	0	0.04	0.05
3	0.01	0.05	0.06
4	0.01	0.04	0.05
5	0	0.07	0.08
6	0.05	0.11	0.12
7	0.01	0.09	0.11
8	0.01	0.08	0.09
9	0.03	0.08	0.10
10	0.04	0.04	0.06
11	0.07	0.08	0.09
12	0.07	0.07	0.09
13	0.06	0.06	0.06
14	0.06	0.06	0.08
15	0.08	0.08	0.08
16	0.13	0.17	0.18
17	0.03	0.05	0.06
18	0.03	0.05	0.06
19	0.05	0.06	0.08
20	0.05	0.06	0.08
21	0.05	0.05	0.08
22	0.08	0.10	0.15
23	0.08	0.10	0.12
24	0.06	0.06	0.08
Mean (X_{ave})	0.04	0.07	0.09
SD (σ)	0.03	0.03	0.03
Coeff. of Var. (%)	75	43	33
$\frac{X_{max} - X_{ave}}{\sigma}$	3.0	3.3	3.0
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.0	1.3
Corrected Mean	**0.04**	**0.07**	**0.08**
Corrected SD	**0.03**	**0.02**	**0.02**

Table C.12. 3-body abrasion results for specimen J12S1.

Specimen	CS2		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.04	0.06	0.05
2	0.03	0.03	0.03
3	0.04	0.04	0.03
4	-	-	-
5	0.03	0.03	0.05
6	0.12	0.14	0.15
7	0.06	0.06	0.09
8	0.04	0.05	0.05
9	0.06	0.20	0.32
10	0.01	0.03	0.03
11	0	0.02	0.04
12	0.03	0.04	0.04
13	0.02	0.03	0.03
14	0.04	0.04	0.05
15	0.04	0.05	0.04
16	0.04	0.07	0.10
17	0.02	0.02	0.03
18	0.04	0.04	0.04
19	0.07	0.07	0.07
20	0.02	0.02	0.04
21	0.05	0.05	0.05
22	0	0	0.02
23	0.08	0.08	0.08
24	0.02	0.02	0.03
Mean (x_{ave})	0.04	0.05	0.06
SD (σ)	0.03	0.04	0.06
Coeff. of Var. (%)	75	80	100
$\frac{X_{max} - X_{ave}}{\sigma}$	2.7	3.8	4.3
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.3	0.7
Corrected Mean	**0.04**	**0.04**	**0.05**
Corrected SD	**0.02**	**0.02**	**0.03**

Table C.13. 3-body abrasion results for specimen CS2, the coarse aggregate control.

Specimen	C1S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.03	0.05	0.15
2	0.02	0.02	0.08
3	0	0.01	0.02
4	0	0	0.01
5	-	-	-
6	0.03	0.03	0.06
7	0.03	0.05	0.08
8	0.07	0.09	0.18
9	0.02	0.04	0.07
10	0.01	0.07	0.07
11	0	0.03	0.04
12	-	-	-
13	0.04	0.05	0.05
14	0.04	0.05	0.06
15	0.04	0.02	0.03
16	-	-	-
17	0	0.02	0.02
18	0	0.02	0.08
19	0.04	0.10	0.14
20	0.05	0.14	0.24
21	0.06	0.18	0.29
22	0.01	0.03	0.07
23	0.05	0.09	0.11
24	-	0	0
Mean (x_{ave})	0.03	0.05	0.09
SD (σ)	0.02	0.05	0.07
Coeff. of Var. (%)	67	100	78
$\frac{x_{max} - x_{ave}}{\sigma}$	2.0	2.6	2.9
$\frac{x_{ave} - x_{min}}{\sigma}$	1.5	1.0	1.3
Corrected Mean	**0.02**	**0.05**	**0.07**
Corrected SD	**0.02**	**0.04**	**0.05**

Table C.14. 2-body abrasion results for specimen C1S1.

Specimen	C2S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	-	-	-
2	0.06	0.12	0.39
3	0.13	0.26	0.47
4	0.16	0.33	0.50
5	0.06	0.05	0.12
6	0.21	0.39	0.49
7	-	-	-
8	-	-	-
9	0.90	1.13	1.19
10	0.28	0.27	0.24
11	0.12	0.14	0.16
12	0.11	0.20	0.53
13	0.11	0.16	0.18
14	0.99	1.12	1.54
15	0.27	0.56	0.76
16	0.05	0.14	0.74
17	0.03	0.10	0.17
18	0.14	0.19	0.26
19	0.18	0.33	0.38
20	0.07	0.11	0.20
21	0.30	0.69	1.26
22	0.32	0.56	0.67
23	-	-	-
24	-	-	-
Mean (x_{ave})	0.24	0.36	0.54
SD (σ)	0.27	0.32	0.41
Coeff. of Var. (%)	113	89	76
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.4	2.4
$\frac{X_{ave} - X_{min}}{\sigma}$	0.8	1.0	1.0
Corrected Mean	**0.15**	**0.27**	**0.48**
Corrected SD	**0.09**	**0.19**	**0.34**

Table C.15. 2-body abrasion results for specimen C2S1.

Specimen	C3S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.10	0.14	0.28
2	0.05	0.08	0.09
3	0	0.01	0.05
4	0.03	0.04	0.06
5	0.05	0.05	0.07
6	0.02	0.02	0.05
7	0.04	0.04	0.05
8	0.05	0.09	0.21
9	0.08	0.09	0.10
10	0.05	0.08	0.11
11	0.03	0.04	0.05
12	0.02	0.02	0.02
13	0.02	0.02	0.03
14	0.04	0.06	0.06
15	0.01	0.01	0.02
16	0.03	0.05	0.05
17	0.03	0.06	0.09
18	0.04	0.05	0.07
19	0.01	0.02	0.05
20	0.02	0.04	0.05
21	0.02	0.04	0.04
22	0.05	0.06	0.07
23	0.10	0.11	0.15
24	0.06	0.11	0.26
Mean (x_{ave})	0.04	0.06	0.09
SD (σ)	0.03	0.03	0.07
Coeff. of Var. (%)	75	50	78
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	2.7	2.7
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.7	1.0
Corrected Mean	**0.04**	**0.05**	**0.07**
Corrected SD	**0.03**	**0.03**	**0.04**

Table C.16. 2-body abrasion results for specimen C3S1.

Specimen	C4S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.08	0.10	0.21
2	0.11	0.12	0.20
3	0	0.01	0.07
4	-	-	-
5	0.05	0.13	0.30
6	0.50	0.69	0.85
7	0.05	0.14	0.27
8	-	-	-
9	0.02	0.08	0.10
10	0.13	0.19	0.29
11	0.08	0.17	0.32
12	0.05	0.04	0.07
13	0	0.05	0.12
14	0.13	0.20	0.25
15	0.09	0.29	0.39
16	-	-	-
17	-	-	-
18	0.06	0.06	0.05
19	0.02	0.05	0.05
20	0.17	0.37	0.57
21	0.05	0.07	0.09
22	0.13	0.17	0.23
23	0.07	0.11	0.16
24	0.09	0.28	0.59
Mean (X_{ave})	0.09	0.17	0.26
SD (σ)	0.11	0.15	0.21
Coeff. of Var. (%)	122	88	81
$\frac{X_{max} - X_{ave}}{\sigma}$	3.7	3.5	2.8
$\frac{X_{ave} - X_{min}}{\sigma}$	0.8	1.1	1.0
Corrected Mean	**0.07**	**0.14**	**0.23**
Corrected SD	**0.05**	**0.10**	**0.16**

Table C.17. 2-body abrasion results for specimen C4S1.

Specimen	M5S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.04	0.08	0.08
2	0.07	0.12	0.11
3	0.01	0.08	0.01
4	0.05	0.09	0.06
5	0.06	0.10	0.05
6	0.07	0.12	0.11
7	0.06	0.11	0.10
8	0.02	0.09	0.07
9	0.03	0.08	0.06
10	0.07	0.12	0.10
11	0.05	0.09	0.05
12	0	0.05	0.04
13	0.03	0.07	0.04
14	0.02	0.07	0.07
15	0.02	0.04	0.03
16	0.03	0.05	0.05
17	0.02	0.04	0.04
18	0.01	0.05	0.01
19	0.10	0.14	0.17
20	0.07	0.10	0.13
21	0.04	0.05	0.03
22	0.03	0.04	0.04
23	0	0.04	0.01
24	0.03	0.08	0.06
Mean (x_{ave})	0.04	0.08	0.06
SD (σ)	0.03	0.03	0.04
Coeff. of Var. (%)	75	38	67
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	2.0	2.8
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.3	1.3
Corrected Mean	**0.04**	**0.08**	**0.06**
Corrected SD	**0.03**	**0.03**	**0.03**

Table C.18. 2-body abrasion results for specimen M5S1.

Specimen	M6aS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.03	0.03	0.05
2	0	0.02	0.02
3	0.04	0.06	0.07
4	-	-	-
5	-	-	-
6	0.09	0.09	0.10
7	0.02	0.02	0.02
8	0.02	0.02	0.03
9	0	0.04	0.06
10	-	-	-
11	-	-	-
12	0.06	0.06	0.06
13	0.05	0.05	0.07
14	-	-	-
15	0.02	0.02	0.02
16	-	-	-
17	0.08	0.11	0.10
18	0.35	0.45	0.50
19	-	-	-
20	0.03	0.04	0.06
21	0.01	0.02	0.03
22	0	0.02	0.03
23	0.08	0.09	0.11
24	-	-	-
Mean (x_{ave})	0.05	0.07	0.08
SD (σ)	0.08	0.11	0.12
Coeff. of Var. (%)	160	158	150
$\frac{X_{max} - X_{ave}}{\sigma}$	3.8	3.5	3.5
$\frac{X_{ave} - X_{min}}{\sigma}$	0.6	0.5	0.5
Corrected Mean	**0.04**	**0.05**	**0.06**
Corrected SD	**0.03**	**0.03**	**0.03**

Table C.19. 2-body abrasion results for specimen M6aS1.

Specimen	M6bS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.13	0.13	0.17
2	0.06	0.12	0.16
3	0.10	0.12	0.18
4	0.09	0.16	0.16
5	0	0.05	0.06
6	0.04	0.12	0.12
7	0.05	0.05	0.05
8	0.09	0.10	0.11
9	0.09	0.11	0.13
10	0.29	0.29	0.29
11	0.11	0.14	0.23
12	0.14	0.14	0.16
13	0.24	0.28	0.34
14	0.10	0.12	0.12
15	0.10	0.10	0.13
16	0.09	0.11	0.13
17	0.15	0.22	0.22
18	0.14	0.15	0.18
19	0.09	0.10	0.13
20	0.10	0.14	0.16
21	0.13	0.13	0.15
22	0.16	0.20	0.22
23	0.23	0.23	0.29
24	0.07	0.10	0.31
Mean (x_{ave})	0.12	0.14	0.18
SD (σ)	0.06	0.06	0.07
Coeff. of Var. (%)	50	43	39
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.5	2.3
$\frac{X_{ave} - X_{min}}{\sigma}$	2.0	1.5	1.9
Corrected Mean	**0.11**	**0.13**	**0.17**
Corrected SD	**0.05**	**0.04**	**0.07**

Table C.20. 2-body abrasion results for specimen M6bS1.

Specimen	M8S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.21	0.33	0.41
2	0.04	0.06	0.14
3	0.12	0.13	0.15
4	0.14	0.17	0.18
5	0.22	0.27	0.31
6	0.15	0.21	0.21
7	0	0.03	0.03
8	0.06	0.10	0.11
9	0.15	0.23	0.26
10	0.02	0.10	0.10
11	0.06	0.06	0.06
12	0.01	0.05	0.03
13	0.05	0.03	0.06
14	0.11	0.12	0.17
15	0.07	0.09	0.08
16	0.01	0.07	0.14
17	0.06	0.09	0.12
18	0.15	0.19	0.20
19	0.08	0.12	0.16
20	0	0.06	0.05
21	0.08	0.16	0.18
22	0.02	0.09	0.09
23	0.18	0.22	0.22
24	0.15	0.14	0.15
Mean (x_{ave})	0.09	0.13	0.15
SD (σ)	0.07	0.08	0.09
Coeff. of Var. (%)	78	62	60
$\frac{X_{max} - X_{ave}}{\sigma}$	1.9	2.5	2.9
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.3	1.3
Corrected Mean	**0.09**	**0.12**	**0.14**
Corrected SD	**0.07**	**0.07**	**0.07**

Table C.21. 2-body abrasion results for specimen M8S1.

Specimen	J9S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.40	0.63	0.70
2	0.04	0.17	0.17
3	0.02	0.03	0.03
4	0.06	0.09	0.18
5	0.14	0.46	0.63
6	0.07	0.17	0.17
7	0.03	0.05	0.05
8	0.28	0.40	0.59
9	0.03	0.04	0.05
10	0.03	0.20	0.37
11	0.13	0.18	0.29
12	0.05	0.05	0.06
13	0.02	0.02	0.02
14	0.06	0.10	0.18
15	0.13	0.20	0.29
16	0.03	0.04	0.12
17	0.02	0.07	0.10
18	0.14	0.35	0.47
19	0.29	0.60	0.79
20	0.08	0.12	0.23
21	0.03	0.03	0.04
22	0	0.04	0.11
23	0.30	0.52	0.65
24	0	0.03	0.05
Mean (x_{ave})	0.10	0.19	0.26
SD (σ)	0.11	0.19	0.24
Coeff. of Var. (%)	110	100	92
$\frac{X_{max} - X_{ave}}{\sigma}$	2.7	2.3	2.2
$\frac{X_{ave} - X_{min}}{\sigma}$	0.9	0.9	1.0
Corrected Mean	**0.09**	**0.15**	**0.24**
Corrected SD	**0.09**	**0.15**	**0.22**

Table C.22. 2-body abrasion results for specimen J9S1.

Specimen	J10S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.06	0.08	0.08
2	0.07	0.08	0.10
3	0.06	0.07	0.08
4	0.06	0.07	0.07
5	0.03	0.03	0.03
6	0.06	0.07	0.09
7	0.05	0.06	0.08
8	0.03	0.04	0.07
9	0.07	0.08	0.10
10	0.06	0.06	0.09
11	0.10	0.13	0.22
12	0.12	0.16	0.18
13	0.13	0.18	0.19
14	0.10	0.11	0.12
15	0.05	0.06	0.07
16	0.06	0.07	0.09
17	0.04	0.06	0.06
18	0.05	0.07	0.08
19	0.03	0.05	0.08
20	0.03	0.05	0.07
21	0.04	0.05	0.07
22	0.09	0.09	0.12
23	0.07	0.09	0.12
24	0.07	0.08	0.10
Mean (x_{ave})	0.06	0.08	0.10
SD (σ)	0.03	0.04	0.04
Coeff. of Var. (%)	50	50	40
$\frac{X_{max} - X_{ave}}{\sigma}$	2.3	2.5	3.0
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.3	1.8
Corrected Mean	**0.06**	**0.07**	**0.09**
Corrected SD	**0.02**	**0.03**	**0.03**

Table C.23. 2-body abrasion results for specimen J10S1.

Specimen	J11S1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.05	0.05	0.08
2	0.22	0.26	0.32
3	0.10	0.18	0.19
4	0.05	0.06	0.10
5	-	-	-
6	0.09	0.14	0.16
7	0.12	0.17	0.29
8	0.09	0.10	0.11
9	0.08	0.11	0.11
10	0.08	0.10	0.09
11	0.12	0.12	0.12
12	0.18	0.19	0.22
13	0.09	0.09	0.10
14	0	0.01	0.03
15	0.29	0.30	0.30
16	0.13	0.13	0.16
17	0.05	0.05	0.06
18	0.06	0.07	0.08
19	0.10	0.15	0.16
20	0.14	0.16	0.24
21	0.21	0.28	0.28
22	0.11	0.20	0.26
23	0.30	0.30	0.36
24	0.10	0.12	0.16
Mean (x_{ave})	0.12	0.15	0.17
SD (σ)	0.07	0.08	0.09
Coeff. of Var. (%)	58	53	53
$\frac{X_{max} - X_{ave}}{\sigma}$	2.6	1.9	2.1
$\frac{X_{ave} - X_{min}}{\sigma}$	1.7	1.8	1.6
Corrected Mean	**0.10**	**0.14**	**0.16**
Corrected SD	**0.05**	**0.08**	**0.09**

Table C.24. 2-body abrasion results for specimen J11S1.

Specimen	J12S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.06	0.07	0.07
2	0.08	0.10	0.11
3	0.05	0.06	0.06
4	0.02	0.03	0.04
5	0.03	0.04	0.04
6	0.03	0.04	0.04
7	0.06	0.09	0.11
8	0.06	0.07	0.08
9	0.06	0.07	0.07
10	0.07	0.10	0.10
11	0.07	0.09	0.10
12	0.09	0.11	0.11
13	0.06	0.07	0.07
14	0.02	0.02	0.04
15	0	0.02	0.03
16	0.08	0.11	0.12
17	0.04	0.05	0.05
18	-	-	-
19	0.03	0.04	0.05
20	0.06	0.07	0.07
21	0.05	0.06	0.06
22	0.05	0.05	0.06
23	0.04	0.05	0.06
24	0.06	0.07	0.07
Mean (x_{ave})	0.05	0.06	0.07
SD (σ)	0.02	0.03	0.03
Coeff. of Var. (%)	40	50	43
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	1.7	1.7
$\frac{X_{ave} - X_{min}}{\sigma}$	2.5	1.3	1.3
Corrected Mean	**0.05**	**0.06**	**0.07**
Corrected SD	**0.02**	**0.03**	**0.03**

Table C.25. 2-body abrasion results for specimen J12S1.

Specimen	CS2		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.07	0.08	0.11
2	0.07	0.12	0.36
3	0.12	0.19	0.27
4	0.10	0.09	0.13
5	0.04	0.05	0.05
6	0.03	0.05	0.05
7	0.07	0.07	0.12
8	0.03	0.04	0.05
9	0	0.02	0.02
10	0.02	0.02	0.04
11	0.04	0.06	0.08
12	0.11	0.13	0.13
13	0.05	0.07	0.08
14	0.07	0.09	0.15
15	0.05	0.05	0.05
16	0.14	0.14	0.14
17	0.11	0.11	0.11
18	0.11	0.14	0.15
19	0.13	0.15	0.18
20	0.05	0.07	0.06
21	0.04	0.04	0.05
22	0.03	0.04	0.04
23	0.03	0.04	0.05
24	0.09	0.10	0.11
Mean (X_{ave})	0.07	0.08	0.11
SD (σ)	0.04	0.05	0.08
Coeff. of Var. (%)	57	63	73
$\frac{X_{max} - X_{ave}}{\sigma}$	1.8	2.2	3.1
$\frac{X_{ave} - X_{min}}{\sigma}$	1.8	1.2	1.1
Corrected Mean	**0.07**	**0.08**	**0.10**
Corrected SD	**0.04**	**0.04**	**0.06**

Table C.26. 2-body abrasion results for specimen CS2, the coarse aggregate control.

Specimen	C1S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.70	1.58	-
2	-	-	-
3	0	0.84	-
4	0	0	-
5	0.01	0.25	-
6	-	-	-
7	0	1.87	-
8	0.79	2.32	-
9	0.35	2.21	-
10	0.23	1.81	-
11	0.38	1.44	-
12	-	-	-
13	-	-	-
14	0	0.40	-
15	0	0.06	-
16	0.62	1.62	-
17	-	-	-
18	-	-	-
19	0.12	0.70	-
20	0.23	1.52	-
21	0.52	1.24	-
22	0	1.25	-
23	0	0.76	-
24	-	-	-
Mean (x_{ave})	0.23	1.17	-
SD (σ)	0.28	0.73	-
Coeff. of Var. (%)	122	62	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	1.6	-
$\frac{X_{ave} - X_{min}}{\sigma}$	0.8	1.6	-
Corrected Mean	**0.16**	**1.17**	-
Corrected SD	**0.21**	**0.73**	-

Table C.27. Wet abrasion results for specimen C1S1.

Specimen	C2S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.46	2.45	-
2	0.82	1.99	-
3	0.86	5.05	-
4	0.30	4.23	-
5	0.89	3.43	-
6	1.63	3.49	-
7	0.88	2.22	-
8	0.30	3.06	-
9	0.17	0.61	-
10	0.09	1.05	-
11	0.86	1.20	-
12	1.54	2.86	-
13	1.07	1.82	-
14	0.84	1.21	-
15	2.21	2.73	-
16	0.11	1.86	-
17	0.48	2.01	-
18	1.09	4.24	-
19	0.96	1.98	-
20	2.23	3.60	-
21	1.97	4.24	-
22	1.54	3.35	-
23	1.15	1.77	-
24	0.90	2.01	-
Mean (x_{ave})	0.97	2.59	-
SD (σ)	0.62	1.16	-
Coeff. of Var. (%)	64	45	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	2.1	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.7	-
Corrected Mean	**0.86**	**2.48**	-
Corrected SD	**0.51**	**1.08**	-

Table C.28. Wet abrasion results for specimen C2S1.

Specimen	C3S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.64	3.30	-
2	0.78	1.94	-
3	0.06	0.50	-
4	0.34	0.81	-
5	0.07	2.70	-
6	0.65	1.01	-
7	0.43	1.57	-
8	1.20	2.46	-
9	0.80	2.28	-
10	0.80	2.71	-
11	1.07	1.91	-
12	0.53	1.89	-
13	0.66	1.93	-
14	0.29	1.36	-
15	1.66	1.69	-
16	0.83	1.45	-
17	1.64	1.75	-
18	1.31	3.38	-
19	0.46	1.94	-
20	0.47	0.98	-
21	0.92	2.46	-
22	0.71	2.11	-
23	0.89	3.56	-
24	1.89	3.71	-
Mean (x_{ave})	0.80	2.06	-
SD (σ)	0.48	0.86	-
Coeff. of Var. (%)	60	40	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.3	1.9	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	1.8	-
Corrected Mean	**0.75**	**2.06**	-
Corrected SD	**0.42**	**0.86**	-

Table C.29. Wet abrasion results for specimen C3S1.

Specimen	C4S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.11	0.46	-
2	0.06	0.15	-
3	0.02	0.99	-
4	0.78	1.49	-
5	0.08	0.51	-
6	0.05	1.12	-
7	0.06	0.95	-
8	0.36	1.84	-
9	0.02	1.14	-
10	0.64	2.04	-
11	0.24	1.21	-
12	0.14	1.16	-
13	0.07	1.07	-
14	0.16	0.57	-
15	0.04	0.52	-
16	-	-	-
17	0.84	1.15	-
18	1.47	2.42	-
19	0.49	2.36	-
20	0.24	1.35	-
21	0.06	0.10	-
22	0.18	1.17	-
23	0.15	0.33	-
24	0.02	0.39	-
Mean (x_{ave})	0.27	1.06	-
SD (σ)	0.36	0.65	-
Coeff. of Var. (%)	133	61	-
$\frac{X_{max} - X_{ave}}{\sigma}$	3.3	2.1	-
$\frac{X_{ave} - X_{min}}{\sigma}$	0.7	1.5	-
Corrected Mean	**0.22**	**1.00**	-
Corrected SD	**0.25**	**0.60**	-

Table C.30. Wet abrasion results for specimen C4S1.

Specimen	M5S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.03	0.03	0.26
2	0.04	0.30	0.67
3	0.03	0.41	1.18
4	0.08	0.52	1.26
5	0.04	0.45	1.08
6	0.08	0.17	1.09
7	0.10	0.42	1.80
8	0.07	0.07	0.48
9	0.08	0.79	-
10	0.03	0.71	-
11	0.09	0.83	-
12	0.27	0.74	-
13	0.08	0.51	-
14	0.04	1.14	-
15	0.06	0.47	-
16	0.46	0.82	-
17	-	-	-
18	0.50	0.50	-
19	0.32	0.73	-
20	0.36	0.90	-
21	0.22	0.95	-
22	0.38	0.93	-
23	0.06	0.72	-
24	0.12	1.21	-
Mean (x_{ave})	0.15	0.62	0.98
SD (σ)	0.15	0.32	0.49
Coeff. of Var. (%)	100	52	50
$\frac{X_{max} - X_{ave}}{\sigma}$	2.3	1.8	1.7
$\frac{X_{ave} - X_{min}}{\sigma}$	0.8	1.8	1.5
Corrected Mean	**0.12**	**0.62**	**0.98**
Corrected SD	**0.11**	**0.32**	**0.49**

Table C.31. Wet abrasion results for specimen M5S1.

Specimen	M6aS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.05	0.05	1.13
2	-	-	-
3	0.04	0.06	0.09
4	0.03	0.03	0.04
5	0.05	0.05	0.06
6	0.03	0.03	0.64
7	0.04	0.04	0.89
8	0.05	0.60	1.03
9	-	-	-
10	0.05	0.02	0.13
11	0.04	0.04	0.49
12	0.06	0.36	0.65
13	0.05	0.07	0.62
14	0.03	0.04	0.53
15	0.08	0.08	1.23
16	0.05	0.06	0.36
17	0.49	1.06	-
18	0.07	1.04	-
19	0.02	0.92	-
20	0.65	1.11	-
21	0.21	0.57	-
22	0.19	1.96	-
23	0.09	0.36	-
24	0.03	1.01	-
Mean (x_{ave})	0.11	0.43	0.56
SD (σ)	0.16	0.53	0.40
Coeff. of Var. (%)	145	123	71
$\frac{X_{max} - X_{ave}}{\sigma}$	3.4	2.9	1.7
$\frac{X_{ave} - X_{min}}{\sigma}$	0.6	0.8	1.3
Corrected Mean	**0.06**	**0.36**	**0.56**
Corrected SD	**0.05**	**0.42**	**0.40**

Table C.32. Wet abrasion results for specimen M6aS1.

Specimen	M6bS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.48	1.50	-
2	0.32	1.86	-
3	0.20	0.62	-
4	0.27	1.00	-
5	0.38	1.12	-
6	0.10	0.28	-
7	0.42	0.57	-
8	0.15	1.21	-
9	0.23	0.73	-
10	0.46	0.62	-
11	0.54	2.17	-
12	0.16	2.40	-
13	0.88	2.39	-
14	0.93	2.51	-
15	0.83	1.65	-
16	1.11	2.61	-
17	0.29	1.66	-
18	1.38	2.14	-
19	1.07	1.62	-
20	0.38	1.73	-
21	0.13	0.94	-
22	0.07	0.45	-
23	0.66	0.97	-
24	0.15	1.24	-
Mean (x_{ave})	0.48	1.42	-
SD (σ)	0.37	0.71	-
Coeff. of Var. (%)	77	50	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.4	1.7	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.1	1.6	-
Corrected Mean	**0.44**	**1.42**	-
Corrected SD	**0.32**	**0.71**	-

Table C.33. Wet abrasion results for specimen M6bS1.

Specimen	M8S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.14	1.87	-
2	0.34	0.91	-
3	0.60	1.56	-
4	0.32	2.07	-
5	0.23	1.98	-
6	0.93	1.85	-
7	0.15	0.72	-
8	0.21	0.93	-
9	0.65	1.77	-
10	0.94	2.00	-
11	0.33	1.17	-
12	0.25	2.60	-
13	0.45	1.67	-
14	0.18	0.91	-
15	0.73	2.03	-
16	0.04	0.81	-
17	0.83	1.53	-
18	0.53	2.14	-
19	1.70	1.95	-
20	0.50	2.68	-
21	0.35	2.34	-
22	0.52	2.80	-
23	1.50	1.98	-
24	0.56	1.51	-
Mean (x_{ave})	0.54	1.74	-
SD (σ)	0.41	0.59	-
Coeff. of Var. (%)	76	34	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	1.8	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.2	1.7	-
Corrected Mean	**0.44**	**1.74**	-
Corrected SD	**0.26**	**0.59**	-

Table C.34. Wet abrasion results for specimen M8S1.

Specimen	J9S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.11	-	-
2	0.68	-	-
3	1.31	-	-
4	1.14	-	-
5	1.04	-	-
6	0.70	-	-
7	1.11	-	-
8	0.37	-	-
9	0.85	-	-
10	1.11	-	-
11	0.86	-	-
12	1.39	-	-
13	1.05	-	-
14	2.02	-	-
15	1.04	-	-
16	1.51	-	-
17	0.17	-	-
18	0.45	-	-
19	1.26	-	-
20	1.30	-	-
21	1.93	-	-
22	1.36	-	-
23	0.47	-	-
24	0.16	-	-
Mean (x_{ave})	0.97	-	-
SD (σ)	0.52	-	-
Coeff. of Var. (%)	54	-	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	-	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.7	-	-
Corrected Mean	**0.93**	-	-
Corrected SD	**0.48**	-	-

Table C.35. Wet abrasion results for specimen J9S1.

Specimen	J10S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.09	0.14	0.19
2	0.08	0.12	0.12
3	0.06	0.10	0.09
4	0.06	0.09	0.10
5	0.05	0.08	0.08
6	0.04	0.07	0.07
7	0.06	0.09	0.14
8	0.07	0.09	0.11
9	0.05	0.08	0.08
10	0.06	0.08	0.09
11	0.05	0.09	0.10
12	0.08	0.11	0.11
13	0.06	0.09	0.56
14	0.05	0.08	0.08
15	0.04	0.07	0.09
16	0.06	0.09	0.13
17	0.05	0.07	0.07
18	0.05	0.08	0.08
19	0.08	0.10	0.10
20	0.09	0.12	0.12
21	0.11	0.14	0.47
22	0.16	0.16	0.61
23	0.11	0.12	0.13
24	0.08	0.11	0.11
Mean (x_{ave})	0.07	0.10	0.16
SD (σ)	0.03	0.02	0.15
Coeff. of Var. (%)	43	20	94
$\frac{X_{max} - X_{ave}}{\sigma}$	3.0	3.0	3.0
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.5	0.6
Corrected Mean	**0.07**	**0.09**	**0.10**
Corrected SD	**0.02**	**0.02**	**0.03**

Table C.36. Wet abrasion results for specimen J10S1.

Specimen	J11S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.11	0.16	-
2	0.09	0.63	-
3	0.21	1.66	-
4	0.12	1.29	-
5	0.23	0.61	-
6	0.10	0.94	-
7	0.24	1.86	-
8	0.16	0.71	-
9	0.13	1.53	-
10	0.14	1.36	-
11	0.07	0.82	-
12	0.07	0.37	-
13	0.03	0.30	-
14	-	-	-
15	0.25	1.27	-
16	0.35	1.03	-
17	0.05	0.16	-
18	0.10	1.27	-
19	0.08	0.45	-
20	0.54	0.97	-
21	0.15	0.86	-
22	0.06	0.45	-
23	0.24	1.59	-
24	0.31	0.84	-
Mean (x_{ave})	0.17	0.92	-
SD (σ)	0.12	0.49	-
Coeff. of Var. (%)	71	53	-
$\frac{X_{max} - X_{ave}}{\sigma}$	3.1	1.9	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.6	-
Corrected Mean	**0.15**	**0.92**	-
Corrected SD	**0.09**	**0.49**	-

Table C.37. Wet abrasion results for specimen J11S1.

Specimen	J12S1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.08	0.12	0.70
2	0.07	0.09	0.11
3	0.07	0.08	0.49
4	0.12	0.18	0.36
5	0.01	0.01	0.01
6	0.04	0.06	0.10
7	0.08	0.08	0.44
8	0.10	0.73	1.17
9	0.08	0.08	0.08
10	0.03	0.03	0.03
11	0.09	0.09	0.04
12	0.05	0.06	0.06
13	0.05	0.06	0.08
14	0.08	0.10	0.21
15	0.04	0.07	0.08
16	0.05	0.04	0.05
17	0.04	0.04	0.05
18	0.07	0.07	0.10
19	0.06	0.07	0.07
20	0.03	0.08	0.07
21	0.06	0.06	0.11
22	0.11	0.34	0.46
23	0.04	0.03	0.06
24	0.06	0.07	0.09
Mean (x_{ave})	0.06	0.11	0.21
SD (σ)	0.03	0.15	0.27
Coeff. of Var. (%)	50	136	129
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	4.1	3.6
$\frac{X_{ave} - X_{min}}{\sigma}$	1.7	0.7	0.7
Corrected Mean	**0.06**	**0.08**	**0.17**
Corrected SD	**0.03**	**0.07**	**0.19**

Table C.38. Wet abrasion results for specimen J12S1.

Specimen	CS2		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.59	0.77	0.96
2	0.34	0.59	0.59
3	0.10	0.83	1.08
4	0.19	0.42	0.82
5	0.08	0.50	1.41
6	0.12	0.36	0.43
7	0.49	1.38	1.82
8	0.50	0.58	3.08
9	0.33	0.63	0.72
10	0.34	1.73	1.71
11	0.23	0.73	1.12
12	0.65	0.85	1.77
13	0.25	0.43	1.11
14	-	-	-
15	0.05	1.06	1.45
16	0.01	0.71	1.77
17	0	0.64	1.41
18	-	-	-
19	0.09	0.44	1.31
20	0.03	0.34	0.89
21	0.15	0.64	0.92
22	0.01	0.29	2.17
23	-	-	-
24	0.04	0.56	0.82
Mean (X_{ave})	0.22	0.69	1.30
SD (σ)	0.20	0.35	0.61
Coeff. of Var. (%)	91	51	47
$\frac{X_{max} - X_{ave}}{\sigma}$	2.2	3.0	2.9
$\frac{X_{ave} - X_{min}}{\sigma}$	1.1	1.1	1.4
Corrected Mean	**0.18**	**0.64**	**1.21**
Corrected SD	**0.16**	**0.26**	**0.47**

Table C.39. Wet abrasion results for specimen CS2, the coarse aggregate control.

Appendix D

Abrasion Test Results for Fine Aggregate Mixes

Specimen	C1FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.20	0.30	0.36
2	0.06	0.11	0.35
3	0.54	0.60	0.62
4	0.43	0.77	0.82
5	0.18	0.20	0.47
6	0	0.01	0.05
7	0.22	0.46	0.61
8	0.32	0.33	0.69
9	0.30	0.39	0.46
10	0.11	0.18	0.21
11	0.21	0.24	0.26
12	0.24	0.44	0.47
13	0.25	0.59	0.73
14	0.19	0.34	0.46
15	0.13	0.21	0.25
16	0.16	0.16	0.19
17	0.10	0.20	0.23
18	0.15	0.21	0.30
19	0.07	0.13	0.24
20	0.34	0.52	0.62
21	0.08	0.21	0.27
22	0.17	0.19	0.29
23	0.17	0.24	0.39
24	0.31	0.39	0.43
Mean (x_{ave})	0.21	0.31	0.41
SD (σ)	0.12	0.18	0.19
Coeff. of Var. (%)	57	58	46
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.6	2.2
$\frac{X_{ave} - X_{min}}{\sigma}$	1.8	1.7	1.9
Corrected Mean	**0.19**	**0.29**	**0.39**
Corrected SD	**0.10**	**0.16**	**0.18**

Table D.1. 3-body abrasion results for specimen C1FS1.

Specimen	C2FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.08	0.36	0.66
2	0.04	0.05	0.06
3	0.13	0.27	0.35
4	0.28	0.41	0.49
5	0.24	0.26	0.37
6	0.03	0.26	0.45
7	-	-	-
8	0.04	0.04	0.06
9	0.14	0.19	0.43
10	-	-	-
11	0.09	0.09	0.10
12	0.05	0.12	0.18
13	0.36	0.38	0.65
14	-	-	-
15	-	-	-
16	0.13	0.36	0.61
17	0.18	0.65	0.85
18	0.28	0.32	0.42
19	0.21	0.53	0.52
20	0	0.12	0.26
21	0.13	0.27	0.62
22	-	-	-
23	0.08	0.12	0.14
24	0.09	0.10	0.30
Mean (X_{ave})	0.16	0.27	0.41
SD (σ)	0.11	0.17	0.23
Coeff. of Var. (%)	69	63	56
$\frac{X_{max} - X_{ave}}{\sigma}$	1.8	2.2	1.9
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	1.4	1.5
Corrected Mean	**0.14**	**0.25**	**0.41**
Corrected SD	**0.10**	**0.14**	**0.23**

Table D.2. 3-body abrasion results for specimen C2FS1.

Specimen	C3FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.24	0.43	0.57
2	0.09	0.29	0.47
3	0.24	0.27	0.44
4	0.28	0.44	0.49
5	0.22	0.32	0.42
6	0.11	0.19	0.21
7	0.26	0.27	0.31
8	0.16	0.19	0.20
9	0.10	0.14	0.31
10	0.19	0.28	0.49
11	0.26	0.38	0.55
12	0.32	0.35	0.42
13	0.32	0.43	0.48
14	0.15	0.32	0.58
15	0.27	0.45	0.52
16	0.07	0.07	0.08
17	0.12	0.13	0.15
18	0.25	0.57	0.98
19	0.30	0.42	0.44
20	0.14	0.14	0.15
21	0.19	0.31	0.36
22	0.23	0.31	0.39
23	0.11	0.13	0.22
24	0.16	0.17	0.19
Mean (x_{ave})	0.20	0.29	0.39
SD (σ)	0.08	0.13	0.19
Coeff. of Var. (%)	40	45	49
$\frac{X_{max} - X_{ave}}{\sigma}$	1.5	2.2	3.1
$\frac{X_{ave} - X_{min}}{\sigma}$	1.6	1.7	1.6
Corrected Mean	**0.20**	**0.28**	**0.37**
Corrected SD	**0.08**	**0.12**	**0.15**

Table D.3. 3-body abrasion results for specimen C3FS1.

Specimen	C4FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.09	0.15	0.17
2	0.26	0.41	0.61
3	0.15	0.17	0.27
4	0.13	0.19	0.24
5	0.12	0.31	0.35
6	0.11	0.23	0.24
7	0.14	0.27	0.29
8	0.05	0.15	0.15
9	0.11	0.16	0.16
10	0.08	0.17	0.28
11	0.16	0.30	0.32
12	0.04	0.19	0.33
13	0.02	0.04	0.05
14	0.32	0.43	0.56
15	0	0	0
16	-	-	-
17	0.20	0.32	0.40
18	0.06	0.06	0.06
19	0.12	0.17	0.17
20	0.17	0.31	0.36
21	0.30	0.36	0.41
22	0.04	0.14	0.24
23	0.18	0.29	0.38
24	0.19	0.45	0.53
Mean (X_{ave})	0.13	0.23	0.29
SD (σ)	0.08	0.12	0.16
Coeff. of Var. (%)	62	52	55
$\frac{X_{max} - X_{ave}}{\sigma}$	2.4	1.8	2.0
$\frac{X_{ave} - X_{min}}{\sigma}$	1.6	1.9	1.8
Corrected Mean	**0.12**	**0.23**	**0.29**
Corrected SD	**0.07**	**0.12**	**0.16**

Table D.4. 3-body abrasion results for specimen C4FS1.

Specimen	M5FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.07	0.18	0.37
2	0.18	0.61	0.63
3	-	0.28	0.45
4	0.13	0.14	0.14
5	0	0.70	1.04
6	0.17	0.35	0.43
7	-	0.20	0.20
8	-	0.06	0.07
9	0	0.04	0.08
10	0.63	0.48	0.66
11	0	1.29	1.38
12	0.23	0.38	0.70
13	-	0.02	0.06
14	0.21	0.28	0.68
15	0.16	0.43	0.47
16	0.03	0.18	0.34
17	0.20	0.22	0.28
18	0.02	0.03	0.04
19	0.11	0.13	0.16
20	0.42	0.65	0.83
21	0.67	0.97	1.27
22	0.05	0.22	0.25
23	0.32	0.46	0.50
24	0.53	0.81	0.81
Mean (X_{ave})	0.21	0.38	0.49
SD (σ)	0.21	0.32	0.38
Coeff. of Var. (%)	100	84	78
$\dfrac{X_{max} - X_{ave}}{\sigma}$	2.2	2.8	2.3
$\dfrac{X_{ave} - X_{min}}{\sigma}$	1.0	1.1	1.2
Corrected Mean	**0.16**	**0.34**	**0.42**
Corrected SD	**0.15**	**0.26**	**0.29**

Table D.5. 3-body abrasion results for specimen M5FS1.

Specimen	M6FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.21	0.21	0.26
2	0.08	0.19	0.21
3	0.16	0.16	0.21
4	0.15	0.18	0.30
5	0.30	0.50	0.52
6	0.07	0.08	0.14
7	0.16	0.26	0.26
8	0.26	0.39	0.43
9	0.30	0.44	0.46
10	0.26	0.57	0.91
11	0.29	0.56	0.71
12	0.12	0.28	0.29
13	0.13	0.21	0.21
14	0.15	0.21	0.24
15	0.11	0.31	0.61
16	0.35	0.56	0.57
17	0.22	0.68	1.10
18	0.51	0.75	0.85
19	0.29	0.63	0.71
20	0.10	0.27	0.54
21	0.37	0.59	1.03
22	0.32	0.35	0.41
23	0.11	0.15	0.15
24	0.18	0.51	1.21
Mean (X_{ave})	0.22	0.38	0.51
SD (σ)	0.11	0.19	0.32
Coeff. of Var. (%)	50	50	63
$\frac{X_{max} - X_{ave}}{\sigma}$	2.6	1.9	2.2
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.6	1.2
Corrected Mean	**0.20**	**0.38**	**0.48**
Corrected SD	**0.09**	**0.19**	**0.29**

Table D.6. 3-body abrasion results for specimen M6FS1.

Specimen	M8FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.20	0.45	0.47
2	0.22	0.26	0.33
3	0.11	0.42	0.44
4	0.21	0.39	0.47
5	0.16	0.54	0.72
6	0.12	0.20	0.24
7	0.04	0.20	0.31
8	0.27	0.34	0.41
9	0.14	0.15	0.25
10	0.18	0.18	0.19
11	0.11	0.14	0.25
12	0.31	0.65	0.82
13	0.32	0.38	0.63
14	0.02	0.06	0.10
15	0.29	0.36	0.40
16	0.01	0.05	0.09
17	0.14	0.28	0.57
18	0.21	0.28	0.31
19	0.10	0.17	0.19
20	0.18	0.19	0.24
21	0.38	0.64	0.66
22	0.30	0.65	0.71
23	0.18	0.22	0.38
24	0.09	0.21	0.31
Mean (x_{ave})	0.18	0.31	0.40
SD (σ)	0.10	0.18	0.20
Coeff. of Var. (%)	56	58	50
$\frac{x_{max} - x_{ave}}{\sigma}$	2.0	1.9	2.1
$\frac{x_{ave} - x_{min}}{\sigma}$	1.7	1.4	1.6
Corrected Mean	**0.17**	**0.31**	**0.38**
Corrected SD	**0.09**	**0.18**	**0.18**

Table D.7. 3-body abrasion results for specimen M8FS1.

Specimen	J9FS1			
Reading No.	5 Min. Depth (mm)	10 Min. Depth (mm)	15 Min. Depth (mm)	30 Min. Depth (mm)
1	0.04	0.14	0.62	0.92
2	0.06	0.06	0.07	0.97
3	0.05	0.11	0.78	0.28
4	0.15	0.39	0.49	2.05
5	0.11	0.41	1.35	1.55
6	-	-	-	-
7	0.04	0.20	0.86	1.25
8	0.38	0.46	1.53	2.24
9	0.13	0.20	0.26	0.84
10	0.06	0.37	0.61	0.76
11	0.11	0.44	0.70	1.23
12	0.18	0.26	0.31	0.45
13	0.09	0.21	0.35	0.87
14	0.08	0.25	0.56	0.74
15	0.11	0.15	0.18	1.47
16	0.15	0.29	0.28	0.58
17	0.08	0.27	0.48	0.85
18	0.03	0.21	0.57	0.76
19	0.14	0.43	0.53	0.57
20	0.20	0.46	0.53	0.67
21	0.17	0.50	0.53	0.97
22	0.21	0.30	0.55	0.42
23	0.08	0.27	0.59	0.97
24	0.22	0.45	0.60	0.55
Mean (x_{ave})	0.12	0.34	0.58	0.95
SD (σ)	0.08	0.27	0.33	0.49
Coeff. of Var. (%)	67	79	57	52
$\frac{x_{max} - x_{ave}}{\sigma}$	3.3	0.6	2.9	2.6
$\frac{x_{ave} - x_{min}}{\sigma}$	1.1	1.0	1.5	1.4
Corrected Mean	**0.11**	**0.29**	**0.50**	**0.84**
Corrected SD	**0.06**	**0.13**	**0.20**	**0.33**

Table D.8. 3-body abrasion results for specimen J9FS1.

Specimen	J10FS1			
Reading No.	**5 Min. Depth (mm)**	**10 Min. Depth (mm)**	**15 Min. Depth (mm)**	**30 Min. Depth (mm)**
1	0.11	0.21	0.27	0.22
2	0.03	0.09	0.13	0.15
3	0.10	0.17	0.19	0.28
4	0.11	0.15	0.38	0.70
5	0.20	0.47	0.61	0.95
6	0.10	0.33	0.40	0.59
7	0.38	0.41	0.53	0.74
8	0.05	0.18	0.37	0.81
9	0	0.10	0.25	0.37
10	0.02	0.17	0.26	0.87
11	0.21	0.45	0.32	0.72
12	0.24	0.44	0.51	0.70
13	0.07	0.34	0.45	0.71
14	0.03	0.18	0.35	0.63
15	0.13	0.49	0.65	0.90
16	0.15	0.45	0.69	0.78
17	0.12	0.45	0.51	-
18	0.15	0.29	0.61	-
19	0.02	0.19	0.57	-
20	0.10	0.58	-	-
21	0.19	0.49	0.79	-
22	0.06	0.43	0.62	-
23	0.05	0.15	0.27	-
24	0.20	0.40	0.58	-
Mean (x_{ave})	0.12	0.32	0.46	0.63
SD (σ)	0.09	0.15	0.18	0.25
Coeff. of Var. (%)	75	47	39	40
$\dfrac{x_{max} - x_{ave}}{\sigma}$	2.9	1.7	1.8	1.3
$\dfrac{x_{ave} - x_{min}}{\sigma}$	1.3	1.5	1.8	1.9
Corrected Mean	**0.11**	**0.32**	**0.46**	**0.63**
Corrected SD	**0.07**	**0.15**	**0.18**	**0.25**

Table D.9. 3-body abrasion results for specimen J10FS1.

Specimen	J11FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.21	0.25	0.25
2	0.01	0.13	0.13
3	0.11	0.26	0.31
4	0.38	0.46	0.75
5	0.38	0.57	0.76
6	0.13	0.13	0.16
7	0.09	0.32	0.34
8	0.63	0.77	1.20
9	0.34	0.68	0.79
10	0.17	0.17	0.21
11	0.15	0.21	0.32
12	0.40	0.72	0.74
13	0.75	1.19	1.28
14	0.45	0.45	0.45
15	0.35	0.35	0.43
16	0.39	0.66	0.66
17	-	-	0.45
18	0.45	0.76	0.82
19	0.53	0.68	0.68
20	0.10	0.15	0.42
21	0	0.15	0.44
22	0.14	0.23	0.40
23	0.54	0.71	0.75
24	0.11	0.38	0.59
Mean (x_{ave})	0.30	0.45	0.56
SD (σ)	0.21	0.28	0.30
Coeff. of Var. (%)	70	62	54
$\frac{X_{max} - X_{ave}}{\sigma}$	2.1	2.6	2.4
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.1	1.4
Corrected Mean	**0.28**	**0.42**	**0.50**
Corrected SD	**0.18**	**0.23**	**0.23**

Table D.10. 3-body abrasion results for specimen J11FS1.

Specimen	J12FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.29	0.34	0.41
2	0.09	0.11	0.18
3	0.15	0.37	0.41
4	0.21	0.27	0.67
5	0	0.05	0.05
6	0	0.06	0.38
7	0.13	0.74	0.96
8	0.26	0.47	0.56
9	0.38	0.70	1.22
10	0.07	0.20	0.21
11	0.12	0.12	0.09
12	0.15	0.20	0.25
13	0.33	0.38	0.38
14	0.03	0.55	0.63
15	0.30	0.36	0.45
16	0.18	0.50	0.69
17	0.11	0.23	0.29
18	0.38	0.43	0.64
19	0	0.02	0.14
20	0.02	0.02	0.14
21	0.32	0.55	0.61
22	0.20	0.22	0.33
23	0.06	0.23	0.27
24	0.20	0.51	0.67
Mean (x_{ave})	0.17	0.32	0.44
SD (σ)	0.12	0.21	0.28
Coeff. of Var. (%)	71	66	64
$\frac{X_{max} - X_{ave}}{\sigma}$	1.8	2.0	2.8
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.4	1.4
Corrected Mean	**0.17**	**0.32**	**0.41**
Corrected SD	**0.12**	**0.21**	**0.24**

Table D.11. 3-body abrasion results for specimen J12FS1.

Specimen	CSF1			
Reading No.	5 Min. Depth (mm)	10 Min. Depth (mm)	15 Min. Depth (mm)	30 Min. Depth (mm)
1	0.09	0.10	0.11	0.25
2	0.10	0.13	0.17	0.24
3	0.15	0.15	0.23	0.27
4	0.17	0.17	0.19	0.24
5	0.10	0.23	0.24	0.26
6	0.13	0.16	0.18	0.21
7	0.08	0.08	0.14	0.26
8	0.32	0.35	0.40	0.52
9	0.25	0.26	0.29	0.33
10	0.14	0.18	0.21	0.37
11	0.14	0.16	0.19	0.27
12	0.14	0.17	0.22	0.27
13	0.08	0.10	0.12	0.19
14	0.13	0.13	0.13	0.22
15	0.08	0.10	0.10	0.20
16	0.13	0.14	0.20	0.31
17	0.09	0.13	0.20	0.26
18	0.11	0.14	0.17	0.24
19	0.10	0.11	0.15	0.18
20	0.10	0.10	0.18	0.22
21	0.13	0.13	0.15	0.22
22	0.13	0.13	0.16	0.17
23	0.15	0.15	0.18	0.27
24	0.07	0.09	0.13	0.19
Mean (X_{ave})	0.13	0.15	0.19	0.26
SD (σ)	0.06	0.06	0.06	0.07
Coeff. of Var. (%)	46	40	32	27
$\frac{X_{max} - X_{ave}}{\sigma}$	3.2	3.3	3.5	3.7
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.2	1.5	1.3
Corrected Mean	**0.12**	**0.14**	**0.18**	**0.25**
Corrected SD	**0.04**	**0.04**	**0.05**	**0.05**

Table D.12. 3-body abrasion results for specimen CSF1, the fine aggregate control.

Specimen	C1FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.33	0.35	0.45
2	0.41	0.44	0.53
3	0.18	0.18	0.55
4	0.25	0.43	0.49
5	0.11	0.11	0.11
6	0.08	0.17	0.39
7	0.20	0.25	0.25
8	0.18	0.22	0.23
9	0.23	0.26	0.30
10	0.09	0.17	0.20
11	0.11	0.12	0.17
12	0.20	0.21	0.32
13	0.20	0.27	0.32
14	0.26	0.26	0.26
15	0.16	0.22	0.22
16	0.27	0.33	0.38
17	0.56	1.02	1.02
18	0.33	0.42	0.46
19	0.07	0.17	0.15
20	0.03	0.13	0.18
21	0.30	0.43	0.51
22	0.24	0.24	0.35
23	0.04	0.08	0.09
24	0.18	0.20	0.47
Mean (x_{ave})	0.21	0.28	0.35
SD (σ)	0.12	0.19	0.20
Coeff. of Var. (%)	57	68	57
$\frac{X_{max} - X_{ave}}{\sigma}$	2.9	3.9	3.4
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	1.1	1.3
Corrected Mean	**0.19**	**0.25**	**0.32**
Corrected SD	**0.10**	**0.11**	**0.14**

Table D.13. 2-body abrasion results for specimen C1FS1.

Specimen	C2FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.10	0.30	0.34
2	0.05	0.11	0.11
3	0.04	0.17	0.21
4	0.14	0.50	0.59
5	0.12	0.27	0.37
6	0.17	0.19	0.23
7	0.06	0.15	0.20
8	0.10	0.38	0.50
9	0.04	0.12	0.15
10	0.03	0.15	0.31
11	0.09	0.09	0.10
12	0.06	0.24	0.28
13	0	0.13	0.18
14	0.25	0.83	1.07
15	0.18	0.21	0.28
16	0.12	0.21	0.29
17	0.16	0.27	0.32
18	0.11	0.16	0.18
19	0.04	0.09	0.11
20	0.10	0.15	0.37
21	0	0	0.03
22	0.02	0.07	0.11
23	0.04	0.13	0.25
24	0.19	0.27	0.36
Mean (x_{ave})	0.09	0.20	0.26
SD (σ)	0.07	0.17	0.21
Coeff. of Var. (%)	78	85	81
$\frac{X_{max} - X_{ave}}{\sigma}$	2.3	3.7	3.9
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.2	1.1
Corrected Mean	**0.09**	**0.19**	**0.26**
Corrected SD	**0.06**	**0.11**	**0.13**

Table D.14. 2-body abrasion results for specimen C2FS1.

Specimen	C3FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.06	0.08	0.09
2	0.10	0.11	0.15
3	0.20	0.27	0.43
4	0.07	0.08	0.08
5	0.25	0.21	0.23
6	0.15	0.15	0.20
7	0.09	0.10	0.12
8	0.08	0.12	0.14
9	-	-	-
10	-	-	-
11	-	-	-
12	-	-	-
13	-	-	-
14	-	-	-
15	-	-	-
16	-	-	-
17	0.13	0.15	0.16
18	0.25	0.31	0.36
19	0.14	0.25	0.30
20	0.12	0.19	0.23
21	0.04	0.11	0.12
22	0.27	0.35	0.41
23	0.12	0.16	0.28
24	0.23	0.35	0.35
Mean (x_{ave})	0.14	0.19	0.23
SD (σ)	0.07	0.09	0.11
Coeff. of Var. (%)	50	47	48
$\frac{X_{max} - X_{ave}}{\sigma}$	1.9	1.8	1.6
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.2	1.4
Corrected Mean	**0.14**	**0.19**	**0.23**
Corrected SD	**0.07**	**0.09**	**0.11**

Table D.15. 2-body abrasion results for specimen C3FS1.

Specimen	C4FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.05	0.15	0.19
2	0.13	0.13	0.14
3	0.24	0.47	0.66
4	0.26	0.41	0.58
5	0.23	0.33	0.33
6	0.19	0.41	0.57
7	0.26	0.47	0.47
8	0.04	0.18	0.29
9	0.10	0.19	0.21
10	0.03	0.15	0.15
11	0.16	0.32	0.48
12	0.31	0.54	0.81
13	0.50	0.56	0.56
14	0.15	0.23	0.33
15	0.13	0.19	0.19
16	0.20	0.24	0.29
17	0.12	0.13	0.15
18	0.11	0.16	0.31
19	0.06	0.18	0.19
20	0.15	0.27	0.32
21	0.07	0.14	0.19
22	0.11	0.13	0.14
23	0.09	0.09	0.09
24	0.19	0.20	0.29
Mean (x_{ave})	0.16	0.26	0.33
SD (σ)	0.10	0.14	0.19
Coeff. of Var. (%)	63	54	58
$\frac{X_{max} - X_{ave}}{\sigma}$	3.4	2.1	2.5
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.2	1.3
Corrected Mean	**0.15**	**0.25**	**0.31**
Corrected SD	**0.08**	**0.13**	**0.17**

Table D.16. 2-body abrasion results for specimen C4FS1.

Specimen	M5FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.14	0.31	0.87
2	0	0.01	0.04
3	0.09	0.32	0.36
4	0.72	0.74	0.80
5	0.25	0.61	0.68
6	0.02	0.02	0.24
7	0.04	0.22	0.29
8	0.61	0.73	0.95
9	0.37	0.43	0.46
10	0.30	0.50	0.67
11	0	0	0.08
12	0.03	0.17	0.29
13	0.32	0.43	0.52
14	0.64	0.81	0.85
15	0.09	0.12	0.21
16	0.06	0.09	0.41
17	0	0.38	0.38
18	0.21	0.30	0.52
19	0.57	0.67	0.77
20	0.18	0.27	0.34
21	0	0.16	0.27
22	0.33	0.41	0.61
23	0.42	0.70	0.72
24	0.05	0.34	0.52
Mean (x_{ave})	0.23	0.36	0.49
SD (σ)	0.23	0.25	0.25
Coeff. of Var. (%)	100	69	51
$\frac{X_{max} - X_{ave}}{\sigma}$	2.1	1.8	1.8
$\frac{X_{ave} - X_{min}}{\sigma}$	1.0	1.4	1.8
Corrected Mean	**0.21**	**0.36**	**0.50**
Corrected SD	**0.21**	**0.25**	**0.25**

Table D.17. 2-body abrasion results for specimen M5FS1.

Specimen	M6FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.44	0.60	0.65
2	0.19	0.34	0.42
3	0.04	0.41	0.47
4	0.12	0.14	0.15
5	0.18	0.20	0.25
6	0.13	0.19	0.27
7	0.13	0.20	0.28
8	0.09	0.16	0.19
9	0.16	0.21	0.24
10	0.11	0.12	0.21
11	0.10	0.38	0.48
12	0.19	0.40	0.47
13	0.23	0.42	0.52
14	0.24	0.38	0.55
15	0.04	0.12	0.20
16	0.18	0.33	0.34
17	0.08	0.10	0.18
18	0.53	0.58	0.61
19	0.34	0.42	0.56
20	0.36	0.36	0.44
21	0.13	0.26	0.35
22	0.23	0.30	0.37
23	0.16	0.24	0.32
24	0.34	0.45	0.45
Mean (X_{ave})	0.20	0.30	0.37
SD (σ)	0.12	0.14	0.15
Coeff. of Var. (%)	60	47	41
$\frac{X_{max} - X_{ave}}{\sigma}$	2.8	2.1	1.9
$\frac{X_{ave} - X_{min}}{\sigma}$	1.3	1.4	1.5
Corrected Mean	**0.19**	**0.29**	**0.37**
Corrected SD	**0.10**	**0.13**	**0.15**

Table D.18. 2-body abrasion results for specimen M6FS1.

Specimen	M8FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.27	0.43	0.45
2	0.35	0.36	0.37
3	0.19	0.33	0.33
4	0.25	0.37	0.38
5	0.16	0.17	0.22
6	0.43	0.51	0.49
7	0.05	0.11	0.12
8	0.13	0.40	0.52
9	0.07	0.19	0.21
10	0.08	0.22	0.24
11	0.13	0.20	0.19
12	0.04	0.09	0.13
13	0.29	0.52	0.74
14	0.27	0.43	0.55
15	0.28	0.35	0.35
16	0.06	0.18	0.34
17	0.14	0.19	0.22
18	0.15	0.20	0.20
19	0.19	0.27	0.43
20	0.22	0.31	0.44
21	0.12	0.18	0.22
22	0.06	0.16	0.32
23	0.17	0.17	0.23
24	0.11	0.30	0.49
Mean (x_{ave})	0.18	0.28	0.34
SD (σ)	0.10	0.12	0.15
Coeff. of Var. (%)	56	43	44
$\frac{X_{max} - X_{ave}}{\sigma}$	2.5	2.0	2.7
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.6	1.5
Corrected Mean	**0.16**	**0.27**	**0.32**
Corrected SD	**0.09**	**0.11**	**0.13**

Table D.19. 2-body abrasion results for specimen M8FS1.

Specimen	J9FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.11	0.24	0.39
2	0.02	0.08	0.14
3	0.13	0.27	0.44
4	0.32	0.46	0.60
5	0.13	0.30	0.54
6	0.04	0.07	0.15
7	0.24	0.33	0.58
8	0.38	0.53	0.59
9	0.04	0.22	-
10	0.07	0.24	0.36
11	0.10	0.34	0.37
12	0.18	0.37	0.39
13	0.18	0.18	0.54
14	0.13	0.30	0.46
15	0.15	0.27	0.30
16	0.24	0.33	0.35
17	0.27	0.43	0.64
18	0.24	0.44	0.54
19	0.05	0.18	0.29
20	0.12	0.28	0.51
21	0.30	0.36	0.39
22	0.20	0.25	0.30
23	0.01	0.02	0.18
24	0.12	0.17	0.23
Mean (X_{ave})	0.16	0.28	0.40
SD (σ)	0.10	0.12	0.16
Coeff. of Var. (%)	63	43	40
$\frac{X_{max} - X_{ave}}{\sigma}$	2.2	2.1	1.5
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	2.2	1.6
Corrected Mean	**0.15**	**0.27**	**0.39**
Corrected SD	**0.09**	**0.12**	**0.16**

Table D.20. 2-body abrasion results for specimen J9FS1.

Specimen	J10FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.14	0.23	0.39
2	0.13	0.22	0.28
3	0.07	0.19	0.26
4	0.18	0.31	0.32
5	0.14	0.17	0.45
6	0.12	0.23	0.47
7	0.11	0.28	0.39
8	0.28	0.48	0.60
9	0.01	0.07	0.18
10	0.08	0.36	0.32
11	0.10	0.12	0.21
12	0.03	0.14	0.32
13	0.04	0.27	0.43
14	0.22	0.65	0.74
15	0.22	0.43	0.52
16	0.12	0.30	0.36
17	0.13	0.26	0.36
18	0.17	0.32	0.32
19	0.11	0.33	0.41
20	0.16	0.23	0.37
21	0.07	0.19	0.40
22	0.18	0.28	0.52
23	0.15	0.26	0.52
24	0.15	0.43	0.47
Mean (x_{ave})	0.13	0.28	0.40
SD (σ)	0.06	0.13	0.13
Coeff. of Var. (%)	46	46	33
$\frac{X_{max} - X_{ave}}{\sigma}$	2.5	2.8	2.6
$\frac{X_{ave} - X_{min}}{\sigma}$	2.0	1.6	1.7
Corrected Mean	**0.12**	**0.27**	**0.39**
Corrected SD	**0.06**	**0.10**	**0.10**

Table D.21. 2-body abrasion results for specimen J10FS1.

Specimen	J11FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.40	0.42	0.56
2	0.25	0.31	0.40
3	0.06	0.11	0.11
4	0.30	0.35	0.37
5	0.25	0.25	0.42
6	0.03	0.14	0.21
7	0.02	0.11	0.20
8	0.63	0.64	0.89
9	0.35	0.35	0.42
10	0.18	0.45	0.56
11	0.18	0.32	0.39
12	0.40	0.56	0.58
13	0.34	0.40	0.53
14	0.03	0.05	0.11
15	0	0.21	0.24
16	1.18	1.30	1.37
17	1.03	1.36	1.45
18	0.69	0.94	1.07
19	0.11	0.19	0.20
20	0.02	0.37	0.37
21	0.06	0.08	0.08
22	0.15	0.24	0.36
23	0.06	0.12	0.12
24	0	0.07	0.07
Mean (x_{ave})	0.28	0.39	0.46
SD (σ)	0.32	0.36	0.38
Coeff. of Var. (%)	114	92	83
$\frac{x_{max} - x_{ave}}{\sigma}$	2.8	2.7	2.6
$\frac{x_{ave} - x_{min}}{\sigma}$	0.9	0.9	1.0
Corrected Mean	**0.21**	**0.30**	**0.38**
Corrected SD	**0.20**	**0.22**	**0.26**

Table D.22. 2-body abrasion results for specimen J11FS1.

Specimen	J12FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.26	0.46	0.54
2	0.13	0.33	0.33
3	0.03	0.10	0.21
4	0.02	0.19	0.27
5	0.32	0.75	1.25
6	0.21	0.57	0.73
7	0.09	0.25	0.42
8	0.09	0.12	0.13
9	0.71	0.94	0.98
10	0.39	0.52	0.58
11	0	0	0
12	0.07	0.23	0.48
13	0.24	0.67	0.87
14	0.12	0.53	0.60
15	0.01	0.03	0.14
16	0.14	0.47	0.70
17	0.07	0.17	0.30
18	0	0.14	0.17
19	0.15	0.90	1.26
20	0.25	0.30	0.37
21	0.08	0.76	0.93
22	0.18	0.57	0.99
23	0.05	0.15	0.26
24	1.42	1.64	1.83
Mean (x_{ave})	0.21	0.45	0.60
SD (σ)	0.30	0.37	0.44
Coeff. of Var. (%)	143	82	73
$\frac{X_{max} - X_{ave}}{\sigma}$	4.0	3.2	2.8
$\frac{X_{ave} - X_{min}}{\sigma}$	0.7	1.2	1.4
Corrected Mean	**0.16**	**0.40**	**0.54**
Corrected SD	**0.16**	**0.28**	**0.36**

Table D.23. 2-body abrasion results for specimen J12FS1.

Specimen	CSF1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.12	0.13	0.13
2	0.26	0.28	0.29
3	0.25	0.29	0.29
4	0.07	0.11	0.11
5	0.02	0.07	0.08
6	0.14	0.19	0.19
7	0.16	0.18	0.23
8	0.07	0.11	0.11
9	0.04	0.07	0.07
10	0.10	0.10	0.12
11	0.14	0.16	0.18
12	0.07	0.11	0.12
13	0.09	0.13	0.14
14	0.19	0.19	0.20
15	0.21	0.22	0.22
16	0.11	0.13	0.14
17	0.10	0.14	0.13
18	0.07	0.10	0.13
19	0.10	0.13	0.13
20	0.09	0.10	0.11
21	0.10	0.13	0.14
22	0.08	0.12	0.12
23	0.22	0.25	0.28
24	0.15	0.18	0.18
Mean (x_{ave})	0.13	0.15	0.16
SD (σ)	0.06	0.06	0.06
Coeff. of Var. (%)	46	40	38
$\frac{X_{max} - X_{ave}}{\sigma}$	2.2	2.3	2.2
$\frac{X_{ave} - X_{min}}{\sigma}$	1.8	1.3	1.3
Corrected Mean	**0.11**	**0.14**	**0.15**
Corrected SD	**0.05**	**0.05**	**0.05**

Table D.24. 2-body abrasion results for specimen CSF1, the fine aggregate control.

Specimen	C1FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.01	0.94	-
2	0.57	1.92	-
3	1.52	1.72	-
4	0.24	0.83	-
5	0.18	0.66	-
6	0.62	1.76	-
7	0.95	1.07	-
8	0.17	0.33	-
9	0.02	0.71	-
10	0.09	0.58	-
11	0.30	0.60	-
12	0.52	0.70	-
13	0.89	1.85	-
14	0.63	2.42	-
15	0.89	2.85	-
16	0.06	0.78	-
17	0.44	1.62	-
18	0.56	0.80	-
19	0.23	0.98	-
20	0.35	2.05	-
21	0.47	0.75	-
22	0.14	0.49	-
23	0.22	0.77	-
24	0.26	1.82	-
Mean (X_{ave})	0.43	1.21	-
SD (σ)	0.36	0.69	-
Coeff. of Var. (%)	84	57	-
$\frac{X_{max} - X_{ave}}{\sigma}$	3.0	2.4	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.2	1.3	-
Corrected Mean	**0.38**	**1.14**	-
Corrected SD	**0.28**	**0.60**	-

Table D.25. Wet abrasion results for specimen C1FS1.

Specimen	C2FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	1.44	-	-
2	0.48	-	-
3	2.49	-	-
4	0.58	-	-
5	0	-	-
6	1.99	-	-
7	0.24	-	-
8	0.18	-	-
9	0.14	-	-
10	0.49	-	-
11	0.70	-	-
12	1.96	-	-
13	1.48	-	-
14	1.01	-	-
15	0.91	-	-
16	1.40	-	-
17	0.42	-	-
18	2.32	-	-
19	0.15	-	-
20	0.56	-	-
21	1.24	-	-
22	3.70	-	-
23	2.61	-	-
24	0.85	-	-
Mean (x_{ave})	1.14	-	-
SD (σ)	0.96	-	-
Coeff. of Var. (%)	84	-	-
$\frac{x_{max} - x_{ave}}{\sigma}$	2.7	-	-
$\frac{x_{ave} - x_{min}}{\sigma}$	1.2	-	-
Corrected Mean	**1.03**	-	-
Corrected SD	**0.80**	-	-

Table D.26. Wet abrasion results for specimen C2FS1.

Specimen	C3FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.08	0.78	-
2	0.12	0.35	-
3	0.06	1.56	-
4	0	1.19	-
5	0.16	0.33	-
6	0.19	0.64	-
7	0.21	0.47	-
8	0.10	0.78	-
9	0.14	-	-
10	0.30	-	-
11	0.39	-	-
12	0.42	-	-
13	0.68	-	-
14	0.29	-	-
15	0.21	-	-
16	0.53	-	-
17	0.68	-	-
18	0.69	-	-
19	0.38	-	-
20	0.65	-	-
21	0.03	-	-
22	0.31	-	-
23	0.76	-	-
24	0.33	-	-
Mean (x_{ave})	0.34	0.70	-
SD (σ)	0.23	0.42	-
Coeff. of Var. (%)	68	60	-
$\frac{X_{max} - X_{ave}}{\sigma}$	1.8	2.0	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	0.9	-
Corrected Mean	**0.34**	**0.56**	-
Corrected SD	**0.23**	**0.20**	-

Table D.27. Wet abrasion results for specimen C3FS1.

Specimen	C4FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.28	0.58	0.58
2	0.33	0.60	0.67
3	0.39	0.62	1.05
4	0.41	0.65	1.07
5	0.48	0.60	1.04
6	0.33	1.17	1.24
7	0.16	0.32	0.95
8	0.24	0.28	0.70
9	-	-	-
10	0.10	0.54	-
11	0.33	0.91	-
12	0.39	0.47	-
13	0.63	0.81	-
14	0.33	0.62	-
15	0.17	0.78	-
16	0.14	0.15	-
17	0.12	0.15	0.15
18	0.26	0.37	0.66
19	0.39	0.62	1.30
20	0.06	0.18	0.38
21	0.10	0.26	0.42
22	0.19	0.25	0.26
23	0.18	0.26	0.42
24	0.15	0.39	0.41
Mean (x_{ave})	0.27	0.50	0.71
SD (σ)	0.14	0.26	0.36
Coeff. of Var. (%)	52	52	51
$\frac{x_{max} - x_{ave}}{\sigma}$	2.6	2.6	1.6
$\frac{x_{ave} - x_{min}}{\sigma}$	1.5	1.3	1.6
Corrected Mean	**0.25**	**0.47**	**0.71**
Corrected SD	**0.12**	**0.22**	**0.36**

Table D.28. Wet abrasion results for specimen C4FS1.

Specimen	M5FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.33	0.94	-
2	0.55	1.15	-
3	0.17	0.85	-
4	0.57	1.46	-
5	0.24	0.59	-
6	0.29	0.89	-
7	0.15	0.67	-
8	0.34	0.69	-
9	0.12	0.61	-
10	0.59	0.70	-
11	0.90	0.90	-
12	0.52	1.28	-
13	0.11	0.80	-
14	0.04	0.24	-
15	0.71	1.17	-
16	0.58	1.15	-
17	0.21	0.71	-
18	0.28	0.67	-
19	0.86	1.70	-
20	0.31	0.56	-
21	0.05	1.19	-
22	0.47	-	-
23	1.09	1.59	-
24	0.34	0.93	-
Mean (x_{ave})	0.41	0.93	-
SD (σ)	0.28	0.36	-
Coeff. of Var. (%)	68	39	-
$\frac{x_{max} - x_{ave}}{\sigma}$	2.4	2.1	-
$\frac{x_{ave} - x_{min}}{\sigma}$	1.3	1.9	-
Corrected Mean	**0.38**	**0.90**	-
Corrected SD	**0.25**	**0.32**	-

Table D.29. Wet abrasion results for specimen M5FS1.

Specimen	M6FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.28	0.58	-
2	0.44	1.31	-
3	0.19	1.23	-
4	0.47	0.98	-
5	0.23	1.12	-
6	0.43	0.73	-
7	0.42	0.65	-
8	0.27	0.27	-
9	0.45	0.51	-
10	0.49	0.64	-
11	0.28	0.72	-
12	0.12	0.13	-
13	0.25	1.69	-
14	0.41	0.97	-
15	0.42	0.85	-
16	0.23	0.27	-
17	0.34	0.51	-
18	0.42	0.42	-
19	0.31	0.49	-
20	0.33	0.86	-
21	0.61	0.82	-
22	0.62	1.00	-
23	0.26	0.92	-
24	0.19	0.25	-
Mean (x_{ave})	0.35	0.75	-
SD (σ)	0.13	0.37	-
Coeff. of Var. (%)	37	49	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.1	2.5	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.8	1.7	-
Corrected Mean	**0.33**	**0.71**	-
Corrected SD	**0.11**	**0.32**	-

Table D.30. Wet abrasion results for specimen M6FS1.

Specimen	M8FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.39	0.65	-
2	0.34	0.48	-
3	0.19	1.07	-
4	0.25	0.31	-
5	0.25	0.65	-
6	0.28	0.32	-
7	0.60	0.82	-
8	0.31	0.36	-
9	0.51	1.18	-
10	0.31	0.80	-
11	0.23	0.41	-
12	0.23	0.84	-
13	0.75	1.49	-
14	0.28	0.68	-
15	0.33	0.51	-
16	0.60	0.99	-
17	0.85	1.08	-
18	0.31	0.42	-
19	0.53	0.69	-
20	0.55	0.62	-
21	0.63	1.28	-
22	0.22	0.52	-
23	0.73	0.92	-
24	0.66	0.94	-
Mean (x_{ave})	0.43	0.75	-
SD (σ)	0.20	0.32	-
Coeff. of Var. (%)	47	43	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.1	2.3	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.2	1.4	-
Corrected Mean	**0.41**	**0.72**	-
Corrected SD	**0.18**	**0.28**	-

Table D.31. Wet abrasion results for specimen M8FS1.

Specimen	J9FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	-	-	-
2	0.49	-	-
3	0.73	-	-
4	0.71	-	-
5	1.06	-	-
6	0.26	-	-
7	0.10	-	-
8	1.20	-	-
9	0.24	-	-
10	0.75	-	-
11	0.38	-	-
12	0.51	-	-
13	1.14	-	-
14	0.52	-	-
15	0.14	-	-
16	0.31	-	-
17	0.94	-	-
18	0.32	-	-
19	0.93	-	-
20	0.54	-	-
21	0.63	-	-
22	0.45	-	-
23	0.59	-	-
24	0.49	-	-
Mean (x_{ave})	0.59	-	-
SD (σ)	0.31	-	-
Coeff. of Var. (%)	53	-	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.0	-	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.6	-	-
Corrected Mean	**0.56**	-	-
Corrected SD	**0.28**	-	-

Table D.32. Wet abrasion results for specimen J9FS1.

Specimen	J10FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.62	0.82	0.92
2	0.49	0.71	0.86
3	0.24	0.27	1.04
4	0.09	0.45	0.58
5	0.56	1.08	1.15
6	0.26	0.30	0.78
7	0.41	0.74	1.53
8	0.28	0.52	0.72
9	0.39	0.93	1.20
10	0.31	0.51	1.42
11	0.53	0.77	1.75
12	0.25	0.59	0.83
13	0.14	0.81	1.91
14	0.15	0.80	2.68
15	0.75	1.27	1.79
16	0.85	1.02	1.23
17	0.41	0.60	0.68
18	0.41	1.08	1.62
19	0.36	0.68	1.00
20	0.28	1.49	2.58
21	0.93	1.19	2.31
22	0.36	0.78	0.97
23	0.24	0.52	1.17
24	0.41	1.05	1.88
Mean (X_{ave})	0.41	0.79	1.36
SD (σ)	0.22	0.30	0.60
Coeff. of Var. (%)	54	38	44
$\frac{X_{max} - X_{ave}}{\sigma}$	2.4	2.3	2.2
$\frac{X_{ave} - X_{min}}{\sigma}$	1.5	1.7	1.1
Corrected Mean	**0.36**	**0.76**	**1.24**
Corrected SD	**0.16**	**0.27**	**0.47**

Table D.33. Wet abrasion results for specimen J10FS1.

Specimen	J11FS1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.48	0.56	-
2	0.56	0.95	-
3	0.10	0.45	-
4	0.07	0.13	-
5	0.63	1.03	-
6	0.40	0.74	-
7	0.16	0.39	-
8	0.65	0.84	-
9	0.33	0.75	-
10	0.10	0.61	-
11	0.24	0.47	-
12	0.22	0.39	-
13	0.08	0.17	-
14	0.22	0.34	-
15	0.72	1.19	-
16	0.34	0.35	-
17	0.83	1.60	-
18	1.11	2.78	-
19	0.40	1.02	-
20	0.12	0.22	-
21	0.42	0.58	-
22	1.01	1.68	-
23	0.45	0.58	-
24	0.50	0.65	-
Mean (x_{ave})	0.42	0.77	-
SD (σ)	0.29	0.59	-
Coeff. of Var. (%)	69	77	-
$\frac{X_{max} - X_{ave}}{\sigma}$	2.4	3.4	-
$\frac{X_{ave} - X_{min}}{\sigma}$	1.2	1.1	-
Corrected Mean	**0.36**	**0.68**	-
Corrected SD	**0.22**	**0.41**	-

Table D.34. Wet abrasion results for specimen J11FS1.

Specimen	J12FS1		
Reading No.	**5 Min. Depth (mm)**	**10 Min Depth (mm)**	**15 Min. Depth (mm)**
1	0.40	0.87	-
2	0.10	1.16	-
3	0.53	1.00	-
4	0.66	1.16	-
5	0.76	1.25	-
6	0.10	1.15	-
7	0.55	1.05	-
8	0.92	1.04	-
9	0.31	0.75	-
10	0.09	0.49	-
11	0.23	0.78	-
12	0.46	1.22	-
13	0.41	0.96	-
14	0.35	1.75	-
15	0.32	0.69	-
16	0.84	1.89	-
17	0.71	-	-
18	0.63	-	-
19	1.10	-	-
20	0.11	-	-
21	0.12	-	-
22	0.86	-	-
23	0.35	-	-
24	0.40	-	-
Mean (x_{ave})	0.47	-	-
SD (σ)	0.29	-	-
Coeff. of Var. (%)	62	-	-
$\frac{x_{max} - x_{ave}}{\sigma}$	2.2	-	-
$\frac{x_{ave} - x_{min}}{\sigma}$	1.3	-	-
Corrected Mean	**0.44**	**1.02**	-
Corrected SD	**0.26**	**0.30**	-

Table D.35. Wet abrasion results for specimen J12FS1.

Specimen	CSF1		
Reading No.	5 Min. Depth (mm)	10 Min Depth (mm)	15 Min. Depth (mm)
1	0.11	0.15	0.38
2	0.11	0.13	0.17
3	0.14	0.16	0.88
4	0.17	0.21	0.39
5	0.08	0.08	0.14
6	0.12	0.12	0.17
7	0.12	0.13	0.36
8	0.08	0.08	0.08
9	0.18	0.43	1.35
10	0.15	0.19	0.34
11	0.05	0.07	0.07
12	0.28	0.41	0.54
13	0.23	0.46	1.25
14	0.24	0.41	0.45
15	0.10	0.11	0.15
16	0.13	0.15	0.44
17	0.14	0.36	0.40
18	0.16	0.32	0.35
19	0.12	0.15	0.74
20	0.20	0.58	0.82
21	0.34	0.58	0.64
22	0.21	0.35	0.40
23	0.08	0.08	0.35
24	0.14	0.18	0.21
Mean (X_{ave})	0.15	0.25	0.46
SD (σ)	0.07	0.16	0.34
Coeff. of Var. (%)	47	64	74
$\frac{X_{max} - X_{ave}}{\sigma}$	2.7	2.1	2.6
$\frac{X_{ave} - X_{min}}{\sigma}$	1.4	1.1	1.1
Corrected Mean	**0.15**	**0.22**	**0.39**
Corrected SD	**0.06**	**0.13**	**0.23**

Table D.36. Wet abrasion results for specimen CSF1, the fine aggregate control.

Appendix E

Statistical Analyses

E.1 Student's *t*-test

The Student's t-test is a recognised, Leaver and Thomas (1974), method for determining whether a significant difference exists between two data sets, i.e. whether each data set belongs to a separate population. The statistic t is defined as the ratio of the difference of the means of two samples to the standard deviation of the difference of their means, and can be represented by the following equation, Leaver and Thomas (1974): -

$$t = \left(x_{ave(a)} - x_{ave(b)}\right)\sqrt{\left[\left(\frac{n_a n_b}{n_a + n_b}\right)\left(\frac{\upsilon}{n_a S_a^2 + n_b S_b^2}\right)\right]}$$

Where : -

$x_{ave(a)}$ = The mean of data set a.

$x_{ave(b)}$ = The mean of data set b.

n_a = The number of readings in data set a.

n_b = The number of readings in data set b.

S_a^2 = The variance of data set a, i.e. the square of the standard deviation of data set a.

S_b^2 = The variance of data set b, i.e. the square of the standard deviation of data set b.

$\upsilon = n_a + n_b - 2$ = The number of degrees of freedom.

The calculated statistic t is compared with values given in 'Student t' tables for specific combinations of degrees of freedom and level of significance (t_{crit})to determine if there is a significant difference between the two data sets. If the calculated value of t is below that of the corresponding value in the table, there is no significant difference between the data sets at the given level of significance. A 5 per cent level of significance has been used for these analyses as it is a commonly used level in engineering and technological applications, Kennedy and Neville (1976). The statistical data from the comparison of 2-body and 3-body abrasion is presented in *Tables E.1* to *E4*, with data set a representing 3-body results and data set b representing 2-body results.

E.1.1 Comparison of the 2-Body and 3-Body Results for the Coarse Aggregate Mixes.

For the data presented in *Tables E.1* and *E.2*, significant differences exist between the 2-body and 3-body results for specimens C1S1, C3S1, M5S1, J9S1, J10S1 and the coarse aggregate control mix CS2.

E.1.2 Comparison of the 2-Body and 3-Body Results for the fine Aggregate Mixes.

For the data presented in *Tables E.3* and *E.4*, significant differences exist between the 2-body and the 3-body results for specimens C2FS1, C3FS1, J10FS1 and J11FS1.

E.1.3 Comparison of the 3-Body and Wet Abrasion Results for the Fine Aggregate Control Mix.

Tables E.5 and E.6 show the statistical data for the comparison of 3-body abrasion with both 10 and 15 minute wet abrasion. The subscript c denotes data for wet abrasion tests. The 10 minute wet abrasion value is that used throughout the project, and does not show a statistical difference from the 3-body results. The 15 minute value does show a statistical difference as the t value is greater than t_{crit}.

E.1.4 Comparison of the 3-Body Abrasion Results from the Left and Centre Slabs.

This statistical analysis was undertaken as part of the test programme examining the effect of varying the content of low-grade coarse aggregate, and the results are presented in *Tables E.7* and *E.8*. Statistical data relating to the 3-body abrasion of the left slab is designated with the subscript d whilst that of the centre slab is designated with the subscript e. Although one data set indicates a significant difference between the two slabs, five of the six did not and so it is considered that the position within the mould did not affect the 3-body abrasion resistance.

Specimen	n_a	n_b	υ
Control (CS2)	22	23	43
C1S1	22	19	39
C2S1	22	18	38
C3S1	22	22	42
C4S1	20	19	37
M5S1	18	23	39
M6aS1	19	15	32
M6bS1	23	23	44
M8S1	22	23	43
J9S1	20	23	41
J10S1	23	22	43
J11S1	22	22	42
J12S1	23	23	44

Table E.1 Number of readings and number of the degrees of freedom for the statistical analysis of the coarse aggregate mixes.

Specimen	$x_{ave(a)}$	$x_{ave(b)}$	S_a^2	S_b^2	t	t_{crit} (5 %)
Control (CS2)	0.05	0.10	0.001	0.004	3.256	2.021
C1S1	0.22	0.07	0.017	0.003	4.560	2.021
C2S1	0.47	0.48	0.063	0.116	0.104	2.021
C3S1	0.32	0.07	0.058	0.002	4.680	2.021
C4S1	0.20	0.23	0.020	0.026	0.602	2.021
M5S1	0.14	0.06	0.017	0.001	2.768	2.021
M6aS1	0.05	0.06	0.002	0.001	0.711	2.042
M6bS1	0.18	0.17	0.008	0.005	0.411	2.021
M8S1	0.19	0.14	0.014	0.005	1.690	2.021
J9S1	0.59	0.24	0.090	0.048	4.300	2.021
J10S1	0.14	0.09	0.005	0.001	2.970	2.021
J11S1	0.19	0.16	0.005	0.008	1.206	2.021
J12S1	0.08	0.07	0.001	0.001	1.049	2.021

Table E.2 The means, variance and *t* values for the statistical analysis of the coarse aggregate mixes.

Specimen	n_a	n_b	υ
Control (CSF1)	23	22	43
C1FS1	23	23	44
C2FS1	20	23	41
C3FS1	23	16	37
C4FS1	23	23	44
M5FS1	22	24	44
M6FS1	23	24	45
M8FS1	23	23	44
J9FS1	21	24	43
J10FS1	24	23	45
J11FS1	23	22	43
J12FS1	23	23	44

Table E.3 Number of readings and number of the degrees of freedom for the statistical analysis of the fine aggregate mixes.

Specimen	$x_{ave(a)}$	$x_{ave(b)}$	S_a^2	S_b^2	t	t_{crit} (5 %)
Control (CSF1)	0.18	0.15	0.003	0.003	1.795	2.021
C1FS1	0.39	0.32	0.032	0.020	1.440	2.021
C2FS1	0.41	0.26	0.053	0.017	2.607	2.021
C3FS1	0.37	0.23	0.023	0.012	3.081	2.021
C4FS1	0.29	0.31	0.026	0.029	0.400	2.021
M5FS1	0.42	0.50	0.084	0.063	0.981	2.021
M6FS1	0.48	0.37	0.084	0.023	1.605	2.021
M8FS1	0.38	0.32	0.032	0.017	1.271	2.021
J9FS1	0.50	0.39	0.040	0.026	1.995	2.021
J10FS1	0.46	0.39	0.032	0.010	2.992	2.021
J11FS1	0.56	0.38	0.090	0.068	2.096	2.021
J12FS1	0.41	0.54	0.058	0.130	1.406	2.021

Table E.4 The means, variance and *t* values for the statistical analysis of the fine aggregate mixes.

Specimen	n_a	n_c	υ
CSF1- 10 min wet	24	24	46
CSF1- 15 min wet	24	24	46

Table E.5 Number of readings and number of degrees of freedom for comparison of 3-body abrasion with 10 and 15 minute wet abrasion of specimen CSF1.

Specimen	$x_{ave(a)}$	$x_{ave(c)}$	S_a^2	S_c^2	t	t_{crit} (5 %)
CSF1- 10 min wet	0.18	0.22	0.0025	0.0169	1.406	2.021
CSF1- 15 min wet	0.18	0.39	0.0025	0.0529	4.370	2.021

Table E.6 The means, variance and t values for comparison of 3-body abrasion with 10 and 15 minute wet abrasion of specimen CSF1.

Specimen	n_d	n_e	υ
0 % C2	23	23	44
12 % C2	23	23	44
25 % C2	23	23	44
38 % C2	22	21	41
50 % C2	23	24	45
75 % C2	23	23	44

Table E.7 Number of readings and number of degrees of freedom for comparison of 3-body abrasion of the left and centre slabs.

Specimen	$x_{ave(d)}$	$x_{ave(e)}$	S_d^2	S_e^2	t	t_{crit} (5 %)
0 % C2	1487.70	1485.39	21.623	29.376	1.551	2.017
12 % C2	1429.09	1433.26	85.933	47.197	1.733	2.017
25 % C2	1484.43	1485.09	159.770	87.423	0.021	2.017
38 % C2	1431.00	1429.38	116.856	65.286	0.815	2.020
50 % C2	1471.52	1470.63	33.408	96.04	0.377	2.017
75 % C2	1446.91	1468.74	324.720	113.423	5.001	2.017

Table E.8 The means, variance and t values for comparison of 3-body abrasion of the left and centre slabs.

Appendix F

Cement Chemistry

Chemical Constituent	% Present
SiO_3	20.20
I.R.	1.00
Al_2O_3	5.50
Fe_2O_3	2.60
CaO	64.00
MgO	1.40
SO_3	3.10
Na_2O	0.10
K_2O	0.78
L.O.I.	1.00
Free Lime	1.70

Table F.1. Chemical Analysis of Blue Circle OPC Cement ex-Cauldon Works.

Appendix G

Mohs' Scale of Hardness

Mineral	Hardness
Talc	1
Gypsum	2
Calcite	3
Fluorspar	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

Table G.1. The Mohs' scale of hardness.