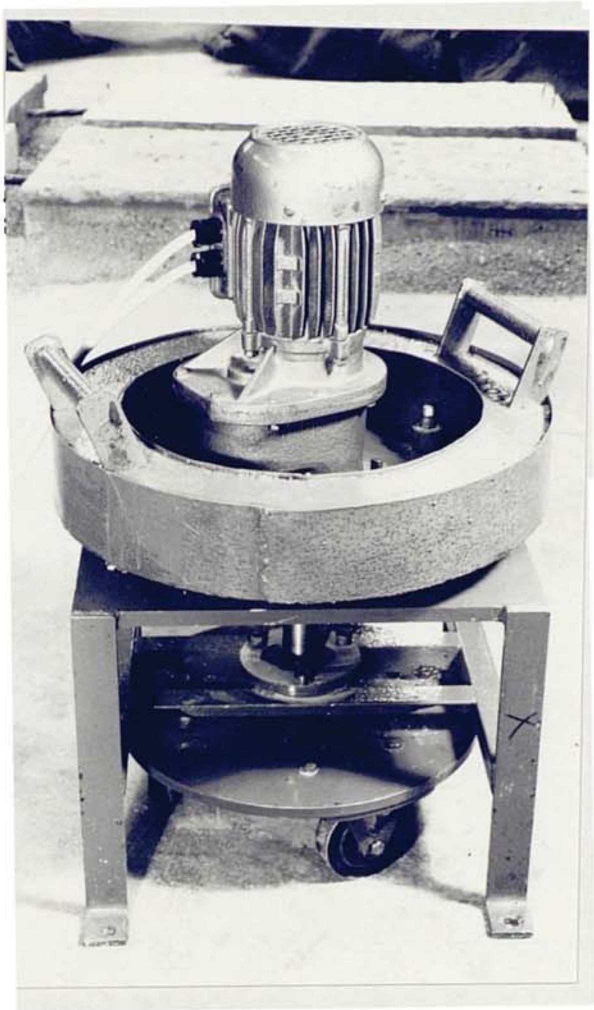

Plate 5.1 The Basic Accelerated Abrasion Apparatus With the Lead Collar

Plate 5.2 The Rolling Wheels Type of Head

# ABRASION RESISTANCE OF CONCRETE

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Thesis submitted for the degree
of Doctor of Philosophy

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To My Wife

THE UNIVERSITY OF ASTON IN BIRMINGHAM

"ABRASION RESISTANCE OF CONCRETE"

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## SUMMARY

This thesis describes an experimental study of the abrasion resistance of concrete at both the macro and micro levels. This is preceded by a review related to friction and wear, methods of test for assessing abrasion resistance, and factors influencing the abrasion resistance of concrete.

A versatile test apparatus was developed to assess the abrasion resistance of concrete. This could be operated in three modes and a standardised procedure was established for all tests. A laboratory programme was undertaken to investigate the influence, on abrasion resistance, of three major factors - finishing techniques, curing regimes and surface treatments. The results clearly show that abrasion resistance was significantly affected by these factors, and tentative mechanisms were postulated to explain these observations.

To substantiate these mechanisms, the concrete specimens from the macro-study were subjected to micro-structural investigation, using such techniques as Mercury Intrusion Porosimetry, Microhardness, Scanning Electron Microscopy, Petrography and Differential Thermal Analysis. The results of this programme clearly demonstrated that the abrasion resistance of concrete is primarily dependent on the microstructure of the concrete nearest to the surface.

The viability of indirectly assessing the abrasion resistance was investigated using three non-destructive techniques - Ultrasonic Pulse Velocity, Schmidt Rebound Hardness, and the Initial Surface Absorption Test. The Initial Surface Absorption was found to be most sensitive to factors which were shown to have influenced the abrasion resistance of concrete.

An extensive field investigation was also undertaken. The results were used to compare site and laboratory practices, and the performance in the accelerated abrasion test with the service wear. From this study, criteria were developed for assessing the quality of concrete floor slabs in terms of abrasion resistance.

KEY WORDS

Abrasion Resistance,
concrete slab,
surface matrix,
microstructure,
pore size distribution

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# CHAPTER 1

## INTRODUCTION

The floor surface in industrial premises is usually the only part of the structure which can be subjected to heavy and continuous wear under the severe, and sometimes exceedingly destructive, service associated with modern industrial activities. It is imperative that the surface of the concrete floor is capable of withstanding the normal service loadings with the minimum of dusting and wear. Dusting can be costly to the factory occupier as the dust, from the surface, can interfere with the operation of precision machinery and delicate processes, and may also impair the quality of the end-product. Premature wear can have severe consequences leading to interuptions in the operations leading to losses of production and, ultimately, to factory closure for repair or replacement. Frequent repairs to concrete floors are expensive as are the associated cost due to factory closure. It is, therefore, clear that the abrasion resistance of concrete slabs in industrial premises is of great importance.

The problem of building durable and abrasion resistant floor is as old as concrete itself (1). Research on abrasion resistance has been recorded for more than 85 years (2). Most of the work has been conducted in the USA. In Europe, this work has mainly been limited to investigations in Sweden and Germany. Very little research has been undertaken in this country during the past 20 years, even though the annual cost of floor construction and repairs, in the UK, is in excess of several hundred millions of pounds (3).

There is no British Standard, or universally accepted method for assessing the abrasion resistance of concrete floors. Many test machines and procedures have been developed during individual investigations. Each has been specific to the particular study, thereby leading to wide disparities between the various test methods. Consequently, there is no universal classification system by which industrial floors may be rated in terms of abrasion resistance, although there are several general classification systems for floors (4,5). This has resulted in a situation where there are often disputes between the owner, consultant and contractor regarding the quality of concrete floor slabs.

The wealth of knowledge which has been accumulated over the years, in the field of abrasion resistance of concrete, is in such a state that concrete floors are still invariably specified in terms of compressive strength rather than the abrasion resistance. It has been found that compressive strength is not a very sensitive measure of the abrasion resistance of concrete (6) and, additionally, other factors such as finishing techniques, which influence the abrasion resistance, have little effect on the compressive strength. This suggests, therefore, that specifying the abrasion resistance in terms of compressive strength can result in over-designed or under-designed floors and, in either case, this is undesirable.

A major problem in the field of the abrasion resistance of concrete is that the mechanism by which material is removed from a concrete floor depends on the type of service to which the floor is exposed. With heavily loaded steel wheels the floor will be subjected to a combination of scratching or scuffing, friction and localised crushing of the surface matrix or aggregate. However, lightly loaded rubber tyres or foot traffic does not cause scratching or crushing, the wear largely being attributed to a rubbing action. This suggests that abrasion resistance has no meaning except in relation to the system which produces the abrasion. Thus, the system for measuring abrasion resistance can only be of value if it simulates the condition obtained in practice. This indicates that some form of classification is desirable for categorising concrete floors in different types of industrial environment.

During the last 85 years the majority of the published work, dealing with the abrasion resistance of concrete, has related to the macro-study of the abrasion resistance of concrete. This research has been directed towards determining those gross factors which influence the abrasion resistance and has included compressive strength, the physical properties of aggregate, finishing techniques, curing, etc. However, very little research effort has been directed towards relating the abrasion resistance to the micro-structure of the concrete as expressed by such parameters as the pore structure. The history of the study of the abrasion resistance of concrete has been characterised by a notable lack of research effort to link the macro-study of abrasion resistance with the micro-structural properties, and so possible explanations of the mechanisms of abrasion resistance have not been adequately related to the micro-structure of concrete.

Although a considerable amount of work has been carried out on the macro-study of abrasion resistance of concrete, the research has suffered over the years from a lack of interest by investigators in current site practices. This has resulted in a situation where the available data are mainly based on laboratory methods of construction which are no longer practised. Much of the existing laboratory data relate to small specimens finished by hand and, invariably, cured under water. This suggests that the applicability of current knowledge to actual floor slabs is open to question. It is remarkable that, although many millions of square metres of concrete floor slabs have been laid in this century, virtually no data are available on their standard or level of performance with respect to abrasion resistance. The construction and finishing has commonly been based on a combination of empiricism and experience.

It is clear that the abrasion resistance of concrete is a property of univeral interest, but one where there is a lack of quality data, based on a controlled methodology, so that it has been difficult to consider abrasion resistance in fundamental terms. This research project has been structured to tackle this dichotomy and, thereby, provide a rational explanation of the mechanisms controlling the abrasion resistance of concrete.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Friction and Wear

Tribology is defined as the Science and Technology of interacting surfaces in relative motion and of the practices relating thereto. It is suggested that the knowledge available from this field may help to explain some of the uncertainties in assessing the abrasion resistance of concrete. It was decided, therefore, to review the relevant literature.

### 2.1.1 Friction

Detailed treatment of the phenomena of friction is beyond the scope of the present work. However, a basic understanding of this subject is necessary for examining the mechanism(s) involved in wear.

#### 2.1.1.1 Laws of Friction

Friction is the resistance to motion which exists whenever two solid bodies in direct or indirect surface contact are made to slide relative to one another.

The two basic laws of friction are:-

(1) Frictional resistance is proportional to the weight of the object which is being moved.

(2) Frictional force is independent of the apparent area of contact.

The above two laws were first deduced by da Vinci (1519) and discussed by Amontons (1699) and later verified experimentally by Coulomb (1785). There is also a third law, attributed to Coulamb, which states that the interfacial resistance between two surfaces is independent of the velocity of sliding.

The two basic laws are generally valid (7). Exceptions to the first law occur when: (a) very hard and very soft material interacts, (b) when a very thin hard surface layer and a softer substrate is involved. Deviations from the second law occur when very smooth and clean surfaces are involved.

The third law which implies that the forces required to start sliding will be the same as the force to maintain sliding, at any specified velocity, has been shown by several researchers (8,9,10) to be invalid. Dokos (8) found that the static coefficient of friction (surfaces at rest) is a function of time of contact, while the kinetic coefficient of friction (surfaces in motion) is a function of velocity.

The static coefficient of friction is usually determined by measuring the force required to move a stationary object placed on a horizontal surface. Care is required to prevent shock loading and to keep the time of sticking under control. A dynamometer is used for measuring the kinetic coefficient of friction. More sophisticated devices for measuring friction have been described by Bowden and Tabor (11).

#### 2.1.1.2 Friction Theories

There are several general theories of friction. A very full and comprehensive account of the work of the various investigators proposing these theories has been given by Kragelskii (12). The view accepted in this country is based on the work of Bowden and Tabor (11) who proposed the Adhesion theory. Briefly, this theory suggests that some adhesion must occur at the regions of rubbing contact and that the shear force required to break these interfacial junctions is primarily responsible for the frictional force. The Adhesion theory has been criticised by Kragelskii (12), and Russian co-workers; this difference of opinion being summarised as follows: "They (Bowden and

Tabor) do not take into account the bulk deformation of the solids. An exception is the friction of highly elastic bodies which, in their opinion, is determined by the elastic hysteresis losses. It is our opinion that the primary factor determining friction is the bulk deformation of the material."

It is interesting to note that in the Adhesion theory, it is stated that friction is independent of roughness. Rabinowicz (7) has clearly demonstrated that the surface roughness does influence friction. He showed that, with very smooth surfaces, the friction tends to be high because the real area of contact increases excessively. In the case of very rough surfaces the friction is high since there is a need during sliding to lift one surface over the hump on the other. With the intermediate range of roughness, friction is at minimum and independent of roughness.

2.1.1.3 Frictional Properties of Brittle Materials

The developments in Tribology have largely been associated with the sliding of metals. It is suggested, however, that the general Adhesion theory is also applicable to brittle materials, such as concrete, and this is supported (11) by the following experimental observations:-

(1) The frictional properties of brittle materials are fairly uniform and of the same order of magnitude as those of metals.

(2) At the frictional interface, brittle fracture is restrained due to high local compressive stresses. This results in a situation whereby the brittle material flows plastically at the contact region, and gives an area of contact proportional to the load, similar to metals.

(3) Strong local adhesion occurs.

(4) The sliding mechanism is similar to that exhibited by metals, the difference being that the sliding surfaces may crack and fragment, but

this usually occurs after the sliding process has taken place.

The main difference between the frictional properties of metals and non-metals is that the surfaces of metals are quite vulnerable to contamination, while non-metal surfaces are not as vulnerable (7). Consequently, there is a large variation in the frictional properties of metals depending on the precise degree of cleanliness, whilst for non-metals there is less variation in the frictional properties.

It is interesting to note that when non-metals slide on other materials, either metal or non-metal, the frictional properties (7) will normally be those of the softer material. Furthermore, the harder material will usually become coated with the debris of the softer material and, in time, this sliding system will be one of the softer material sliding on itself.

#### 2.1.1.4 Rolling Friction

Rolling friction can be divided into two (7) separate cases:

(1) Rolling body is of irregular shape (e.g. a boulder or pebble).

(2) Rolling body is of near perfect geometric shape with a smooth surface.

The latter case is of interest in the present work. The resistance to motion of such a rolling body is due to a combination of several factors:

(1) Slip at the region of contact. If the contact of two bodies (say, a sphere and its track) were a point, then pure rolling condition prevails. But in practice the region of contact is elastically (and in extreme cases) plastically deformed. This results in a situation where contact is made over an area of some size, the points within it lying in different planes (see Figure 2.1). Therefore, pure rolling action cannot take place except at a very small number of points, but

at the other points there is a combination of rolling, together with a small degree of sliding or slip (7).

(2) Hysteresis losses.

(3) Other friction losses during rolling, e.g. loss of energy caused by lack of perfection of the rolling geometry, and losses caused by plastic deformation of asperities on the rolling surfaces, if these surfaces are not perfectly smooth.

Generally, the force of rolling friction is a very small fraction of the applied load, for example (7), the coefficient of rolling friction is about 0.001 for a hard steel roller on a hard steel surface.

### 2.1.2 Wear

Wear can be defined as the unintentional removal of material from the surface of bodies moving in contact with one another. Wear is believed to occur by the displacement and detachment of small fragments from a surface. The rate at which a given surface wears depends on several factors, such as surface microstructure, type of contact material, type of relative movement, nature of loading. Wear may be due to a combination of elementary mechanisms and it is often difficult to describe accurately the type of wear occuring in any given application. However, mechanical wear has been traditionally sub-divided into five categories (14):

(1) Adhesive Wear: This type of wear occurs when one smooth surface slides over another smooth surface under pressure, providing intimate contact between asperities. The detailed mechanism by which adhesion wear occurs is still a controversial topic, but the traditional explanation is based on the Adhesion Theory of Bowden and Tabor (11).

(2) Abrasive Wear: This is defined as the removal of material due to sliding contact with abrasive particles or a rough surface.

(3) Erosive Wear: Erosion occurs when particles impinge on the surface, resulting in both deformation and removal of surface material.

4) Fretting: This is due to slight oscillatory motions between two mating surfaces under load. The important difference between fretting and general reciprocating motion is that the former undergoes very small oscillatory motion.

(5) Fracture Wear: This form of wear is the result of the fracture failure of the material surface or sub-surface due to sliding, rolling or impacting motion.

The present work is mainly concerned with abrasive and fracture wear. Thus, the basic mechanisms and controlling factors of these types of wear are examined in the following sections.

2.1.2.1 Abrasive Wear

The abrasive wear process has been, traditionally, divided (14) into two groups: Two-body and Three-body abrasive wear.

(1) Two-body abrasive wear. This type of wear occurs when a rough surface or fixed abrasive particles slide across a surface to remove material (15).

(2) Three-body abrasive wear. Here the particles are loose and may move relative to one another, possibly rotating while sliding across the wearing surface (16).

Rabinowicz (16) carried out a detailed study of three-body abrasive wear. In this study he showed that, under similar loading conditions, the wear produced by three-body abrasion was an order of magnitude less than that produced by two-body abrasion. He suggested that this was because in the three-body abrasive wear, the abrasives spent some 90% of the time rolling and only 10% of the time sliding and abrading the surface.

2.1.2.1.1 Abrasive Wear Model

A simple quantitative expression for the volume of material removed during two-body abrasive wear was developed by Rabinowicz (7) who considered a rigid conical asperity,e.g.an abrasive cone, with sides of slope $\theta$, shown in Figure 2.2. He proposed that under a load P, the abrasive cone penetrates the softer surface, of hardness H, to an extent given by:

$$P = H\pi r^2$$

The volume V of the surface material removed during a horizontal motion x of the cone is a prism of base area rZ and height x. Thus

$$V = rzx$$
$$= r^2 x \operatorname{Tan} \theta \text{ (using } Z = r \operatorname{Tan} \theta)$$
$$= \frac{Px\operatorname{Tan}\theta}{H\pi}$$

Where the abrasive cones have different angles, a statistical average value Tan $\overline{\theta}$ may be selected to represent a given abrasive surface. By replacing $(\tan \theta)/\pi$ by k/3 the previous equation may be written as

$$V = \frac{KPx}{3H}$$

here K is the dimensionless abrasive wear coefficient.

This equation expresses some of the basic characteristics of abrasive wear. The volume of material removed is directly proportional to the load and distance travelled, and is inversely proportional to the hardness of the softer material.

In addition to the simplification of the shape of the abrasive cone, one item should be noted. The expression describes the amount of material which is displaced from its original position in the softer material. This displaced material is not necessarily detached from the base material. Under some conditions, it may be plastically deformed to the side of the groove with no material being removed.

The expression has been used widely by investigators in both metallic and non-metallic materials research. Many investigators have found that the wear resistance $\frac{Px}{V}$ is directly proportional to Vickers hardness number for many metallic materials (16-19), and also for a few non-metallic materials (20-22).

#### 2.1.2.2 Fracture Wear

There are two types of fracture wear. The first is observed in metallic materials, and the second is observed in brittle materials. The first type will not be discussed. Brittle fracture wear manifests itself in the form of cracks transverse to the direction of motion, and so layers of material spall off from the surfaces (7,13).

It has been found that the rate of wear of brittle materials is very high and rather variable, depending on specimen production and preparation (7). Rabinowicz (7) has suggested that the wear becomes higher for materials whose tensile strength ($\sigma_t$) is less than one third of their compressive strength ($\sigma_c$). It is suggested that, the maximum tensile stress behind a typical junction is about one third the compressive stress under the junction, Figure2.3. Thus, if the compressive stress is of the order of the yield stress, and if the tensile stress is less than one third of the yield value, tensile failure will take place behind the junction. For concrete, the relationship between compressive and tensile strength is variable (23), but the tensile strength will always be less than one third of the compressive strength.

## 2.2 Definition of Abrasion Resistance of Concrete Slab

In the previous section it was shown that the mechanisms by which wear occurs are complex and are difficult to accurately describe. This complexity is magnified when the abrasion resistance of concrete and, in particular, concrete slabs in an industrial environment, is considered. In such environments, the slabs are exposed to widely different service conditions (24).

Abrasion resistance has been defined by the ACI (25 ) as "the ability of a surface to resist being worn away by rubbing and friction". On the other hand, the ASTM Definition of Termsrelating to Erosion by Cavitation and Impingement, (26) defines abrasion as "wear by displacement of materials from a solid surface due to hard particles or hard protuberances sliding along the surface". Prior (27) has classified the wear of concrete surface by abrasion into four main types:-

1) Wear on concrete floors, due to foot traffic, light trucking and skidding, scraping, or sliding of objects on the surface (attrition).

(2) Wear on concrete road surfaces due to the movement of heavy vehicles (attrition plus scraping plus percussion).

(3) Wear on hydraulic structure, such as dams, spillways, bridge abutments and tunnels, due to the abrasive action of materials carried by water at low velocities, known as abrasive erosion (attrition plus scraping).

4) Wear on concrete dams, spillways and tunnels, where a high hydraulic gradient is present, generally known as cavitation erosion (percussion).

The ACI and the ASTM definitions relate only to abrasive wear, while Prior's classification includes abrasive, fracture and erosive wear, as defined in Section 2.1.2.

From the multiplicity of these definitions, it is clear that the term "abrasion resistance of concrete" can cover several situations, and that in each situation different wear mechanisms will prevail. This suggests that there is a need to specify a definition which will be appropriate for the present work. The definition required must cover the the mechanism of wear which may be encountered in industrial situations. Thus, the abrasion resistance of a concrete slab in an industrial environment may be defined as the ability of the concrete surface to resist being worn away by rubbing, rolling, sliding, cutting and impact forces. This definition covers the ACI and the ASTM's definitions, and the first two types of wear in the Prior classification. Furthermore, this definition is a combination of abrasive and fracture wear, as defined in Section 2.1.2.

It should be noted that, although throughout this thesis reference is made to concrete slabs, the results can equally apply to both slabs and floors.

## 2.3 Classification of Industrial Slabs

Generally, concrete floors have been classified into a number of categories (28). For the purpose of the present work, a concrete slab in an industrial environment may be classified according to the type of duty it will be exposed to during its service life, and the classification in Table 2.1 is proposed. It is recognised that this classification may be criticised as it is rather general and broad, but a more specific and less general classification would have made the investigation very complicated without necessarily producing any significant improvement in the conclusions.

## 2.4 Assessment of Abrasion Resistance of Concrete Slabs

The mechanism by which material is removed from a concrete slab depends on the type of service to which the slab is exposed. For example, heavily loaded steel wheels will subject the slabs to a combination of scratching or scuffing, friction and localised crushing of the surface material or aggregate. However, lightly loaded rubber tyred or foot traffic does not cause scratching or crushing and wear will only be caused by rubbing action. It is clear that at least two types of wear mechanisms are operating in the former situation, namely abrasive and fracture wear, while in the latter situation, only abrasive wear is involved. This indicates the complex nature of the wear mechanisms involved in the industrial environment. Any assessment of abrasion resistance of concrete slabs, in terms of obtaining useful data as a basis for service life prediction, must recognise this variation in the wear mechanisms. However, most investigators have used accelerated tests, which only simulate one type of wear mechanism, to assess the abrasion resistance of concrete.

### 2.4.1 Requirements of Abrasion Test Method

Sawyer (29) suggested that any test method should satisfy the following requirements:

(1) The test specimen should be subjected to processes that are similar to those experienced in practice.

(2) The test must be severe enough to cause deterioration of any concrete surface.

(3) The test must be sensitive to variation in surface conditions.

(4) The test specimen should be easy to make, store and handle.

(5) The test method should be easy to follow, and the cost and time of testing should not be excessive.

(6) The test results should be reproducible.

It is considered that some of these conditions are essential for an acceptable test method (conditions 1,3,5,6), while others are not necessary (condition 4). Furthermore, the second condition is in direct conflict with the first condition, which is the most important requirement. For example, if the forces experienced in practice are not very severe, then the test method must also not be severe, and so the second condition cannot be satisfied. It is proposed that even if all six prescribed conditions are satisfied then the test method, at best, can only rank different concretes. This is mainly due to the absence of a very important requirement, namely the portability of the apparatus. This is essential if in-situ tests are to be conducted, so as to determine the correlation between the accelerated performance and the service performance. Such data being used to provide a service life prediction.

The conditions which are, therefore, considered to be essential for a viable test method may be summarised as follows:-

(1) The test method must subject the test surface to a treatment that is expected in service.

(2) The test method must be sensitive to variations in surface conditions.

(3) The test results must be repeatable.

(4) The test apparatus must be portable, so that in-situ tests may be carried out.

(5) The test method must be easy to follow, and the cost and time of testing should not be excessive.

### 2.4.2 The Measurement of Abrasion Resistance

Most investigators have reported abrasion resistance as a relative value, either by weight loss or depth of wear. Some investigators have converted this weight loss to volume loss. This method will only be accurate for small laboratory specimens and so its value is rather limited. A depth gauge, such as a bridge micrometer,is normally used in the depth of wear method. The procedure is to measure the depth of wear at a significant number of points after a set interval of exposure to the test. Such a technique may be used both in the laboratory and field investigations. In the present work, the depth of wear has been taken as a direct measure of the resistance of concrete slab to abrasion.

### 2.4.3 Methods of Test for Abrasion Resistance of Concrete

This literature survey has revealed that there are almost as many methods for testing the abrasion resistance as there have been investigators. This may be attributed to the nature of the various actions that produce abrasion damage, and to the lack of understanding of the exact mechanism of wear. The following are descriptions of some of the methods which have been used to assess the abrasion resistance of concrete.

#### 2.4.3.1 Rattler-Type of Test

In this method a concrete specimen (either cylinder or cube) is placed in a rotating steel drum containing a specified number of steel spheres. The drum is tumbled for a period of time or a set number of revolutions. Wear is measured by the weight loss.

Early investigators, such as Abrams (30,31), Scholer and Allen (32), used Rattler type apparatus, such as the Deval and the Los Angeles tests to assess abrasion resistance of concrete. A modification of Los Angeles Rattler has been used by Scofield (33), called Talbot-Jones Rattler Test.

The above methods are only suitable for assessing the wear resistance of aggregate rather than concrete. The problem is that the concrete specimen receives a pounding action which is not commonly associated with abrasion damage of concrete. However, many investigators (30 - 33) have used this type of apparatus in their investigation of wear resistance of concrete.

2.4.3.2 Shot-Blast Test

In the Shot-Blast test, the specimen is placed a specified distance away from a nozzle which ejects several thousand pieces of broken steel or sand shots under pressure.

The Shot-Blast test has been used by several investigators (34 - 38) to assess the abrasion resistance of concrete. The original Shot-Blast test used the Ruemelin Cabinet (34). This has been modified and is now included as an ASTM Standard Test (C418-76).

Shot-Blast techniques are considered to simulate the wear conditions existing in hydraulic structure subjected to abrasive materials carried by water flowing at low to medium velocities (39). Thus, the wear mechanism is that of abrasive erosion and it is suggested that, since this mechanism is different to that experienced by concrete slabs, such a test procedure is not appropriate for assessing the abrasion resistance of these concrete slabs. As indicated earlier, the test method should simulate the field exposure. Furthermore, the applicability of the conclusions reached by some researchers, using this type of apparatus in their investigations, must be open to question.

2.4.3.3 Reciprocating Type of Test

The use of reciprocating apparatus has been rather limited in the investigation of abrasion resistance of concrete. This type of test causes wear by the rubbing action of a reciprocating disc. When an abrasive grit is used, the motion of the disc causes the particles, which are trapped underneath the disc, to slide across the surface as the disc continues with its reciprocating motion.

The reciprocating test simulates the abrasive wear which is normally associated with foot traffic and the moving of light steel racks or light machinery without wheels. The main reason that this type of test has not been used more extensively may be that its mode of action is considered to be less aggressive than required. However, the test method is appropriate for simulating the forces acting on slabs in a light industrial environment, and so it would satisfy the first of the five specified conditions.

This principle was used by A'Court (40, 41) to design a reciprocating machine which was adopted as the British Standard Abrasion Test (B.S. 798; 1953) for Concrete, but it has since been withdrawn. The main problem with this test method (40) was that it used the weight loss method for assessing abrasion.

2.4.3.4 Revolving Disc Method

In this method the test surface is abraded by a rotating disc, usually steel, which is continuously fed with specified abrasive grit. Thus, the revolving disc introduces frictional forces by rubbing and grinding, while the combined action of the disc and grit produce sliding and scuffing. The revolving disc machine, in conjunction with abrasive grit, has been used by several researchers (21,42-45).

Several research programmes (46,47) have been initiated by the ASTM C-9 Sub-Committee, to evaluate the performance of Revolving Disc, Dressing Wheel and Ball Bearing machines. The Revolving Disc method was shown (46) to reproduce test results with the lowest variation. This was attributed (46) to the fact that, irrespective of the type of surface being abraded, the grinding motion tended to create a smooth surface. Consequently the revolving disc method has been adopted as one of the three procedures used in the ASTM Standard (C-779) for assessing the abrasion resistance of a horizontal concrete surface. In the ASTM method, the wear is measured after 30 and 60 minutes with a depth micrometer. Davis and Troxell (47) investigating the performance of the Revolving Disc, found that the depth of wear produced in the period between 30 and 60 minutes was about the same for ordinary concrete as for a heavy duty concrete surface. Prior (27) suggests that once the surface material has worn away, the disc will then proceed to ride on the hardest piece of aggregate. In practice, however, traffic will wear around these harder particles leaving them protruding and susceptible to impact. A further objection to this method is that the test surface is subjected to grinding rather than to rubbing (46). These points suggest that there is deviation between the action which this machine is simulating and that prevailing in a light industrial environment.

2.4.3.5 Dressing Wheel Method

The dressing wheel machine is the second test method detailed in ASTM Standard (C-779) for assessing the abrasion resistance of a horizontal concrete surface. This method is dependent upon the abrasive action of three sets of loaded steel dressing wheels riding in a circular path over a test surface. The action of a dressing wheel on a concrete surface results in a rough circular path, which is usually irregular, i.e. troughs and peaks. This results in a higher coefficient of variation than that obtained with the revolving disc. Klieger and Brinkerhoff (46), reported a value of 18% with the dressing wheels, compared with 7% for the revolving disc. They have also criticised (46) the ASTM test by suggesting that the machine is unable to follow the shape of a given test surface at the start of the test, periods ranging from 9 to 26 minutes being reported before 100% contact was made. They further suggested that, if the dressing wheel head could be redesigned so that the cutters are in contact with the surface at all times, the coefficient of variation could be reduced.

It has been suggested (47) that the dressing wheel subjects the test surface to high concentrated compressive forces which produce high impact stress, similar to the rolling, pounding and cutting action of the steel wheels of a fork lift truck. It is, therefore, suggested that condition one is satisfied if the action required is that of the conditions prevailing in heavy industrial environments. The dressing wheel system was found to be sensitive to surface variation (37,38,48) and so the second condition is also satisfied. While the third condition may not be satisfied with high coefficient of variation (46). The ASTM machine is portable, easy to use and the test is carried out in 30 minutes, and so the fourth and the fifth conditions for acceptability of test method are also satisfied. It, therefore, appears to be a promising test for assessing concrete slabs for use in heavy industrial environments.

2.4.3.6 Ball Bearing Method

In this method the surface is abraded by a series of ball bearings rotating under a specified load, water may also be employed as a cutting aid. The Ball Bearing method has been described by Plassmann (49) and was adopted as the basis of German Standard Test (DIN 5195) in 1953, but was withdrawn in 1957. However, a similar machine has been adopted as the third test method of the ASTM Standard (C-779). The ASTM Ball Bearing machine uses a series of eight ball bearings rotating under a load at a speed of 1000 rpm and using water as a cutting aid.

Several researchers (29,37-38,50-51) have used this machine in their investigations. It has been found (37-38) that the resulting depth of wear with this method is far greater than the revolving disc and the dressing wheel test. Due to the severity of this test, it has been suggested (24,39) that its action (high impact, compressive forces) may reproduce the conditions of wear experienced under very severe conditions, such as steel wheeled trolleys. However, Klieger and Brinkerhoff (46) are of the opinion that the ball bearing test does not provide a true picture of the abrasion resistance of the surface under test, because of the inability of the machine to become flexible as the test progresses. They have suggested that, at the beginning of the test, the entire movable superstructure above the test surface moves as a solid unit as the surface starts to wear. However, as the test progresses, both hard and soft spots are encountered along the path of abrasion, resulting in troughs and peaks. At the high angular speeds (1000 rpm) the ball bearings start to bounce, and create a rougher path of abrasion. Furthermore, the ball bearings are unable to move up and down with the load over the peaks and down in the troughs. This state is reflected in the very high coefficient of variation obtained, which ranges between 11% and 45% (46).

A further criticism of the ASTM method is that the surface of concrete is tested wet. Higher depths of wear have been found (29) with wet surfaces and, additionally, industrial slabs are not usually kept wet continuously. Thus the ball bearing test does not appear to simulate the conditions to which a heavy industrial floor may be exposed.

From the above discussion it can be concluded that the first and third conditions are not satisfied by the ball bearing method. Furthermore, considering the very high coefficient of variation associated with this test (46), the conclusions produced for investigations using this type of test must, therefore, be open to question.

#### 2.4.3.7 Rolling Wheel Type of Machine

The rolling and turning actions of wheels has been used by many researchers for the investigation of abrasion resistance of concrete, (52-59) although there has been considerable variation between the different techniques. One of the earliest methods, described by Covell (52), and modified by Ahlers et al (53), utilised truck wheels. This equipment consisted of a frame carrying four, loaded, steel truck wheels, that described circles of four different diameters. Wastlund and Eriksson (55) used a machine which consisted of two truck wheels with solid rubber tyres under load, together with two steel truck wheels also under load. The rubber tyres were driven while the steel wheels were carried round by the same framework but on separate tracks. Anderson and Bartran (56) replaced the blades of a pan mixer with a steel castor from a lift truck, the spindle on which the castor was mounted was restrained from rotating so that the castor rolled without skidding.

The National Swedish Institute for Materials Testing (NSIMT) has developed a rolling wheel type of machine (57), which uses three wheels made from high quality steel castors. These wheels are attached to a steel disc which revolves and makes the wheels roll and slip against the concrete surface. This machine has been used by several researchers (58-59), but most notable the NSIMT, for assessing the abrasion resistance of concrete. No information is available on the reproducibility of this machine. The Cement and Concrete Association (C & C A) constructed a rolling wheel machine(2), similar to the Swedish machine, but there is little published information on the performance of this machine.

The action of the rolling wheel type of machine subjects the concrete surface to rolling, sliding as well as impact (53,57). There is no published data which compares this type of machine with either the dressing wheel or the revolving disc. However, from the action of these three types of machines it can be speculated that the rolling wheel machine will be less aggressive than the dressing wheel machine and more aggressive than the revolving disc. This would suggest that the rolling wheel simulates the actions which are common in the medium industrial environment. Therefore, the first condition is satisfied for simulating forces in medium industrial environment, and so this type of machine should be suitable for assessing concrete slabs, for such environments.

#### 2.4.3.8 Other Types of Apparatus

Other types of machine have been used (60), although only on an infrequent basis. However, these machines only involve minor modifications to the seven basic modes described previously, and so they will not be considered further.

A summary table has been provided, Table 2.2. This summarises various types of test methods which have been discussed, together with the reference to the investigators using each method. Furthermore, the applicability of these methods, according to the five conditions specified for the acceptability of an abrasion test method, has also been included in this table.

## 2.5 Factors Influencing Abrasion Resistance of Concrete

From the literature survey, the main factors that are considered to have a significant effect on the abrasion resistance of concrete may be summarised as follows:-

1) Compressive Strength
2) The Physical Properties of Aggregate
3) Finishing Techniques
4) Surface Treatments
5) Curing

### 2.5.1 Compressive Strength

The relationship between abrasion resistance and compressive strength of concrete has been the subject of many investigations (29-30,35-36,38,43). It has been generally concluded that Compressive Strength is the single most important factor controlling the abrasion resistance of concrete, with the abrasion resistance increasing with compressive strength.

Smith (38) found that the abrasion resistance of concrete varied directly with both compressive strength and cement content and inversely with water-cement ratio. This confirmed earlier studies (29-30) which established that the abrasion resistance increased with increased cement content. However, it has been suggested (6,61) that there is an upper beyond which any further increase in the cement content has only a limited effect on the long term abrasion resistance of concrete, this cement content being around 335Kg/$m^3$.

The strength is related to porosity, or air content, and so several investigators (36) have examined the influence of air content on abrasion resistance. Generally, the air-entrained concrete was found to have a similar resistance to the plain concrete, providing both were of equal strength (36).

From the previous comments it may be implied that almost any factor which affects the compressive strength of concrete will also influence the abrasion resistance. If it is accepted that the compressive strength is the sole criterion governing abrasion resistance, then the provision of a durable concrete slab would be simply achieved by specifying high strength concrete. However, it has been found by Rushing (6) and others (41,61) that some mixes with high compressive strength exhibited lower abrasion resistance than mixes with lower compressive strengths. Of particular note is the importance of techniques which alter the surface characteristics (e.g. finishing techniques, surface treatments), without significantly influencing the compressive strength, as measured by cube or cylinder crushing tests. It is, therefore, clear that other factors must be considered and that compressive strength cannot be used as the sole criterion for the abrasion resistance of concrete surface.

### 2.5.2 The Physical Properties of Aggregates

Considerable research effort has been directed towards assessing the influence of aggregate on the abrasion resistance of concrete. It is convenient to consider the coarse and fine aggregates separately.

#### 2.5.2.1 The Coarse Aggregate

The influence of coarse aggregate has been covered in a number of major research programmes (31,38,44,62,66,67). The early investigations were carried out by Abrams(31) and, Jackson and Pauls (62). Abrams (31) concluded that the wear resistance of concrete was less dependent on the qualities of the coarse aggregate used in the wearing courses than had generally been supposed. Jackson and Pauls (62) also 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. In another extensive investigation Scripture et al (44) found no correlation between the hardness of the coarse aggregates, as measured by the Scratch test (63), and the abrasion resistance of the resulting concrete mixes. These conclusions are contrary to the commonly held opinion that the harder the aggregate the more wear resistant the concrete floor.

More recently, Smith (38) found no significant correlation between the abrasion resistance of concrete and the quality of the coarse aggregate as measured by either the Sodium Sulphate Soundness test (64) or by the Los Angeles abrasion test (65); the former measures the resistance of the aggregate to disintegration during weathering and the latter measures the impact losses from an aggregate which is rotated with an abrasive in a steel drum. However, he concluded that concrete containing soft limestone was less resistant to abrasion than similar concrete containing harder aggregate. Furthermore, this effect was evident in concrete with strengths below 55 $N/mm^2$, but above this strength level, the effect of aggregate on wear resistance was found to be reduced greatly. Similar conclusions were also presented by Collins and Waters (66). Recently, Liu (67) correlated the abrasion resistance of concrete and the hardness of the aggregate as measured by Mohs hardness values. This investigation was concerned with the resistance of concrete subjected to the abrasive action of water-borne particles in a stilling basin and, therefore, the results may not be applicable to this particular study.

Although the previous comments are contrary to normal belief, it is quite reasonable since, initially, it is the surface matrix that resists the abrasive forces. The coarse aggregate becomes involved only when there has been sufficient wear to expose (a significant amount of) the coarse particles.

In the UK there is a wear resistance test for aggregates in the B.S. 812 (68) but, as far as is known, there is no published paper which attempts to investigate the relationship between the abrasion resistance of concrete, and abrasion resistance of aggregate as measured by this test.

As was explained in Section 2.4.3, many techniques have been used to assess the abrasion resistance of concrete, with the mechanisms of wear depending on the particular technique. This is likely to influence the conclusions derived in different investigations with particular aggregates. However, Smith (38) in his investigation, using three different methods of testing - shot blasting, dressing wheels and rolling steel balls, found that although the methods gave different results, they produced similar trends.

It is clear from the foregoing that there is very little evidence to suggest any significant correlation between the abrasion resistance of concrete and the quality of coarse aggregate. Indeed, the evidence suggests that it is the matrix which dominates the abrasion resistance of concrete slabs.

Several researchers (44,48,53) have investigated the influence of artificially produced aggregate on the abrasion resistance of concrete. Naturally occuring aggregates such as crushed rocks and gravels are relatively brittle and tend to shatter under impact load. In contrast, artificially produced materials such as metallic aggregate tend to be ductile and less likely to fracture under abrasive forces. Scripture et al (44) found that the abrasion resistance of concrete containing malleable Iron was far greater than the abrasion resistance of concrete containing naturally occuring aggregates. This increase was attributed to the ability of the malleable materials to withstand impact load without shattering, and to its relatively high resistance to abrasion.

The shape of coarse aggregate has been investigated by Schuman and Tucker (43). With irregular or angular aggregate more water was required for placing and finishing than with rounded aggregate. This resulted in higher water-cement ratios and this had a direct influence on the abrasion resistance of concrete. A large proportion of irregular or angular aggregates have flat fracture faces which tend to align with the surface during the trowelling operation. This produces a high aggregate area to mortar-matrix ratio at the surface, which may be expected to produce a harder wearing surface (69). Furthermore, the angular shape of aggregate is thought to improve bond with the matrix . Thus, the effect of shape and texture will depend on the relative importance of several phenomena.

Witte and Backstron (36) found that the maximum size of coarse aggregate did not affect the abrasion resistance when the comparison was undertaken on mixes of equal strength. However,the ACI Standard on construction of concrete floors (5) recommends that the largest size aggregate (19-39 mm) should only be used on floors which carry light to medium traffic. For heavy duty concrete surface, the maximum size aggregate should be limited to 13mm.

#### 2.5.2.2 The Fine Aggregate

Several researchers, among them Price (71), and Smith (38), have investigated the effect of variations in sand content of the abrasion resistance. Smith (38) verified the work reported by Price (71) and suggested that, in general, an increase in the percentage of sand in a mix results in a decrease in abrasion resistance. Schuman and Tucker (43) compared the abrasion resistance of specimens of mortar with specimens containing coarse aggregate. They found that very high abrasion resistance could be obtained with specimens of mortar but, when part of the sand was replaced with coarse aggregate, the resulting mix gave an even higher abrasion resistance at a lower cost.

The presence of a large amount of fine material (e.g. material passing the 300μmm and 150μmm sieves) in the aggregates has been found by A'Court (41) and others (72) to reduce the abrasion resistance of concrete.

### 2.5.3 Finishing Techniques

The influence of different finishing techniques on abrasion resistance of concrete has been investigated by a number of researchers (41,43,48,50,73).

Since fresh concrete contains more water than required for the process of hydration and more fine sand than necessary to fill the voids between the coarse aggregate particles, some segregation of the constituents of concrete results during compaction and finishing. This will produce "bleeding" leading to the formation of water-rich surface layer. If left to harden, the surface will be very weak due to high local water-cement ratio. However, if the concrete surface is trowelled after this bleed water has evaporated, it will recompact the surface and reduce the water-cement ratio. This may result in further bleeding, and if the trowelling process is repeated until no water is brought to the surface, the resultant surface should be very strong (5).

Schuman and Tucker (43) reported that delaying the trowelling for 3 or more hours after placing concrete tended to increase abrasion resistance. This was confirmed by A'Court, (41) who found that the number of trowellings was also critical. However, Scripture et al (44) were not able to confirm the findings of Schuman and Tucker (43), or A'Court (41). They suggested that there was no significant difference in the resistance to abrasion obtained with three different types of finishing: single-delayed trowelling, double-delayed trowelling, and single-immediate trowelling.

In a series of tests Fentress (50), using the German wear test machine, showed that lower abrasion resistance resulted when a float finish was used rather than a steel. A similar effect occurred when premature finishing was compared with delayed finishing. He also found that additional hard steel trowelling increases the abrasion resistance. Other investigators, among them Spellman and Ames (61), have also concluded that additional and delayed trowelling increases the abrasion resistance of concrete.

These results on the additional and delayed trowelling are all based on laboratory investigations in which hand floating and trowelling was used, rather than machine finishing. Very few research studies have produced test slabs using commercial finishing equipment and, even where employed, they have only been used on a small number of specimens. Scripture, (48) for instance, reported that the abrasion resistance of specimens finished with machine floating was far superior to that of the hand finished specimen. This conclusion, however, was only based on two test results from one slab. As a further example, Malinowski and Pawlowski, (73) reported that the abrasion resistance of a concrete slab increased by about 100% when a secondary delayed machine trowelling was used. Again, this conclusion is based on only one experiment,and more importantly, the delayed trowelling was applied to only one part of the same slab. The vibration associated with power trowelling releases water which remained undisturbed on the area not subjected to delayed trowelling, thus creating a weaker surface than that achieved by delayed trowelling.

Vacuum dewatering, in conjunction with power floating and trowelling, has been used as a finishing technique. Evidence (56,73-79) indicates that this technique increases the abrasion resistance of a concrete surface. However, the starting water-cement ratio of a concrete which is to be treated with vacuum dewatering process is higher than the concrete which is used in the traditional method. This causes a problem in assessing the benefits of vacuum treatment over the traditional method. This difficulty is reflected in some of the claims made by investigators. Cron (78) claims that the vacuum dewatering process increases the abrasion resistance of concrete surfaces by as much as 300%, whilst Paulsson (79) suggests that, for a concrete surface treated by the vacuum process, the wear is 16-39% less than traditionally laid floors. In both these cases it is not clear whether the values obtained are from similar concretes with and without vacuum treatment.

Another finishing technique is early-age-grinding (52,80). The main advantage of this method is the elimination of the time lapse between floating and repeated trowelling. Only limited evidence is available on the performance of this process. It has, however, been found (56) that, by comparison with the traditional concrete slabs, (e.g. powerfloated and powertrowelled) early-age grinding results in a lower abrasion resistance. There are other finishing techniques, e.g. vibratory absorption process (81), which exist but their use has not been widespread. Furthermore, other techniques which may be available, are usually variations of those already discussed.

It is clear that there are numerous papers which have reported the increase of abrasion resistance due to different finishing techniques. However, very few published papers have been found which present explanations, in quantitative terms, of the mechanisms by which this increase is achieved. Most investigators have only given a general statement attributing the increase to densification of the surface matrix. One of the few attempts to explain the behaviour was made by Malinowski and Wenander (82), who suggested that mechanical surface treatment increases the specific surface of cement, while vacuum dewatering reduces the water-cement ratio of the concrete surface. It is suggested that both mechanisms reduce the capillary radius of cement mortar and concrete. This reduces the thermal and moisture gradient in the concrete slab and the result is increased density, strength and abrasion resistance. This theory has not been validated by experimental data, although techniques are available for measuring accurately the specific surface of cement (83).

### 2.5.4 Surface Treatment

There is a variety of treatments available for modifying the concrete surface. Several writers (69,84-85) have attempted to classify the various surface treatments, but such classifications have been of a general nature, i.e. they are concerned with prevention of damage to the concrete surface, due to both chemical and abrasive action. In the present work, surface treatment of concrete slabs is divided into two broad categories: (a) surface treatment applied to fresh concrete, (b) surface treatment applied to hardened concrete.

It should be noted that there are generally two types of concrete floor, monolithic and base slab followed by a delayed topping. Monolithic floors are finished (base) slabs, whereas toppings are separate courses (usually 10-50mm thick) which are installed on top of the base slab. Furthermore, toppings can be sub-divided into two groups: (a) cement-based floor topping, (b) epoxy floor toppings. In the present work the cement-based floor toppings are considered as essentially monolithic, whose surface is treated. Epoxy floor toppings will not be discussed, since their main purpose is chemical-resistant (86), rather than abrasion resistance.

### 2.5.4.1 Surface Treatment Applied to Fresh Concrete

The application of various types of "dry shake" as surface treatment, has been investigated by several researchers (43-44,48,50,53). These shakes consist of dry cement or a mixture of cement with various types of aggregates, either metallic or non-metallic, which are sprinkled on the surface of fresh concrete. Investigators have generally concluded that these dry shakes increase the abrasion resistance of concrete slabs. However, it is not clear whether this increase can be attributed to the introduction of extra cement or to the benefit derived from the introduction of harder material into the surface (metallic or non-metallic material).

There are other surface treatments which have been used to increase the abrasion resistance, such as polymer impregnated concrete, and steel fibre-reinforced concrete. The former has been used for highway bridges and the latter is used mainly for airport runway pavements. Very few abrasion tests have been conducted on these types of surfaces (87-88). Due to their cost, it is unlikely that they will be considered for floor slabs in conventional factories and so they have not been considered in this investigation.

2.5.4.2 Surface Treatment Applied to Hardened Concrete

There are many types of chemical surface treatment which may be applied to hardened concrete (84), but very little published material is available in which the performance of the various treatments have been compared in terms of abrasion results. Most researchers (37,40,43,61,89) have concentrated on assessing the performance of a limited number of concrete surface hardeners, such as magnesium or zinc fluosilicate, sodium silicate and linseed oil.

It has been concluded (37,40,43,61) that concrete surface hardeners improve abrasion resistance of concrete, and that these treatments are more effective with poorly cured and lower quality concretes (43,89). This has been attributed (43,89) to chemical reactions, sodium silicate reacts with free lime near the surface to produce hard calcium silicate and sodium silicate glass in the pores, whilst fluosilicates produce chemically inert calcium fluoride which tends to block the pores. However, if the surface of the concrete is porous, with a relatively small quantity of free lime available, the resultant reaction is that the pores would be filled with unreacted powder, producing alkaline dust (69).

Smith undertook (37) a comparison of the benefits derived from magnesium fluosilicate and zinc fluosilicate. He found that the magnesium fluosilicate was more resistant to rubbing action (simulated by revolving disc machine), whilst the zinc fluosilicate was more resistant to impact wear (simulated by dressing wheel machine). This implies that the results of various investigations may be difficult to compare, since different test methods have been used by the various investigators.

Most of the published information on other types of concrete surface treatments - e.g.in-surface seals and paints - relates to the protection of concrete from attack by the chemical (90), rather than abrasion performance.

2.5.5 Curing

It has been established by many investigators that proper curing increases the compressive strength of concrete (91). Since there is, in general, a relationship between compressive strength and abrasion resistance of concrete, it is to be expected that curing conditions also influence the abrasion resistance. It has been found by Spellman and Ames (61), that abrasion resistance is influenced more by curing procedure than by other variables such as slump and finishing techniques.

Several investigators (29,43,92) have shown that as the days of moist curing increase, there is a significant increase in abrasion resistance. Sawyer (29) pointed out that curing becomes more important as the cement content becomes reduced. Fentress (50) found that the immediate application of a curing compound (details of which are not available) after finishing resulted in a higher abrasion resistance than moist burlap curing for three days. However, no curing gave a better result than the delayed (24 hours after finishing) application of a curing compound.

Previous investigators have provided valuable information on the influence of curing on the abrasion resistance of concrete. However, there is a lack of comparable research data on the effect of various curing regimes on different concrete strengths and different finishing techniques.

## 2.6 Summary

The review of this section has demonstrated that research on abrasion resistance has been active for many years, and there is an extensive body of results available. However, it also demonstrated that this research, in particular on concrete slabs, has been generally inadequate and fragmented. It can be summarised as follows:-

(1) The exact mechanism by which material is removed from a concrete slab subject to abrasion is complex and not fully understood. Furthermore, little attention has been paid to the body of knowledge available in tribology.

(2) There is no one test method which simulates the forces that concrete slabs are subjected to in an industrial environment.

(3) There is no standard by which the quality of a concrete slab may be assessed so far as its abrasion resistance is concerned.

(4) The influence of certain factors on abrasion resistance of concrete is generally established, e.g. mix design.

(5) Research has largely been focused on the macro-study of abrasion resistance of concrete.

(6) This research has failed to recognise the importance of microstructure of concrete on abrasion resistance, i.e. micro-study of structure of concrete, e.g. influence of pore structure on abrasion resistance.

(7) There is a lack of comparability between test results, mainly due to the use of different test methods.

(8) Most research conclusions are not conclusive, because they are

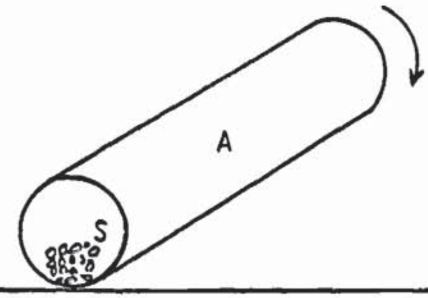
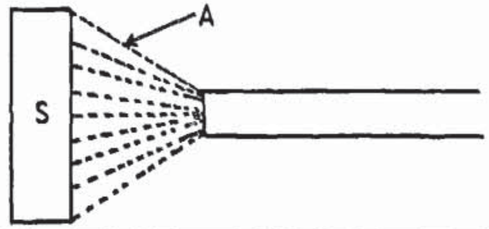
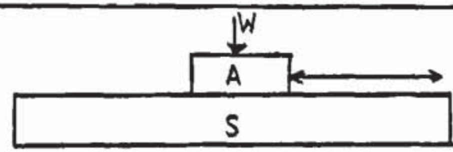
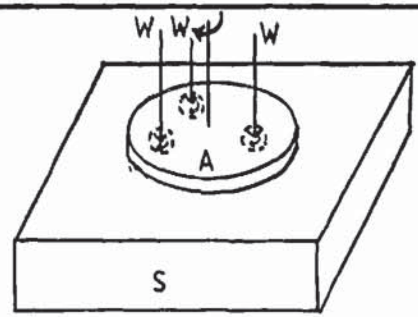
based on few experimental data.

(9) Much of the research is laboratory-orientated, and has failed to recognise the importance of site practices.

(10) There is no reliable information on the relationship between laboratory and field practices.

| Type of Industrial Environment | Usual Traffic | Type of Abrasion |
|---|---|---|
| Light Industrial | Foot traffic, Vehicles with pneumatic and rubber tyres | Rubbing |
| Medium Industrial | Trucks with solid polyurethane wheels | Rubbing, Rolling, Sliding and Light impact |
| Heavy Industrial | Heavily loaded trucks with solid steel wheels | Severe Rubbing, Rolling, Sliding, Cutting and Heavy Impact |

TABLE 2.1 Proposed Classification for Industrial Slabs

| TYPE OF TEST | INVESTIGATORS | SPECIFIED CONDITIONS (See Section 2.4.1) 1 | 2 | 3 | 4 | 5 | COMMENT | SCHEMATIC ILLUSTRATION OF THE BASIC PRINCIPLE |
|---|---|---|---|---|---|---|---|---|
| RATTLER | Abrams (30,31)<br>Scholer et al (32)<br>Scofield (33) | NO | YES | NOT SPEC-IFIED | NO | YES | Only applicable for Wear Test of Aggregate |  |
| SHOT BLAST | Meissner et al (34)<br>Kennedy (35)<br>Witte et al (36)<br>Smith (37,38)<br>Rushing (6) | NO | YES | NOT SPEC IFIED | NO | YES | Useful for Simulating Abrasive Erosion |  |
| RECIPRO CATING | A'Court (40,41) | YES | YES | NOT SPEC IFIED | NO | YES | Simulates Light Industrial Conditions |  |
| REVOLVING DISC | Shank (42)<br>Schuman et al (43)<br>Scripture et al (44)<br>Kessler (45)<br>Klieger et al (46)<br>Davis (47) | DEBAT-ABLE | YES | YES | YES | YES | Simulates Rubbing and Grinding. It is debatable if this is the condition in Light Industrial Environment |  |

NOTE: A = ABRASIVE, S - SPECIMEN, W = WEIGHT

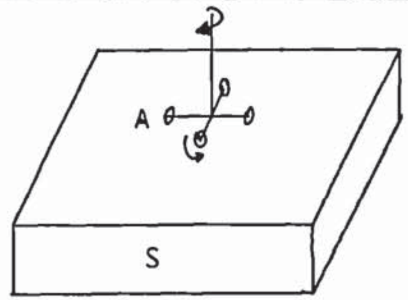
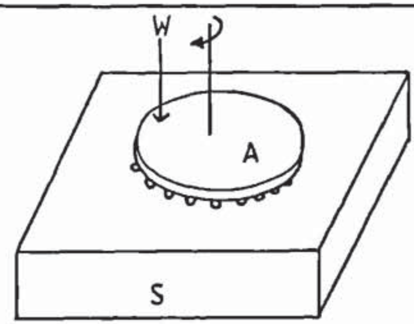
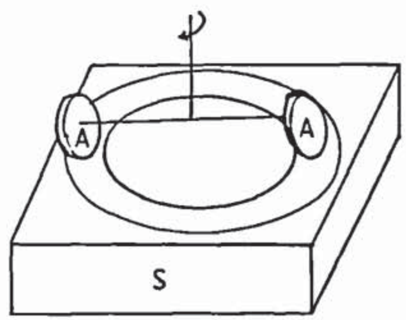
| Type of Test | INVESTIGATORS | SPECIFIED CONDITIONS (See Section 2.4.1) | | | | | COMMENT | SCHEMATIC ILLUSTRATION OF THE BASIC PRINCIPLE |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | |
| DRESSING WHEELS | Smith (37,38)<br>Scripture (48)<br>Klieger et al (46)<br>Davis (47) | YES | YES | YES | YES | YES | Simulates Rolling, Sliding, Cutting, and Impact. Similar to condition in heavy Industrial Environment |  |
| BALL BEARING | Plassmann (49)<br>Sawyer (29)<br>Smith (37,38)<br>Fentrss (50)<br>Soroka (51)<br>Klieger et al (46)<br>Davis (47) | NO | YES | NO | YES | YES | This is a very severe test, and does not simulate the conditions present in heavy Industrial Environment |  |
| ROLLING WHEELS | Covell (52)<br>Ahler (53)<br>Emley et al (54)<br>Wastlund (55)<br>Andeson (56)<br>N.S.I.M.T. (57,58)<br>Pawlowski et al (59) | YES | YES | NOT SPEC-IFIED | YES | YES | Simulating Rolling, Sliding and Light Impact. Similar to conditions in medium Industrial Environment |  |

TABLE 2.2 Continued

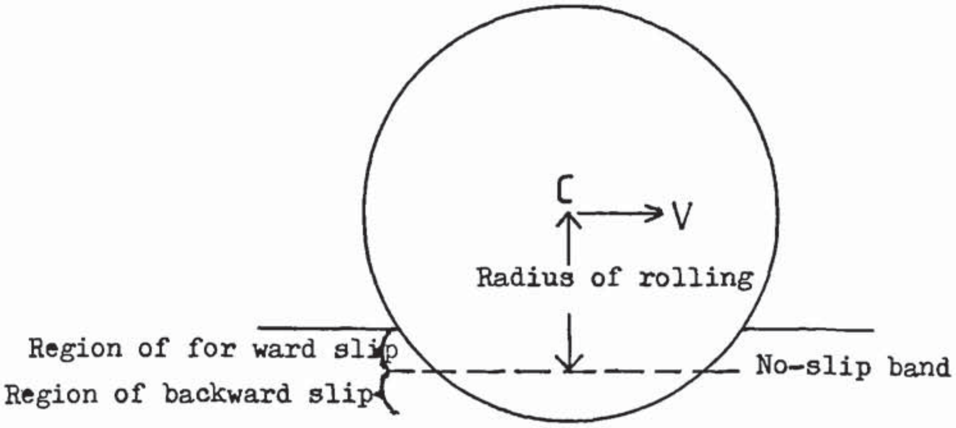



FIGURE 2.1 A Sphere is Rolling on a Flat Surface
(After Rabinowicz (7) )

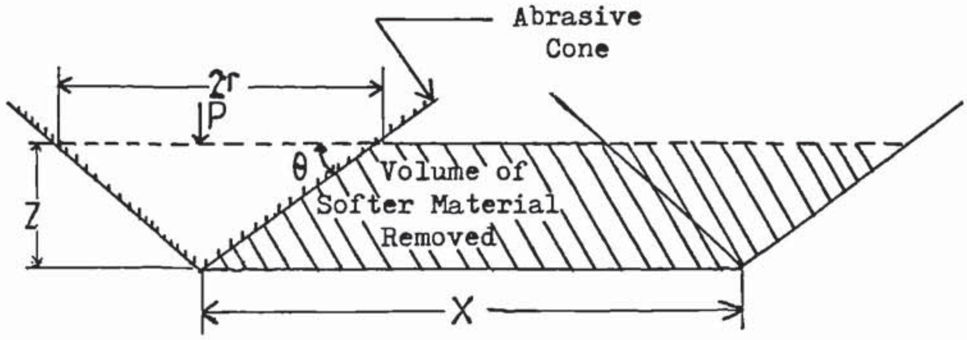



FIGURE 2.2 Abrasive Wear Model
(After Rabinowicz (7) )

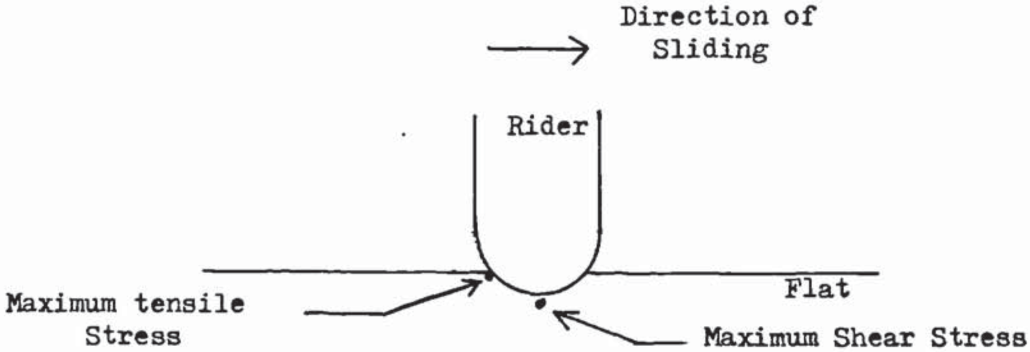



FIGURE 2.3 Position of Maximum Tesile Stress
(After Rabinowicz (7) )

# CHAPTER 3

## SCOPE OF INVESTIGATION

### 3.1 General Outline

The general aims of the work reported in this thesis may be summarised as follows:-

(1) The development of apparatus and a standardised testing procedure for assessing the abrasion resistance of concrete slabs exposed to various levels of industrial traffic.

(2) To study the influence of such factors as finishing techniques, curing regimes, and surface treatments on the abrasion resistance of concrete. This to include observations on both the macroscopic and the microscopic scales.

(3) To investigate the possibility of assessing abrasion resistance through indirect and non-destructive methods.

(4) A field investigation of the behaviour of in-situ slabs in various industrial environments.

### 3.2 Concrete Mix Design

During the development of apparatus and the establishment of a standardised testing procedure, five types of concrete mix were used. In the initial programme, two concrete mixes were used, one with a high free water-cement ratio (mix A1) and one of much lower free water-cement ratio (mix A2). For the comparative study, three types of concrete mixes were used (mix B1, B2 and B3). The main reason for using three different water-cement ratios in this part of the programme was to assess the sensitivity of different types of abrasion head to variations in mix design.

In the main laboratory programme, which investigated the influence of finishing techniques, curing regimes and surface treatments on the abrasion resistance of concrete, three other concrete mixes were selected - mix B4, B5 and B6, with free water-cement ratios of 0.44, 0.52 and 0.65 respectively. These three water-cement ratios were used so that assessment could be made of the influence of water-cement ratio on the variables under investigation. The selected water-cement ratios were considered to be the most suitable for the variables under investigation. For example, had a free water-cement ratio lower than 0.44 been employed, it would have been very difficult to construct some of the slabs, particularly those for the study of mixes with reduced water contents. Furthermore, mixes B1, B2 and B3 were not used in this part of the programme because the cube strength of mix B3, with the highest free water-cement ratio, was quite high for in the programme, at least one concrete mix was required with low cube strength. It is interesting to note that it was quite difficult to produce a low quality concrete mix in the laboratory.

## 3.3 Development of Apparatus and Standardised Test Procedure

The C & CA accelerated abrasion test machine (2) was used as the basis for developing a versatile testing apparatus, with three modes of action, and for the establishment of a standardised test procedure, for assessing the abrasion resistance of concrete slabs in various industrial environments. In this programme a total of 51 slabs, 1.00 x 0.50 x 0.10 m, were tested, using the various types of heads developed during the investigation.

## 3.4 Macro-study of Abrasion Resistance

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

(1) Finishing techniques - Hand Finishing (H.F.), Power Finishing

(P.F.), Repeated Power Finishing (R.P.F.), Vacuum Dewatering (V.D.).
(2) Curing regimes - Air Curing (A.C.), Wet Burlap (W.P.), Plastic Sheeting (P.S.), three types of liquid membrane-forming compounds.
(3) Surface treatments - five liquid surface treatments and four dry shakes.

In this study a total of 144 slabs of size 1.00 x 0.50 x 0.1 m were tested.

## 3.5 Micro-structural Study of Abrasion Resistance

Whilst the macro-study could provide evidence of changes in the abrasion resistance of concrete, it would not provide information on the micro-structure of concrete. This information was considered essential in developing an explanation of the behaviour on the macro-scale. The main purpose of the micro-structural study was, therefore, to examine the micro-structure of the concrete in order to seek supporting evidence for the explanations of the behaviour observed in the macro-study. The investigation of micro-structure of concrete was performed using five techniques: Mercury Intrusion Porosimetry, Microhardness, Scanning Electron Microscopy, Petrographic Examination, and Differential Thermal Analysis.

## 3.6 Indirect and Non-destructive Methods for Assessing Abrasion Resistance

The accelerated abrasion test is really a destructive test, and so non-destructive techniques were considered as alternatives for assessing abrasion resistance of concrete, such assessments would be indirect. Three methods, which have been used for assessing the quality of in-situ concrete, were investigated: Ultrasonic Pulse Velocity, Schmidt Rebound Hardness, and the Initial Surface Absorption Test. This study was carried out on the slabs used in the macro-study. Measurements made with these non-destructive methods were related to the abrasion values determined in the macro-study.

### 3.7 Field Investigation

This part of the programme was specifically designed to assess the relationships between:

(1) the slabs finished in the laboratory using the normal laboratory method (e.g. hand finishing) and, the slab constructed on site using the normal site finishing techniques (e.g. power finishing),

(2) the actual service performance of concrete slabs in industrial environment, and the performance in the accelerated abrasion test(s).

This study involved taking measurements both on newly constructed sites and on in-service floors. It was preceded by a written survey to select floors for investigation.

CHAPTER 4

# ENGINEERING PROPERTIES OF MATERIALS

## 4.1 Introduction

This Chapter outlines the details of the materials used in the manufacture of specimens. The methods adopted for specimen preparation are not discussed in this section, the individual details being given in Chapters 5, 6 and 7.

## 4.2 Cement

All the concrete specimen slabs have been prepared from a single batch of blended, typical, ordinary Portland cement of constant uniformity, supplied in bags by the Blue Circle Cement Company. The chemical analysis of this cement is given in Table A.1 of Appendix A.

## 4.3 Aggregate

### 4.3.1 Coarse aggregate

The coarse aggregate was Bunter quartzite, an Upper Trent Valley aggregate from Weeford Quarry. The 20 - 10 mm aggregate was natural and the 10 - 5 mm was crushed.

### 4.3.2 Fine Aggregate

The fine aggregate was blended to conform to the grading curve provided in Figure A.1 of Appendix A. The blended fine aggregate was natural sand and may be considered to conform to the "Zone 2" sand in the B.S 882:1973 grading zone. Both the coarse and fine aggregate were washed at the source, and dried in the laboratory before use.

## 4.4 Steel

Mild steel reinforcing bars were used to reinforce the concrete slab specimens. The size, length and bar layout are given in Chapter 6.

## 4.5 Water

Tap water was used throughout the programme, in all the concrete mixes.

## 4.6 Concrete Mix Design

Eight different concrete mixes were used through the programme with the following free water-cement ratios:-

(1) Mix A1 = 0.56

(2) Mix A2 = 0.40

(3) Mix B1 = 0.37

(4) Mix B2 = 0.47

(5) Mix B3 = 0.60

(6) Mix B4 = 0.44

(7) Mix B5 = 0.52

(8) Mix B6 = 0.65

The mix details are provided in Appendix B.

# CHAPTER 5

# DEVELOPMENT OF ACCELERATED ABRASION TEST APPARATUS AND STANDARDISED TESTING PROCEDURE

## 5.1 Introduction

The literature review demonstrated that a wide range of test apparatus has been developed to study the abrasion resistance of concrete. Some of these apparatus were able to simulate only the forces associated with one type of industrial environment, whereas three industrial environments need to be considered, namely, light, medium and heavy. It was also shown that no single method simulated all the forces to which concrete slabs are subjected in an industrial environment (Table 2.1). The implication of these findings is that either several test apparatus need to be used to simulate the forces present in the different industrial environment, or that one apparatus must be developed so that its mode of action may be altered to suit the action it is required to simulate. The scope of the possible testing regimes is very wide and should encompass reciprocating action to simulate light industrial traffic, rolling wheel to simulate the medium industrial environment, whilst the traffic in the heavy industrial environment would probably involve the use of dressing wheel apparatus. It was decided that the development of a versatile apparatus would be more advantageous than the use of three different sets of apparatus. It is worth mentioning that, in the study of metal wear it has been recognised that different wear testing machines are necessary to simulate different types of wear (93). Workers in the field have concentrated their efforts in developing tests in which one of the several forms of wear predominates. The approach used in this investigation is similar to that employed by those workers in the field of metal wear.

## 5.2 The Initial Programme

The main purpose of the programme was to develop an accelerated abrasion apparatus whose mode of action may be easily changed. There are two means by which this objective may be achieved, namely:- (1) investigate existing apparatus to determine whether they may be modified, (2) design new apparatus to achieve the required performance.

Three existing apparatuses were considered, the ASTM dressing wheel (C-779), the Swedish (NSIMT) equipment (57) and the C & C A rolling wheels (2). It was considered that each could form the basis for the development of a versatile test system, and that no real advantage would arise from considering additional, new designs. In addition, by adapting existing equipment, it was considered that similar apparatuses, located in other institutions, could be used for assessing the reproducibility of the proposed test. Therefore, it was decided that the use of an existing apparatus should be investigated further.

Whilst the ASTM and the National Swedish Institution testing apparatuses were found to be commercially available in the USA and Sweden, their cost and delivery time were excessive. In addition, no organizations were located in the UK which had employed either of these apparatuses, and so these were not considered for the test programme. Enquiries were made regarding the C & C A machine and it was found that the C & C A was willing to co-operate with the investigation. Discussions were held with Mr R Chaplin of the C & C A, and permission was obtained for the University to build a machine based on the C & C A design. Once the machine had been completed, it was decided to carry out a comparative study to examine the performance of the basic machine.

5.2.1 Description of Basic Apparatus

The machine at the University of Aston was constructed using the specification provided by the C & C A, a working drawing is provided in Figure D.1 of Appendix D. This basic machine was a replica of the prototype built at the C & C A. The machine with its rolling wheel type of head produces accelerated wear by means of three specially hardened steel wheels (KEA 180 Steel) attached to a circular steel plate. This plate is connected to a shaft, driven by an electric motor (0.25 KW, 1350 Rev/Min), so that the wheels abrade a circular path over a horizontal surface. A general photograph of the basic abrasion apparatus is shown in Plate 5.1. The rolling wheel type of head is shown in Plate 5.2.

The wheels abrade a circular path (see Figure D.2, Appendix D) 20mm wide, whose depth is measured to determine the extent of abrasion. While the test is running, the machine is held in position by means of two bolts inserted through the machine legs into the slab. This prevents the machine from moving laterally, but it does not restrict the vertical movement as the wheels pass over the concrete surface. In the prototype machine, the total dead load of 63 Kg controlled the pressure underneath the wheels. This was achieved with a lead collar, the load being transmitted through the drive shaft. As the wheels run round the circular path, they are also able to rotate on their individual axles and so transfer the force from the total load to the concrete surface. For a given machine the rate of wear is dependent on the pressure, the relative velocity (in magnitude and direction) and the abrasive characteristic of the surface, and so it was essential to use the same load (controlling the pressure) on both machines.

The adopted procedure involved exposing the test surface to fifteen minutes of abrasion with the rolling wheels. The extent of the abrasion damage was determined by measuring the depth of wear of a series of eight locations around the abrasion path. A circular cardboard template, whose circumference coincided with the outer perimeter of the abrasion path, was used to mark these locations on the abrasion path before the test. The points of measurement were numbered around the circumference so that the readings before and after the test could be taken at the same location. These measurements were made with either a dial gauge or a bridge micrometer.

With the completion of the abrasion machine it was considered essential to undertake a comparative study to assess the behaviour of the two machines - Aston and C & C A. This programme involved the use of both machines at the University and at the C & C A.

### 5.2.2 Comparative Tests at the University of Aston

The machine constructed at the University of Aston was identical to the C & C A machine. However, whilst both lead collars were the same weight (40 Kg), their dimensions were different with the diameter of the Aston collar being greater than that of the C & C A collar. It was considered that this difference in the dimensions could produce some difference in the loading mode, for an additional bending moment could be developed in the drive shaft, if a collar became eccentrically located during a test. Such an effect would influence the results of the comparative tests. In order to overcome this, the test slabs were designed so that the following three tests could be conducted on each slab.

(1) C & C A machine with its own lead collar

(2) Aston machine with its own lead collar

(3) Aston machine with C & C A lead collar

For this series of tests, 6 test slabs (1.0 x 0.5 x 0.1m) were cast using two different concrete mix designs, (mix A1 and A2) which are given in Appendix B. For these determinations, three individual tests were performed for each test format. In all cases, the depth of abrasion was measured using a dial gauge mounted on a metal bridge. In addition, the speed of each machine (Rev/Min) was checked with a stroboscope.

In this series, 18 tests were conducted, and the summary of the results is provided in Table 5.1. Significance tests were carried out on the results, and these are detailed in Tables C.1 and C.2 in Appendix C.1 . It was found that there was no significant difference in the depth of abrasion obtained due to different test format. This indicates that there was no difference between the two machines, and that the shape of the collars was not a significant factor.

### 5.2.3 Comparative Tests at The C & C A

This programme was conducted at the C & C A, Wexham Springs , and the two machines were only used with their own collars. Three concrete slabs were tested using two concrete mixes, 6 tests were conducted by each machine,and a summary of the results is provided in Table 5.1. The testing procedure used was similar to the one at Aston,except that a bridge micrometer was used to measure depth.

Significance tests were carried out on the results of these tests, and this information is presented in Table C.3 in Appendix C.1. The findings were similar to those of the comparative test at Aston, in that no significant difference was found in the depth of abrasion obtained by the two machines.

### 5.2.4 Result of the Comparative Study

A summary of the results obtained both at Aston and the C & C A is provided in Table 5.1. These values have been obtained from detailed results, an extract of which is given in Table A.2 in Appendix A. From this initial investigation it was concluded that the basic apparatus, with its rolling wheel action, produces results which are reproducible and this forms a useful base from which to develop the required versatile apparatus. This is particularly noteworthy since in other investigations (94) an accelerated wear machine built to the same specification for examination of the skidding resistance of concrete surfaces, was not able to produce reproducible results. Modification of the basic apparatus may be possible by changing either the plate which carries the abrasive heads or just replacing the abrasive heads. It is, therefore, suggested that this basic apparatus may be utilized for further development.

It should be noted that the comments regarding reproducibility have been derived from a basic statistical analayis, and that the precision of the test method, according to the B.S 5497: Part 1:1979 (95), was not determined. This was not possible since, at the time of this comparative study, a standardised test procedure had not been established. For example, the number of tests required to establish a reliable depth of abrasion was not specified. In the Aston series, three tests were carried out on each mix, while in the C & C A study, two tests were performed on one mix whilst four tests were carried out on the other mix. Furthermore, B.S 5497 (95) requires at least eight laboratories to be included in the programme before the standard analysis may be applied. However, in Appendix C.2, such an analysis (95) has been performed, and this provides values for repeatability (r) and reproducibility (R). These values are provided in Table C.25 in Appendix C.2.

## 5.3 The Development of a Standardised Testing Procedure

Before a comparative testing programme may be undertaken, it is necessary to develop a standardised test procedure to be adopted throughout the investigation.

### 5.3.1 Method of Assessing Depth of Abrasion

The literature review suggested that two main methods have been used to assess the abrasion resistance - weight loss and the depth of wear. The first method could not be employed in this programme as the laboratory specimens were too heavy for accurate detection of the slight changes in weight. Equally important, this method could not be used for accurate field investigations. The depth of wear, however, may be used for both laboratory and field study, and so this was adopted for quantifying abrasion resistance in this investigation.

Two devices were considered for measuring the depth of wear, a bridge micrometer as used at the C & C A, and a dial gauge mounted on a metal bridge as used at Aston. The dial gauge was adopted, rather than a bridge micrometer, because it was considered that the smaller size of the point of the dial gauge would be more sensitive to variations in depth, than the broader point of the bridge micrometer. However, it was necessary to determine whether there was any difference between the results obtained with these two devices and, so, during the comparative tests at the C & C A, readings were taken with both the bridge micrometer and dial gauge. These results are given in Table 5.2 and the statistical data is given in Table C.4 in Appendix C.1. This analysis found that there were no significant differences between the depth of abrasion measured with the two devices. The dial gauge, however, was found to be much easier and quicker to use for such determinations. As both devices produced similar results, it was decided to use a dial gauge for the remainder of the work in view of its speed and ease of application.

During the initial comparative programme the extent of the abrasion damage was assessed at eight equally spaced points around the path of abrasion. During this comparative study it was observed that the depth of the abrasion path was not uniform and, in some cases, there were three equally spaced high spots and three equally spacedlow points around the abrasion path. This gave rise to the concern that significant variations may result in the measured depth of abrasion, depending on the location of the measuring points around the abrasion path. In addition, there could be variations across the width of the groove formed by the wheels, the normal practice being to take the readings in the centre of this groove, i.e. 10mm from each side. These effects were investigated in a series of abrasion tests. These tests were organised as follows:-

(1) Location of the readings: Two sets of eight readings were recorded around each abrasion path and the results are given in Table 5.3. The Student's-t test was used to compare the two sets of data and this analysis is summarised in Table C.5 in Appendix C.1. These clearly show that no significant differences were found between the two sets of data.

(2) Frequency and Location of the readings: To assess these effects it was decided to increase the number of measurement locations around the path of abrasion from 8 to 12 equally spaced positions. In addition, for each of these positions, two readings were taken as indicated in Figure D.2 in Appendix D. Thus, the total number of readings was increased from 8 to 24. A total of 18 sets of readings were recorded, typical results are given in Table A.3 in Appendix A. The results were subjected to a Student's-t analysis and the values are summarised in Table C.6 of Appendix C.1. No significant difference was found between the depth of abrasion based on 8 readings

and on 24 readings.

In some tests it was observed that three high, or low, points could be produced in the abrasion path, these are discussed in more detail in Section 5.5.1.2. It should be noted, however, that with 8 readings only one of the high and one of the low points could be located at a reading position, since 3 is not a factor of 8. With 12 readings, it is possible for all the three high and low points to be located on the marked position since 3 is a factor of 12. No significant differences were detected between the results of the two methods, and so it is suggested that the effects of these high and low points cancel each other, resulting in a representative value for the mean depth of abrasion. It would appear, therefore, that no significant advantage is achieved by recording 24 readings as opposed to 8 readings. The main disadvantage is the extra time required to take the readings, and so, it was decided to adopt the 8 reading method for assessing abrasion depth throughout the subsequent investigation.

### 5.3.2 Dimensions of Test Slab

Generally, slab thickness varies from 125 to 275mm depending on the intensities of traffic and the expected loading within the industrial environment (28). In order to determine the appropriate slab thickness for the proposed study, a series of tests were conducted on slabs of different thicknesses. A total of 9 slabs were constructed with thicknesses of 50mm, 100mm, and 150mm. It was considered that as the maximum particle size was 20mm it would not be necessary to consider slabs thicker than 150mm. In addition, such thick slabs would also have been difficult to handle within the laboratory. For each of the selected thicknesses, 9 abrasion tests were carried out using the accelerated abrasion apparatus with its rolling wheel type of head. A summary of the results of these tests is shown in Table 5.4. These results were analysed using Student's-t test and the values are given in Table C.7 of Appendix C.1. From this analysis, it is clear that there was no significant difference between the abrasion depth found with the slabs of different thicknesses. The above investigation demonstrated that abrasion resistance of concrete was not generally influenced by the slab thickness, and so any of the above slab thicknesses could be considered for use. However, the following points were noted during the investigation and influenced the decision regarding the selection of an appropriate slab thickness for the main investigation:-

(1) In the case of the 50mm thick slab, when the holes were drilled in the slab to prevent the lateral movement of the accelerated abrasion machine, in some cases this operation caused the slab to break at the location of the hole, due to the thinness of the slab.

(2) The 50mm slab thickness limits the maximum size of coarse aggregates which may be used.

(3) The 50mm thick slabs were convenient to handle, but vulnerable to breakage.

(4) The 150mm thick slabs were heavy to handle and so required additional staff or machine plant for routine testing.

(5) The 150mm thick slabs require large amounts of material for the production of routine specimens.

(6) In this series of tests, the slabs were finished by the application of hand floating immediately after tamping. This was done to eliminate the effects of different waiting times required for different slab thicknesses, before trowelling may be applied. It should be noted that the waiting time increases with slab thickness, so that with a 150mm slab thickness being subjected to repeated and

delayed trowelling, it may not be possible to finish the slab until the late hours of the evening or early hours of the next morning. This would clearly make the investigation more difficult to conduct.

Based on the above observation, the 100mm thickness was adopted as the standard slab thickness of the specimens used throughout the programme.

The other dimensions of the test slab are dependent on the minimum number of tests required to determine a mean value for abrasion resistance. This minimum number is discussed in Section 5.3.4, and the dimensions of the test slab were selected to cater for this minimum number.

### 5.3.3 Duration of Abrasion Test

The degree of abrasion damage is dependent on the characteristic of the accelerated abrasion test machine used, and the characteristic of the test surface. This suggests that it is not possible to base the duration of a standard abrasion test on anything other than experience gained from test results comparing different durations and concrete.

The duration of the abrasion tests during the initial programme was 15 minutes, this being the value also employed by the C & C A. However, the suitability of this test period has not been assessed experimentally. This was carried out as part of the comparative study of the three types of head and is detailed in Section 5.5.1.7.

### 5.3.4 Minimum Number of Tests for Mean Depth of Abrasion

In the comparative study, carried out at Aston and at the C & C A, different numbers of tests were used to calculate the mean depth of abrasion for the various concrete mixes, these results being summarised in Table 5.1. However, it is necessary to establish the minimum number of tests for a meaningful result. It is suggested (96) that a suitable criterion for such a decision is that there should be 95% probability that the difference, between the sample estimate of the mean value and that obtainable from averaging all values from a very high number of tests, should not exceed the allowable sampling error (e). The minimum acceptable sample size (n) for 95% confidence is given by:

$$n = \left(1.96 \frac{V}{e}\right)^2$$

where V = Coefficient of Variation %

e = Allowable Sampling Error %

n = Minimum Acceptable Sample Size

In order to use the above formula, it is necessary to have a value for the coefficient of variation (V). Using the available results, the coefficient of variation for the rolling wheel type of head is 7%. If the allowable sampling error for a material like concrete is taken (97) to be about 8%, then the minimum number of tests required is 3. Based on this, three tests were adopted as the standard number for the determination of the mean depth of abrasion. The minimum dimension required for three abrasion tests is 1.00 x 0.50m. Thus, the dimensions of 1.00 x 0.50 x 0.10m was adopted as the standard slab size of the specimens used throughout the programme.

## 5.4 The Development of Alternative Types of Head

In the literature review it was suggested that slabs in industrial premises can generally be subjected to three levels of abrasion, Table 2.1, with different mechanisms of wear being predominant for each exposure. Thus, it is implied that it is necessary for the required accelerated abrasion apparatus to produce rubbing to simulate the light industrial environment, rubbing, rolling, sliding and light impact for the medium industrial environment, and severe rubbing, rolling, sliding, cutting and heavy impact for the heavy industrial environment. The basic apparatus described in the previous section may be considered to simulate the actions which are the most common in the medium industrial environment. Therefore, it is necessary to consider modification of the basic apparatus to produce the actions associated with light or heavy industrial environments.

The forces acting on a slab in a light industrial environment were found to be best simulated by those types of apparatus whose primary action was rubbing (Section 2.4.3.3). In order to simulate this type of action, whilst employing the revolving mode of the basic apparatus, it was decided that the rolling wheels should be replaced by steel pads, to produce the rubbing action. The dressing wheel type of apparatus has been found (see Section 2.4.3.5) to simulate the action to which slabs are subjected in the heavy industrial environment. It was, therefore, decided to replace the rolling wheels of the basic apparatus with dressing wheels, to produce the mode of action which simulates abrasion in the heavy industrial environment.

### 5.4.1 The Revolving Pads Type of Head

It was decided to fix the revolving pads to the steel plate used to carry the rolling wheels, but the wheel carriers were modified to take the pads. These pads were formed from similar material, KEA 180 Steel, to that used for the rolling wheels. The height of each pad was selected to be compatible with the existing structure of the machine (see Appendix D, Figure D.1, Section N), and the contact area of each pad was 20 x 20mm, so that the width of the circular abrasion path would be similar to that produced by the rolling wheels. This design permitted the rapid conversion of the machine from one mode of action to the other.

Attempts were made to operate the apparatus in its new mode of action but, due to development of high frictional forces between the test surface and the pads, the machine was not able to rotate the pads on the test surface. To overcome this problem, the shape of the pads was redesigned and the power of the driving motor was also increased. The edge of each pad head was ground to produce a 5mm chamfer in the direction of motion (see Appendix D, Figure D.1, Section N). This reduced the contact area of each pad to 15 x 20mm, but the width of the path of abrasion remained as before. By inclining the leading edge of the pads, they were able to pass over any high spots that existed in the test surface. These modified pads are shown in Plate 5.3. The driving motor was increased from a 0.25 KW to 0.75 KW. It should be mentioned that the number of revolutions per minute of the new motor was 4 per cent higher than that of the old motor. Furthermore, the new motor was heavier and so the weight of the lead collar was adjusted to compensate for this difference. The collar was reduced to 31Kg with total load remaining at 63Kg. After these modifications, the apparatus was operated with its new mode of action and found to be ready for the comparative tests.

### 5.4.2 The Dressing Wheel Type of Head

The dressing wheel type of head was designed so that it would fit the wheel carrier used for the rolling wheel assembly. This was achieved by constructing three sets of dressing wheels with a total width of 20mm. Each consisted of four cutters, and five spacers which were free to rotate independently, as detailed in Appendix D, Figure D.1, Section O. The cutters were constructed from KEA 180 Steel. The design allows the rolling wheels to be unscrewed and replaced by the dressing wheels. The dressing wheels produced a circular abrasion path of 20mm width, similar to that of both the rolling wheels and the revolving pads.

During the trial runs with this system, it was found that the apparatus was able to function for a few minutes before the motor stopped. When the 0.75 KW motor was used, the wheel carrier plate rotated for a few more minutes before the motor stopped. It was observed that the dust around the path of abrasion was darker than usual. When the dressing wheels were inspected, the teeth of the cutters were found to have worn away badly, particularly on one side. The axle carrying the cutters and the spacers had also been worn with a number of tracks scored on the surface. It is suggested that, initially, the cutters of the dressing wheels were able to turn freely but as the support axles began to wear, the wheels could no longer turn freely, due to uneven wear of the axle. The 0.25 KW motor was not sufficiently powerful to slide the cutter over the test surface, and so it stopped. When the more powerful motor was used, the cutters were forced to slide over the test surface, causing higher wear on one side of the dressing wheels. However, as the cutter further penetrated the test surface, additional power was required for motion but this could not be supplied and so the more powerful motor also stopped.

From the above, it was concluded that the following modifications were necessary:-

(1) Prevention of wear on the centre piece (axle)

(2) Reduction of the rate of wear on the teeth of the cutters.

The prevention of wear on the centre piece was achieved by placing ball bearings (2mm diameter) between the cutter and the centre piece (see Appendix D, Figure D.1, Section O). The reduction of the wear rate on the teeth of the cutter was achieved by subjecting them to the following heat treatment, pre-heat 750 degrees C - 800 degrees C, hardening from 980 degrees C into oil, double temper from 500 degrees C - 520 degrees C.

Following these modifications, preliminary tests showed that both the 0.25 KW and 0.75 KW motors were able to turn the dressing wheel head, and that very little wear was seen on the centre piece carrying the cutters. The rate of wear on the teeth of the cutter was also reduced. It was, therefore, considered that this form of the apparatus could be used in the comparative study, with the drive being provided by the 0.25 KW motor rather than the 0.75 KW motor. The final form of the dressing wheels is shown in Plate 5.4.

## 5.5 Comparative Study of the Various Types of Head

The aim of this part of the programme was to examine:-

(1) The relative performance of the three types of head.

(2) The mechanisms by which each head abraded the concrete surfaces.

To achieve these objectives, some 27 slabs were constructed from three different concrete mixes. The details of the mixes have been provided in Appendix B (mix B1, B2 and B3). The constructional procedure is similar to that described in Sections 6.4 and 6.4.1, and all the slabs were subjected to the same process. Similarly, all the slabs were cured by the wet burlap, similar to section 6.4.6. It is, therefore, considered that any variation due to construction or curing had been minimised. The quality of the concrete was controlled by cube crushing strength, these were crushed according to section 6.5.2.1, and a summary of the results is provided in Table A.4 in Appendix A. For each type of head, 27 abrasion tests were performed. In all these tests measurements of the depth of abrasion were taken after 2, 5, 10, 15 and 30 minute exposure, the abrasion path being cleared of debris before the readings were taken with the dial gauge.

A summary of the test results is provided in Tables 5.5 to 5.7. An initial inspection of these results indicated that the revolving pads had produced rather more wear than had been expected. This was attributed to the impact caused by the lead collar bouncing as the pads rotate, and was not associated with the action which it was required to simulate. It was, therefore, decided to perform a further series of tests using the revolving pads without the lead collar. This was carried out by constructing 9 more slabs, using the same concrete mixes, and 27 abrasion tests were performed. These results are shown in Table 5.8. The plots of rate of abrasion are shown in Figures 5.1 to 5.3 for the different types of head with each of the three mixes.

### 5.5.1 Relative Performance of the Three Types of Head

The results of this programme demonstrate that the action of the dressing wheels is the most aggressive and that of the revolving pads, both with and without the lead collar, the least aggressive. This is apparent from the plots in all three Figures 5.1 to 5.3. It is interesting to note that the results from the rolling wheels and the revolving pads with the lead collar are very similar. This may be attributed to the impact effects introduced by the lead collar during the running of both the rolling wheels and the revolving pads types of head. By removing the lead collar, these impact forces were reduced, but not eliminated, and this is confirmed by the resultant decrease in the abrasion rate as shown in Figures 5.1 to 5.3.

To present the observations in a clear form, it is suggested that the performance of the three types of head may be considered in the following section.

#### 5.5.1.1 Overall Behaviour of Machine on the Test Surface

With all the three types of head little vibration was noted in the early stages of the tests. As each test progressed more vibration was noted and it appeared to depend on the type of head and the abrasion resistance of the test surface. For example, only limited vibration was seen in the case of the revolving pads on mix B1, with considerable vibration being observed in the case of the dressing wheels on the mix B3. As the test progressed the surface matrix of the test surface was penetrated and so the head encountered coarse aggregate and a rougher surface. The vibration created in this manner resulted in the machine and the lead collar moving in the vertical direction, and the lead collar revolved slowly around the motor. These movements resulted in the test surface being subjected to impact. The magnitude of these impact forces being very dependent on both the load and on the amount of vibration.

In the case of the revolving pads, without the lead collar, little vibration was noted in the first 15 minutes of the test for the three concrete mixes, although the vibration increased during the following 15 minutes. During the initial 15 minutes of the test, the rolling wheels type of head exhibited more vibration than the revolving pads but, in the next fifteen minutes of the test, the vibration was increased noticeably, particularly with mix B3. Similar observations were made for the dressing wheels, but the difference being that even during the first 15 minutes of the test, this type of head produced much more vibration than the rolling wheels in the same period. Furthermore, in the last 15 minutes of the dressing wheels test on mix B3, the vibration was so severe that, on some occasions, excessive impact forces were developed as the whole machine bounced on the surface of the slab.

5.5.1.2 Abrasion Path

The abrasion path produced by the different types of head, after different durations, was examined. The main points may be summarised as follows:-

(a) The abrasion path was not generally uniform. This is mainly due to the heterogeneity of the test material.

(b) The non-uniformity of the abrasion path, generally increased with the duration of the test and the degree of aggressiveness of the testing action, and decreased with the increasing quality of the concrete.

(c) When a test surface was not horizontal, the resulting abrasion path was found to be deeper around one side of the path.

(d) Some of the abrasion paths were found to have three equally spaced high points and three equally spaced low points. This was most evident in abrasion paths produced by the rolling wheels type of head on the lower quality concrete, mix B3, and for tests of 30 minutes duration. A possible explanation is that when one of the wheels encounters protruding aggregates, it goes over it and therefore it is lifted. As the wheels are mounted on a rigid base, if one wheel rises over a lump then the other two will also rise, thus creating equally spaced high and low points. The main reason this effect was not so evident in the case of the dressing wheels type of head is due to the aggressive nature so that when the wheels encountered coarse aggregates, they either wore away the aggregate, along with other parts of the surface, or dislodged the protruding aggregate. In the case of the revolving pads, this effect was not as evident as the rolling wheels, mainly because less aggregates were encountered, due to the more limited total wear.

(e) Across the abrasion path produced by the dressing wheels, there was a series of troughs and peaks, the cutters producing the troughs and the spacers resulting in the peaks.

5.5.1.3 Wearing Quality of the Three Types of Head

(a) The hardening process used for the dressing wheel cutters (see section 5.4.2) was found to be effective, but not sufficient to prevent wearing of the cutters after a long period of service. It was found that after several tests the dressing wheel cutters started to show signs of wear. New dressing wheel cutters were used after every nine tests.

(b) Throughout this series of tests the same rolling wheels were used, and no apparent sign of wear was detected.

(c) Signs of wear were detected on the surface of the revolving pads after 18 tests, and so a new set of pads were used after every 18 tests.

5.5.1.4 The Angular Velocity

A revolution counter was connected to the circular plate carrying the different types of head, in order to determine the angular velocity during the test period. It was found that the angular velocity varied between 170 to 177 rev/min, depending on the type of head being used. The average number of rev/min for the reolving pad, dressing wheels and rolling wheels were 170, 173, 177 respectively.

5.5.1.5 The Repeatability of the Test Techniques

The term repeatability refers to the variability, or rather smallness of variability, between replicate results obtained on the same material with the same machine. The repeatability of the test results is affected by the following factors:

(1) Rapid wear of the types of head and the failure to replace them regularly.

(2) Failure to remove dust and debris from test surface at a specified interval.

(3) Improper selection of a representative test area or specimen.

(4) Uniformity and consistent quality of surface texture and the concrete.

(5) Arbitrary increase in the length of test.

(6) Insufficient number of abrasion readings.

The influence of the above factors was minimised in the present series of tests by the development of standardised procedure for specimen production and testing.

The statistical assessment, summarised in Tables 5.5 to 5.8, shows that the dressing wheels technique produced more variable results than the other techniques. The coefficient of variation for tests with the dressing wheels ranged from 12 to 30 percent, whereas the values for the rolling wheels and the revolving pads were within a narrow band from 5 to 9 percent. It is suggested that if new sets of cutters were to be used after every six tests, then the repeatability of the test results with the dressing wheels type of head could be greatly improved. This would, however, be rather expensive for routine testing.

Another way to compare the various techniques of test with each other is to plot the standard deviation against the depth of abrasion. The more parallel the plotted graph line is to the abscissa, the more desirable the method of test becomes from the standpoint of repeatability (46). This comparison has been made in Figure 5.4 and clearly demonstrates the desirability of both the rolling wheels and the revolving pads types of head so far as repeatability is concerned. It also confirms that the dressing wheels method is less desirable than the other two techniques.

#### 5.5.1.6 Sensitivity to Mix Designs

For the sake of clarity the rates of abrasion for the three different mixes have been plotted on three graphs, Figures 5.1 to 5.3, rather than one graph. The detailed results, given in Tables 5.5 to 5.8, show that all three types of head were able to distinguish between the three concrete mixes used, and this is confirmed by Student's-t test data given in Table C.8 of Appendix C.1.

The average depth of abrasion against free water-cement ratios, for the 15 minutes test, has been plotted in Figure 5.5. This clearly shows the correlation between the depth of abrasion and free water-cement ratio for the various test techniques. It should be noted that high correlation coefficients that were obtained are mainly due to the limited number of water-cement ratios used (n=3).

It is suggested that, if several extremely high quality concrete surfaces were to be tested, then the least aggressive testing technique (e.g. revolving pads type) might not have been able to distinguish between the various test surfaces. It is, however, important to remember that high quality concrete surfaces are most likely to be used in medium to heavy industrial environments, and so the testing technique most appropriate in such situations would either be the rolling wheels or the dressing wheels method.

#### 5.5.1.7 Duration of Test

The rates of abrasion, illustrated in Figures 5.1 to 5.3, show that there was a progressive reduction in the rate of abrasion as the test period increased. This reduction was far greater with the revolving pads, and the rolling wheels, than with the dressing wheels. The dressing wheels were able to abrade the aggregates whereas the other two types of head had only limited effect on the individual particles. The rate of abrasion, therefore, was limited by the hard particles which could not be damaged by these two types of head.

It is not clear from the above graphs the optimum duration which might be used for a standard test. The duration used, (e.g. 2,5,10,15 and 30 minutes) were generally sufficient to distinguish between the different concrete mixes tested. It does appear that the relative effects of the three heads were subject to some re-arrangement with short test periods of less than 5 minutes. This can be seen on Figures 5.2 and 5.3. However, with the exception of the dressing wheels, the rate of abrasion after some 15 minutes had generally become quite low and uniform.

The selection of any standard duration must be arbitrary since it is extremely difficult, if not impossible, to determine it otherwise. However, based on the discussion presented above (e.g. running of the tests, abrasion path, wearing quality of the heads, repeatability and sensitivity of the techniques), and the experience gained during the comparative studies, it was decided to adopt the 15 minutes period as the standard throughout the remainder of the investigation.

### 5.5.2 The Mechanisms by which Abrasion Damage is Caused

According to the abrasion theory (7) discussed in the literature review, high specific pressures are developed at the point of contact between the abrasive and the test surfaces, and these result in a continuous state of plastic deformation being developed in a small hemispherical volume beneath the impression. Plastic deformation can be envisaged with metallic materials but, for material like concrete, plastic behaviour is more of an abstraction. It is probable that with concrete there is a rapid transition from elastic deformation to breakdown by microcracking, splitting and fragmentation. In the present work a quantitative analysis of these suppositions was not attempted, due to the complex nature of both the processes and the material.

It has been suggested that the revolving pads mainly caused abrasion by rubbing, the rolling wheels by rolling and light impact and the dressing wheels by highly concentrated compressive forces and high impact. One way of illustrating these mechanisms is to compare the resultant abrasion damage caused by each of the heads as shown in Figure 5.5. From this graph it is clear that the least aggressive mode of action, due to the revolving pads without the lead collar, produces a line which is both closest and most nearly parallel to the abscissa than the relationships produced by the others. In contrast, the most aggressive mode of action produces a line which is the farthest and least parallel from the abscissa. It is suggested that the difference between the lines produced by the revolving pads, without the lead collar, and the rolling wheels is mainly due to the presence of rolling and light impact forces. Furthermore, the difference between the lines produced by the rolling wheels and the dressing wheels is mainly due to the presence of the cutting action and high impact forces.

The appearance of the various paths of abrasion, produced by the different types of heads, also indicates the presence of different abrasion mechanisms. For example, in the paths produced both by the dressing wheels and by the rolling wheels, there was evidence of shattering, yielding or debonding of the aggregate particles. In the path produced by the revolving pads there was, however, evidence of polishing. In the former cases the evidence suggests the influence of impact forces, while in the latter case the polishing is attributed to a rubbing action. It should be noted that during the rolling action, whether with the rolling wheels or the dressing wheels type of head, some slip occurs which has the effect of producing rubbing, sliding and cutting action depending on the nature of the head. No sign of tensile cracks were observed in the surface matrix (by the naked eye) of the paths of abrasion with any of the various types of head. However, the rupture of the aggregate matrix bond may be attributed to the development of cracks around this interface. The development of cracks within the matrix could be a topic for further study.

At the start of an abrasion test, irrespective of the head, the test surfaces were relatively clean, but as the test progressed, abrasion damage occurred resulting in the production of loose abraded material. From Section 2, on Friction and Wear, it is clear that at the start of the test the mechanism of wear was two body, but as the test progressed, there was a transition from two body to three body wear. This transition is very much dependent on both the testing technique and on the quality of the testing surface. Due to the different mechanisms involved in two and three body wear, the rate of abrasion during two body wear will be higher than during three body wear. The implication being that the rate of abrasion for each testing duration was not linear as was assumed in the plots shown in Figures 5.1 to 5.3. The possibility of removing the abraded materials from the path of abrasion during the test was investigated. This was achieved by blowing air on the abrasion path. It was found that although some of the abraded material was removed the testing heads were covered with the debris of abraded materials. The resultant depth of abrasion using this method was not significantly different from the standard method used, and so the additional complication of providing a blower did not appear to be justified.

The relationships shown in Figures 5.1 to 5.3 illustrate the mechanisms by which the concrete surface resisted abrasion. The surface matrix initially resisted the abrasive forces but, once this was penetrated, the aggregate/paste bonds resist the abrasive forces. This is indicated by the reduction of the rate of abrasion in all of the graphs. This rate is dependent on both the degree of the aggressiveness of the test method and initially on the quality of the surface matrix and later on the concrete itself. This is clearly apparent from a consideration of all the results plotted in these three Figures, 5.1 to 5.3. It is suggested that, characteristically, the first part of any curve of rate of abrasion for concrete reflects the influence of the surface matrix but, once penetrated, the next part of the curve is indicative of the quality of all the components of the concrete.

In these series of tests the results of revolving pads both with and without the lead collar were presented, mainly to demonstrate the effect of the lead collar. However, for all the subsequent work, the revolving pads were only employed without the lead collar. Thus, in the remainder of this thesis, unless specific mention is made of the lead collar, the revolving pads are only considered in their unsurcharged mode of operation.

## 5.6 Discussion

In section 2.4.1 of the literature review, five conditions were specified for the acceptability of any abrasion test method. It is necessary to assess the degree to which these five conditions are satisfied by the test methods developed.

### 5.6.1 Condition 1 - Simulation of Service Conditions

The first condition is the ability of the test method to subject a test surface to a treatment which is similar to that of the service exposure.

5.6.1.1 Revolving Pads

From the experimental results and observations, it is clear that the mode of action of this apparatus was the least aggressive and caused abrasion damage mainly by rubbing. This mode is similar to the actions which exist in the light industrial environment (see Table 2.1). It is, therefore, reasonable to suggest that the revolving pads subject the test surface to similar forces which may be encountered during the service life of a slab in a light industrial environment, and so the first condition is satisfied for such an environment.

5.6.1.2 Rolling Wheels

It has been demonstrated that this head subjects the test surface to a combination of rolling and light impact forces. Such conditions occur in the medium industrial environment in which fork lift trucks and light steel wheeled traffic operate. Such traffic damages the slab by rubbing, rolling, sliding and light impact. The mode of action of the rolling wheels type of head simulates this action, and so the first condition is satisfied for the medium industrial environment.

5.6.1.3 Dressing Wheels

This type of head was found to be the most aggressive of the three employed in this study. It caused abrasion damage by the combination of rolling, impact and cutting forces. These types of forces are generally associated with the heavy industrial environment. Thus, the dressing wheels would appear to simulate such conditions, and so be appropriate for assessing floors in the heavy industrial environment.

It is clear that the combination of all three types of head should be able to simulate those forces which are present in all industrial environments. Indeed, the apparatus with its various types of action satisfies the first condition for the acceptability of test method.

### 5.6.2 Condition 2 - Sensitivity

The second condition is that the test method must be sensitive to variation in surface condition. In section 5.5.1.6 it was demonstrated that all three types of head were sensitive to variation in the concrete mix design. It can be stated that all three heads satisfy the second condition.

### 5.6.3 Condition 3 - Repeatability

The third condition is the repeatability of the test methods. The repeatability of the test methods have been fully discussed in section 5.5.1.5, and it is clear that the test methods produce results which are generally repeatable.

### 5.6.4 Condition 4 - Portability

The fourth condition is the portability of the testing apparatus. The testing apparatus with its three modes of action is fully portable, and may be used on site, and so the fourth condition is fully satisfied.

### 5.6.5 Condition 5 - Ease of Use

The fifth condition is that the test method must be easy to follow, and the cost and time of testing should not be excessive. From the standardised testing procedure, it is clear that the test method is easy to follow and that the duration of the test is not excessive. So far as the cost of testing is concerned, it is clear from section 5.5.1.3 that the rolling wheels and the rolling pads need to be replaced less frequently than the dressing wheels. This indicates that the cost of carrying out tests using the dressing wheels type of head would be more than the other types. However, this does not mean that the cost would be excessive for a limited number of tests. It is, therefore, suggested that the fifth condition is satisfied.

The above discussion indicates that generally the specified conditions, for the acceptability of abrasion test methods, are satisfied by the test methods and procedure developed.

It is necessary to consider the mode of action which should be used in the proposed laboratory testing programme for comparative purposes. The criterion which was used was that the selected head should need replacing only after a large number of tests. The only type of head which satisfies this criterion was the rolling wheels (see section 5.5.1.3), and so this head was adopted for purposes of laboratory investigation.

## 5.7 SUMMARY

The work reported in this chapter may be summarised as follows:-

(1) A versatile apparatus with three modes of action, has been developed for assessing the abrasion resistance of concrete slabs in the industrial environment.

(2) A standardised testing procedure has been developed.

(3) The testing methods and procedure developed satisfy the conditions for acceptability of an abrasion test method.

| Mix No. | Machine A = Aston C = C & CA | Collar | Slab No. | Depth of Abrasion (mm) | Mean Depth of Abrasion (mm) |
|---|---|---|---|---|---|
| A1 | A | A | 1 | 0.78 | 0.66 |
| | A | A | 2 | 0.71 | |
| | A | A | 3 | 0.50 | |
| | C | C | 1 | 0.56 | 0.65 |
| | C | C | 2 | 0.82 | |
| | C | C | 3 | 0.58 | |
| | A | C | 1 | 0.74 | 0.71 |
| | A | C | 2 | 0.71 | |
| | A | C | 3 | 0.67 | |
| A2 | A | A | 1 | 0.46 | 0.48 |
| | A | A | 2 | 0.53 | |
| | A | A | 3 | 0.46 | |
| | C | C | 1 | 0.42 | 0.48 |
| | C | C | 2 | 0.44 | |
| | C | C | 3 | 0.58 | |
| | A | C | 1 | 0.44 | 0.46 |
| | A | C | 2 | 0.44 | |
| | A | C | 3 | 0.50 | |
| C & CA 1 | A | A | 1 | 1.50 | 1.84 |
| | A | A | 1 | 2.18 | |
| | C | C | 1 | 2.25 | 1.83 |
| | C | C | 1 | 1.40 | |
| C & CA 2 | A | A | 2 | 0.20 | 0.20 |
| | A | A | 2 | 0.14 | |
| | A | A | 3 | 0.21 | |
| | A | A | 3 | 0.23 | |
| | C | C | 2 | 0.26 | 0.25 |
| | C | C | 2 | 0.28 | |
| | C | C | 3 | 0.24 | |
| | C | C | 3 | 0.22 | |

TABLE 5.1 Summary of Comparative Tests Carried Out at The University of Aston and at the C & CA

| Mix No. | Depth of Abrasion (mm) | |
|---|---|---|
| | Bridge micrometer reading | Dial gauge reading |
| C & CA 1 | 1.5 | 1.35 |
| | 2.18 | 2.04 |
| C & CA 2 | 0.20 | 0.21 |
| | 0.14 | 0.16 |
| | 0.24 | 0.26 |
| | 0.22 | 0.28 |
| | 0.21 | 0.24 |
| | 0.23 | 0.25 |

TABLE 5.2 Summary of the Depth of Abrasion Readings Recorded by Bridge Micrometer and Dial Gauge at the C & CA

| Slab No. | Depth of Abrasion (mm) | |
|---|---|---|
| | Set 1 | Set 2 |
| 1 | 0.69 | 0.70 |
| | 0.70 | 0.70 |
| | 0.70 | 0.68 |
| 2 | 0.73 | 0.75 |
| | 0.61 | 0.63 |
| | 0.78 | 0.75 |
| 3 | 0.68 | 0.66 |
| | 0.76 | 0.76 |
| | 0.76 | 0.74 |
| 4 | 1.73 | 1.70 |
| | 1.44 | 1.51 |
| | 1.22 | 1.30 |
| 5 | 1.37 | 1.33 |
| | 1.48 | 1.52 |
| | 1.93 | 1.79 |
| 6 | 1.67 | 1.61 |
| | 1.60 | 1.70 |
| | 2.16 | 2.25 |

TABLE 5.3 Summary of the Results of Two Sets of 8 Readings Recorded Around Each Abrasion Path

| Slab Thickness (mm) | Mean* Depth of Abrasion (mm) |
|---|---|
| 50 | 0.80 |
| 100 | 0.79 |
| 150 | 0.82 |

* Each mean is the average of 9 abrasion tests

TABLE 5.4 Summary of Test Results for Different Slab Thicknesses

| Mix No. | Free W/C Ratio | Period of Abrasion (Min) | Slab 1 Test No. | | | Slab 2 Test No. | | | Slab 3 Test No. | | | Mean depth of Abrasion (mm) | S.d $\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | | |
| B1 | 0.37 | 2 | 0.10 | 0.14 | 0.11 | 0.12 | 0.13 | 0.10 | 0.13 | 0.15 | 0.11 | 0.12 | 0.017 |
| | | 5 | 0.21 | 0.26 | 0.25 | 0.22 | 0.23 | 0.22 | 0.24 | 0.25 | 0.20 | 0.23 | 0.019 |
| | | 10 | 0.26 | 0.30 | 0.29 | 0.26 | 0.27 | 0.28 | 0.29 | 0.27 | 0.26 | 0.28 | 0.014 |
| | | 15 | 0.31 | 0.36 | 0.34 | 0.29 | 0.30 | 0.30 | 0.32 | 0.33 | 0.30 | 0.32 | 0.022 |
| | | 30 | 0.39 | 0.41 | 0.40 | 0.40 | 0.38 | 0.39 | 0.36 | 0.40 | 0.39 | 0.39 | 0.014 |
| B2 | 0.47 | 2 | 0.32 | 0.34 | 0.30 | 0.25 | 0.35 | 0.31 | 0.30 | 0.28 | 0.31 | 0.31 | 0.028 |
| | | 5 | 0.37 | 0.39 | 0.36 | 0.34 | 0.39 | 0.38 | 0.36 | 0.37 | 0.43 | 0.38 | 0.024 |
| | | 10 | 0.43 | 0.47 | 0.44 | 0.42 | 0.49 | 0.45 | 0.45 | 0.44 | 0.53 | 0.46 | 0.032 |
| | | 15 | 0.55 | 0.62 | 0.53 | 0.58 | 0.65 | 0.59 | 0.54 | 0.55 | 0.59 | 0.58 | 0.037 |
| | | 30 | 0.63 | 0.70 | 0.63 | 0.66 | 0.76 | 0.64 | 0.66 | 0.65 | 0.68 | 0.67 | 0.039 |
| B3 | 0.60 | 2 | 0.46 | 0.36 | 0.42 | 0.36 | 0.44 | 0.39 | 0.39 | 0.38 | 0.41 | 0.40 | 0.032 |
| | | 5 | 0.60 | 0.51 | 0.55 | 0.50 | 0.58 | 0.53 | 0.57 | 0.54 | 0.55 | 0.55 | 0.030 |
| | | 10 | 0.71 | 0.65 | 0.69 | 0.63 | 0.72 | 0.66 | 0.67 | 0.70 | 0.66 | 0.68 | 0.028 |
| | | 15 | 0.82 | 0.73 | 0.78 | 0.76 | 0.85 | 0.73 | 0.72 | 0.78 | 0.79 | 0.77 | 0.041 |
| | | 30 | 1.10 | 1.05 | 1.08 | 1.05 | 1.10 | 1.00 | 0.97 | 0.99 | 1.02 | 1.04 | 0.045 |

TABLE 5.5 Summary of the Revolving Pads (with the lead collar) Test Results

| Mix No. | Free W/C Ratio | Period of Abrasion (Min) | Slab 1 Test No 1 | Slab 1 Test No 2 | Slab 1 Test No 3 | Slab 2 Test No 1 | Slab 2 Test No 2 | Slab 2 Test No 3 | Slab 3 Test No 1 | Slab 3 Test No 2 | Slab 3 Test No 3 | Mean depth of Abrasion (mm) | S.d $\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 0.37 | 2 | 0.20 | 0.14 | 0.13 | 0.15 | 0.17 | 0.14 | 0.15 | 0.13 | 0.17 | 0.16 | 0.022 |
| | | 5 | 0.29 | 0.21 | 0.20 | 0.23 | 0.26 | 0.23 | 0.23 | 0.21 | 0.27 | 0.24 | 0.029 |
| | | 10 | 0.35 | 0.28 | 0.28 | 0.29 | 0.32 | 0.29 | 0.31 | 0.27 | 0.33 | 0.30 | 0.025 |
| | | 15 | 0.39 | 0.32 | 0.31 | 0.33 | 0.34 | 0.35 | 0.35 | 0.29 | 0.37 | 0.34 | 0.029 |
| | | 30 | 0.43 | 0.40 | 0.38 | 0.39 | 0.39 | 0.42 | 0.40 | 0.36 | 0.41 | 0.40 | 0.020 |
| B2 | 0.47 | 2 | 0.28 | 0.20 | 0.32 | 0.30 | 0.23 | 0.22 | 0.29 | 0.26 | 0.28 | 0.26 | 0.038 |
| | | 5 | 0.42 | 0.36 | 0.43 | 0.42 | 0.41 | 0.31 | 0.45 | 0.41 | 0.39 | 0.40 | 0.040 |
| | | 10 | 0.51 | 0.44 | 0.52 | 0.54 | 0.50 | 0.42 | 0.53 | 0.52 | 0.48 | 0.49 | 0.039 |
| | | 15 | 0.60 | 0.51 | 0.60 | 0.62 | 0.59 | 0.50 | 0.63 | 0.60 | 0.59 | 0.58 | 0.043 |
| | | 30 | 0.72 | 0.63 | 0.62 | 0.66 | 0.68 | 0.59 | 0.72 | 0.72 | 0.70 | 0.67 | 0.046 |
| B3 | 0.60 | 2 | 0.36 | 0.40 | 0.36 | 0.32 | 0.34 | 0.43 | 0.15 | 0.38 | 0.32 | 0.34 | 0.075 |
| | | 5 | 0.62 | 0.62 | 0.55 | 0.53 | 0.52 | 0.65 | 0.33 | 0.62 | 0.51 | 0.55 | 0.092 |
| | | 10 | 0.72 | 0.76 | 0.66 | 0.68 | 0.65 | 0.74 | 0.45 | 0.87 | 0.66 | 0.69 | 0.106 |
| | | 15 | 0.81 | 0.87 | 0.74 | 0.80 | 0.72 | 0.88 | 0.68 | 0.97 | 0.80 | 0.81 | 0.084 |
| | | 30 | 1.15 | 1.25 | 1.10 | 1.12 | 1.00 | 1.18 | 0.99 | 1.17 | 1.09 | 1.16 | 0.079 |

TABLE 5.6 Summary of the Rolling Wheels Test Results

| Mix No. | Free W/C Ratio | Period of Abrasion (Min) | Slab 1 Test No. | | | Slab 2 Test No. | | | Slab 3 Test No. | | | Mean Depth of Abrasion (mm) | S.d 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | | |
| B1 | 0.37 | 2 | 0.18 | 0.18 | 0.21 | 0.22 | 0.17 | 0.22 | 0.25 | 0.22 | 0.20 | 0.20 | 0.024 |
| | | 5 | 0.36 | 0.39 | 0.32 | 0.34 | 0.32 | 0.30 | 0.35 | 0.35 | 0.36 | 0.34 | 0.025 |
| | | 10 | 0.59 | 0.63 | 0.49 | 0.66 | 0.44 | 0.48 | 0.51 | 0.46 | 0.48 | 0.53 | 0.075 |
| | | 15 | 0.75 | 0.76 | 0.71 | 0.78 | 0.56 | 0.62 | 0.65 | 0.68 | 0.61 | 0.68 | 0.071 |
| | | 30 | 1.43 | 1.32 | 1.26 | 1.29 | 1.25 | 0.97 | 1.00 | 1.02 | 0.89 | 1.16 | 0.179 |
| B2 | 0.47 | 2 | 0.53 | 0.26 | 0.36 | 0.32 | 0.32 | 0.35 | 0.37 | 0.27 | 0.28 | 0.34 | 0.077 |
| | | 5 | 0.88 | 0.41 | 0.61 | 0.59 | 0.68 | 0.68 | 0.53 | 0.51 | 0.45 | 0.59 | 0.134 |
| | | 10 | 1.38 | 0.81 | 0.98 | 0.91 | 0.93 | 1.04 | 0.73 | 0.90 | 0.80 | 0.94 | 0.179 |
| | | 15 | 1.90 | 1.25 | 1.32 | 1.27 | 1.26 | 1.40 | 0.90 | 1.18 | 1.00 | 1.28 | 0.266 |
| | | 30 | 3.38 | 2.23 | 2.35 | 2.46 | 2.01 | 2.20 | 1.75 | 1.91 | 1.94 | 2.25 | 0.454 |
| B3 | 0.60 | 2 | 1.10 | 1.22 | 0.98 | 0.77 | 1.00 | 0.65 | 0.75 | 0.71 | 0.64 | 0.87 | 0.199 |
| | | 5 | 1.58 | 1.64 | 1.32 | 1.06 | 1.62 | 0.98 | 1.09 | 1.00 | 0.88 | 1.24 | 0.286 |
| | | 10 | 2.59 | 2.58 | 1.96 | 1.83 | 2.14 | 1.48 | 1.47 | 1.69 | 1.25 | 1.89 | 0.451 |
| | | 15 | 3.50 | 3.87 | 2.42 | 2.56 | 2.79 | 2.05 | 1.95 | 2.29 | 1.65 | 2.56 | 0.683 |
| | | 30 | 5.69 | 6.02 | 4.51 | 4.53 | 4.79 | 3.98 | 2.98 | 3.95 | 2.29 | 4.30 | 1.117 |

TABLE 5.7 Summary of the Dressing Wheels Test Results

| Mix No. | Free W/C Ratio | Period of Abrasion (Min) | Slab 1 Test No 1 | Slab 1 Test No 2 | Slab 1 Test No 3 | Slab 2 Test No 1 | Slab 2 Test No 2 | Slab 2 Test No 3 | Slab 3 Test No 1 | Slab 3 Test No 2 | Slab 3 Test No 3 | Mean depth of Abrasion (mm) | S.d $\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 0.37 | 2 | 0.11 | 0.12 | 0.12 | 0.11 | 0.13 | 0.09 | 0.12 | 0.10 | 0.13 | 0.11 | 0.013 |
| | | 5 | 0.21 | 0.22 | 0.20 | 0.19 | 0.23 | 0.18 | 0.20 | 0.15 | 0.23 | 0.20 | 0.024 |
| | | 10 | 0.27 | 0.29 | 0.24 | 0.23 | 0.27 | 0.25 | 0.24 | 0.20 | 0.28 | 0.25 | 0.027 |
| | | 15 | 0.28 | 0.30 | 0.27 | 0.26 | 0.29 | 0.27 | 0.25 | 0.24 | 0.30 | 0.27 | 0.020 |
| | | 30 | 0.33 | 0.35 | 0.32 | 0.30 | 0.34 | 0.32 | 0.32 | 0.29 | 0.35 | 0.32 | 0.019 |
| B2 | 0.47 | 2 | 0.29 | 0.25 | 0.28 | 0.24 | 0.27 | 0.23 | 0.25 | 0.30 | 0.25 | 0.26 | 0.023 |
| | | 5 | 0.37 | 0.33 | 0.39 | 0.34 | 0.34 | 0.31 | 0.33 | 0.36 | 0.31 | 0.34 | 0.025 |
| | | 10 | 0.46 | 0.44 | 0.45 | 0.43 | 0.43 | 0.42 | 0.40 | 0.47 | 0.40 | 0.43 | 0.022 |
| | | 15 | 0.53 | 0.52 | 0.52 | 0.52 | 0.51 | 0.48 | 0.47 | 0.54 | 0.45 | 0.50 | 0.029 |
| | | 30 | 0.63 | 0.61 | 0.60 | 0.60 | 0.57 | 0.54 | 0.56 | 0.60 | 0.52 | 0.58 | 0.034 |
| B3 | 0.60 | 2 | 0.31 | 0.32 | 0.33 | 0.29 | 0.33 | 0.34 | 0.34 | 0.36 | 0.28 | 0.32 | 0.024 |
| | | 5 | 0.45 | 0.43 | 0.47 | 0.45 | 0.47 | 0.46 | 0.48 | 0.50 | 0.40 | 0.46 | 0.027 |
| | | 10 | 0.62 | 0.59 | 0.61 | 0.60 | 0.63 | 0.63 | 0.62 | 0.66 | 0.55 | 0.61 | 0.029 |
| | | 15 | 0.70 | 0.65 | 0.71 | 0.69 | 0.72 | 0.70 | 0.70 | 0.75 | 0.61 | 0.69 | 0.038 |
| | | 30 | 0.86 | 0.83 | 0.90 | 0.85 | 0.89 | 0.87 | 0.88 | 0.96 | 0.80 | 0.87 | 0.043 |

TABLE 5.8 Summary of the Revolving Pad Test Results (without the lead collar)

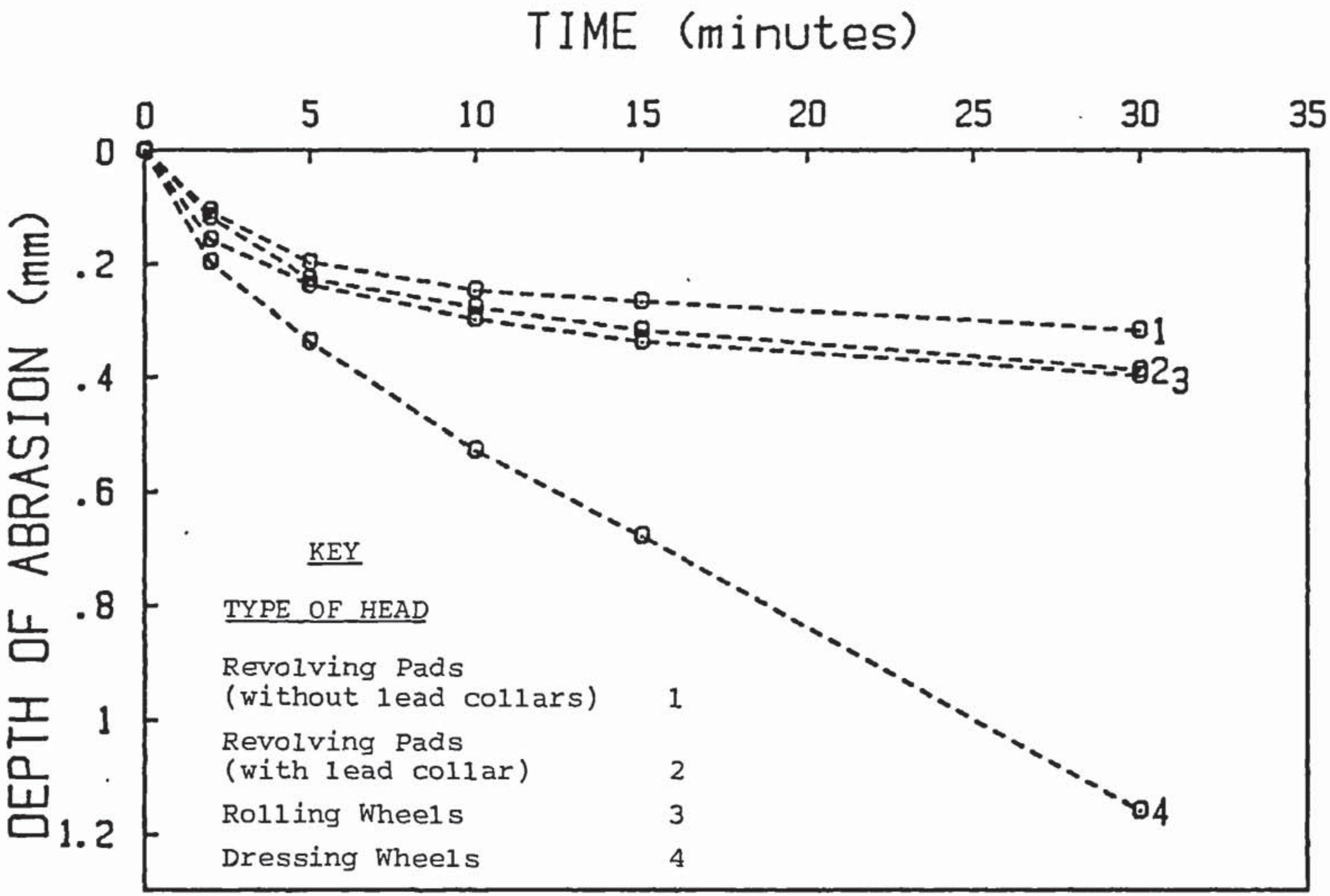



FIGURE 5.1 Rate of Abrasion for MIX B1

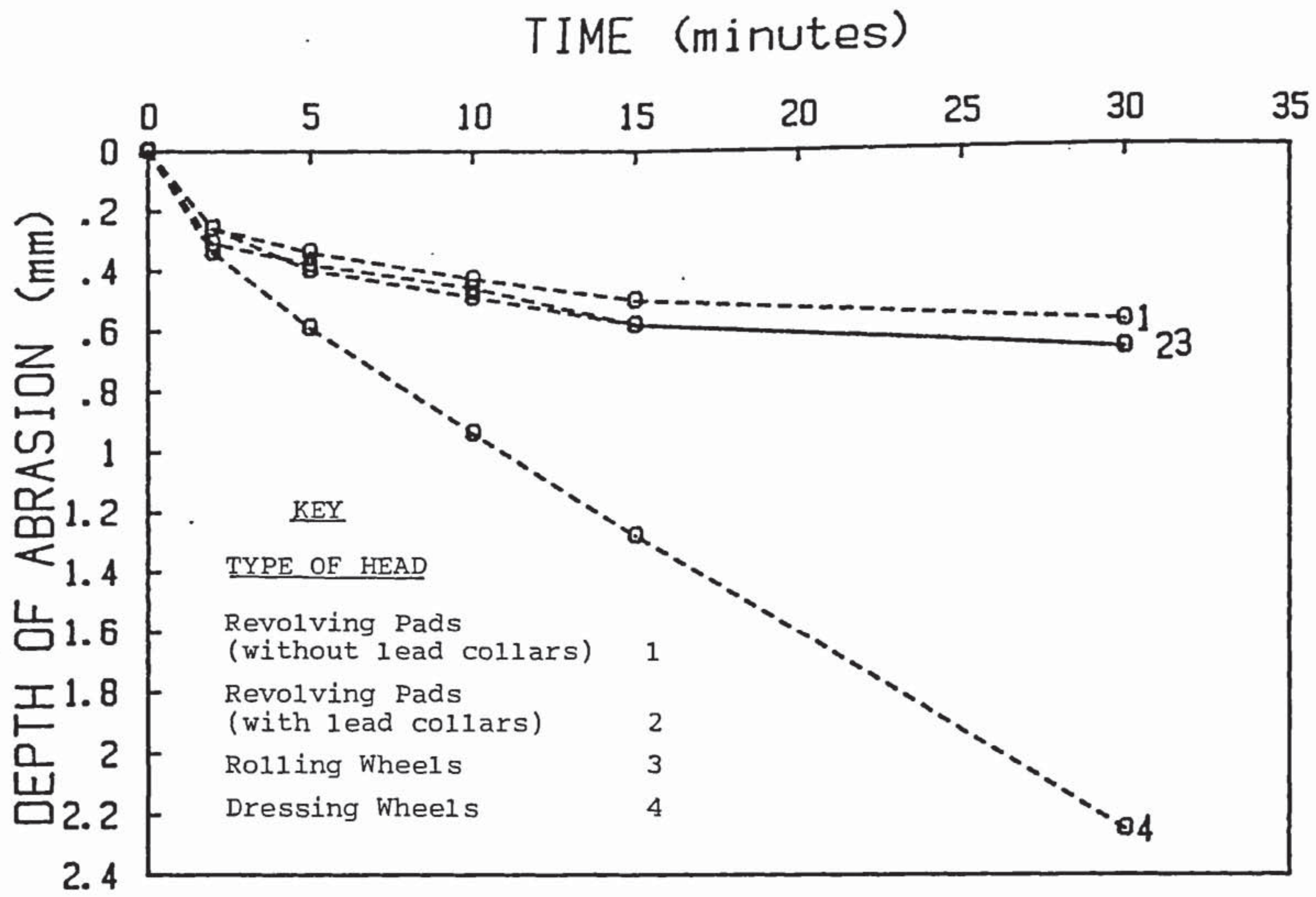



FIGURE 5.2 Rate of Abrasion for MIX B2

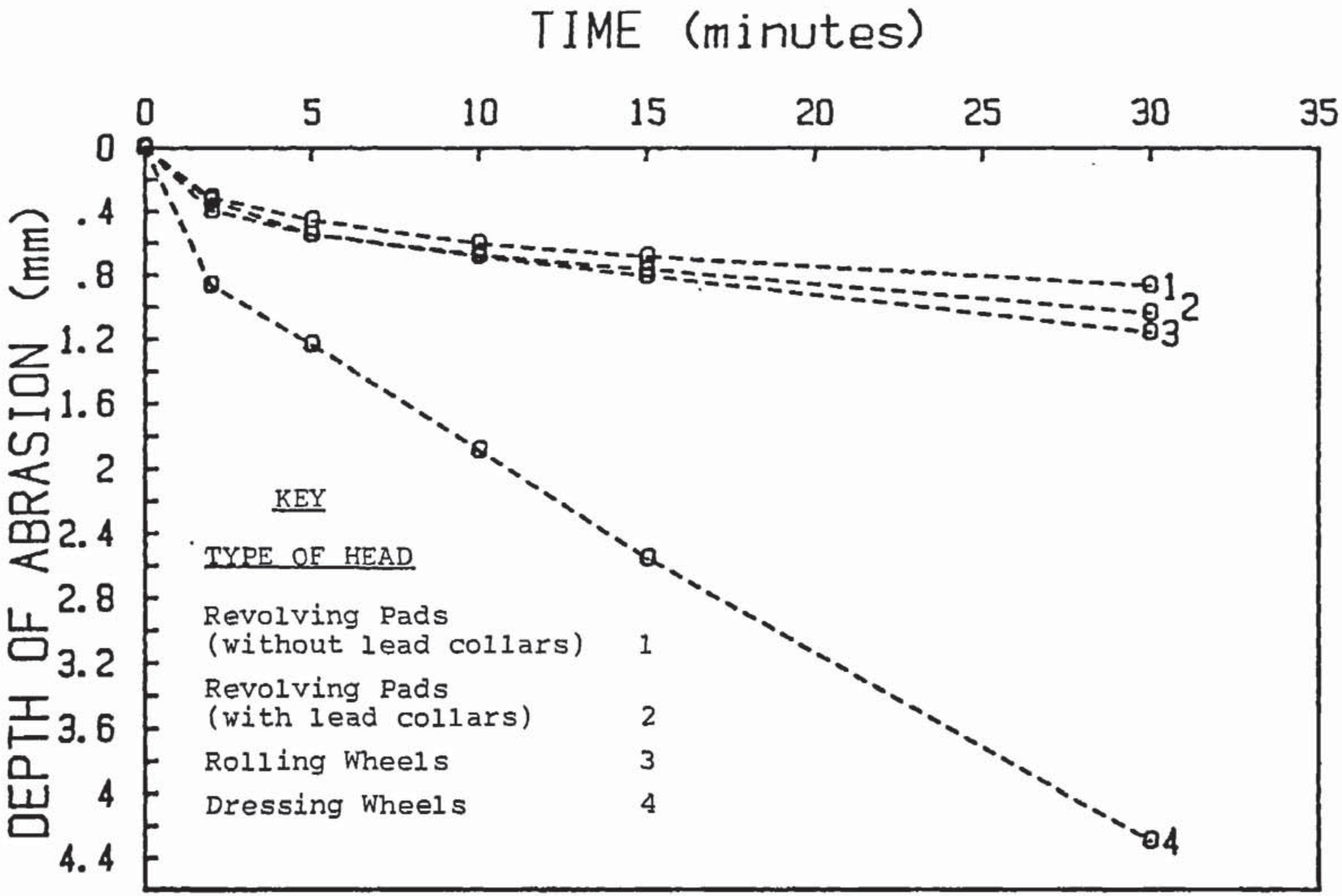



FIGURE 5.3 Rate of Abrasion for MIX B3

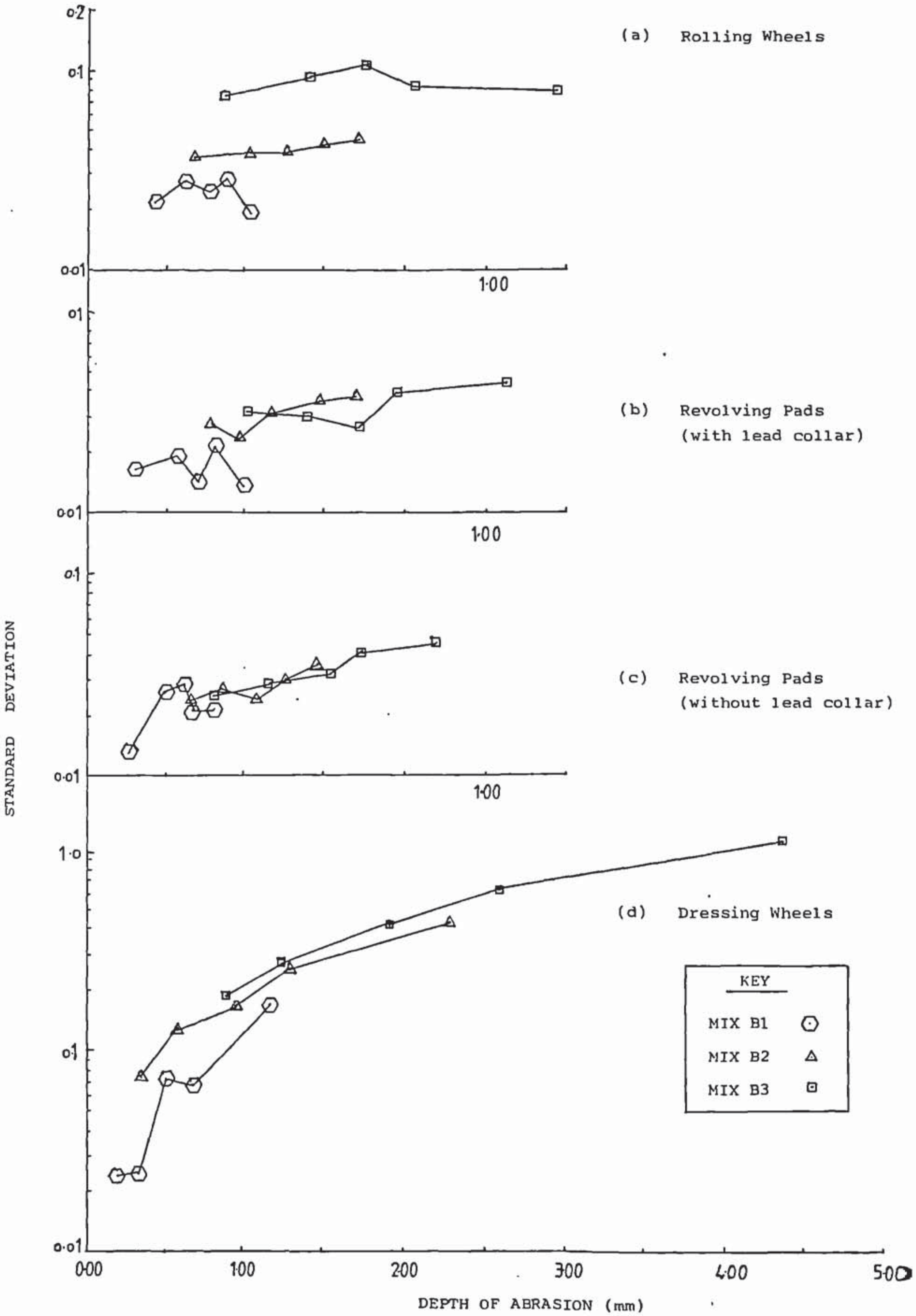



FIGURE 5.4 Standard Deviation V's Depth of Abrasion

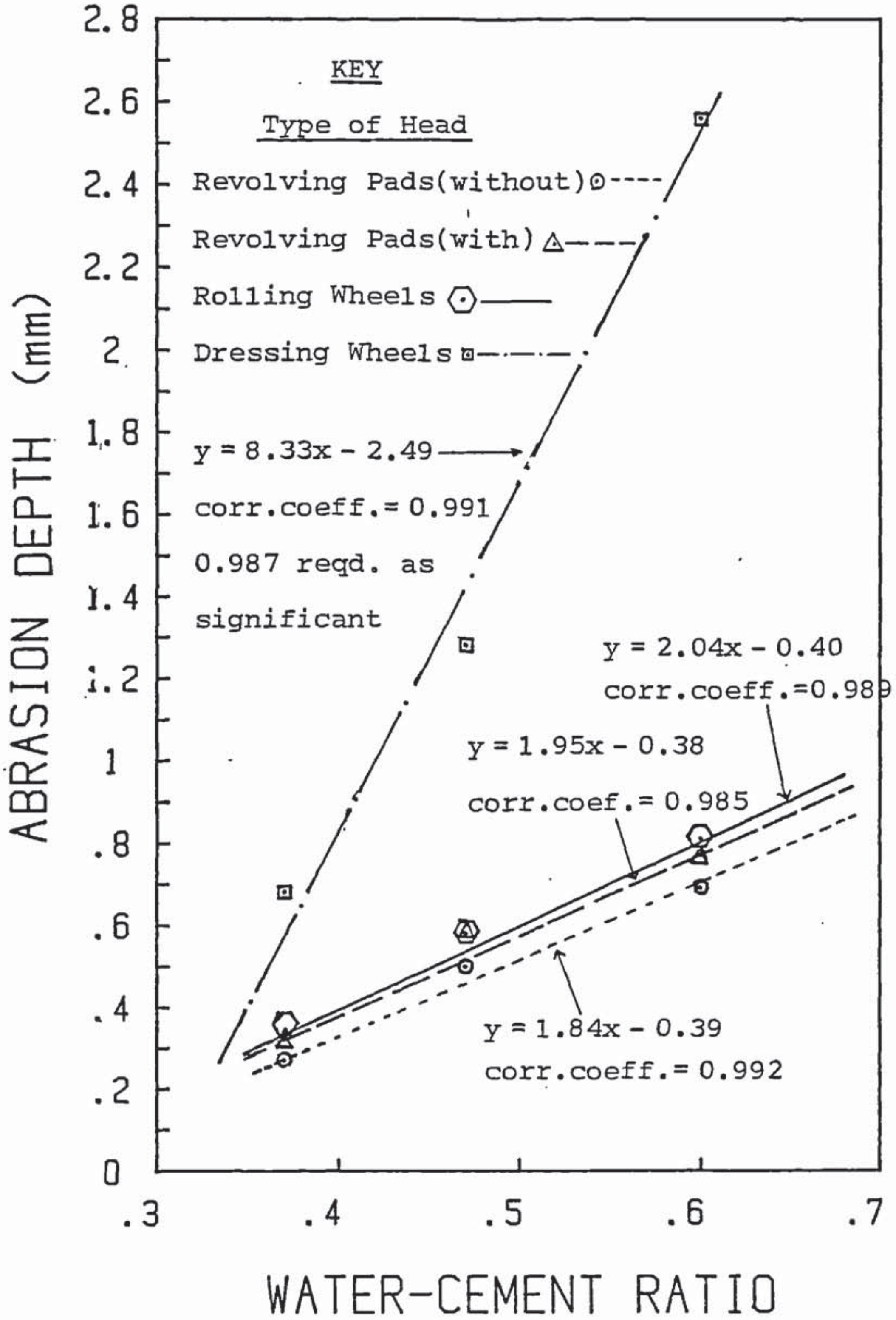



FIGURE 5.5 Abrasion Depth V's Water-Cement Ratio

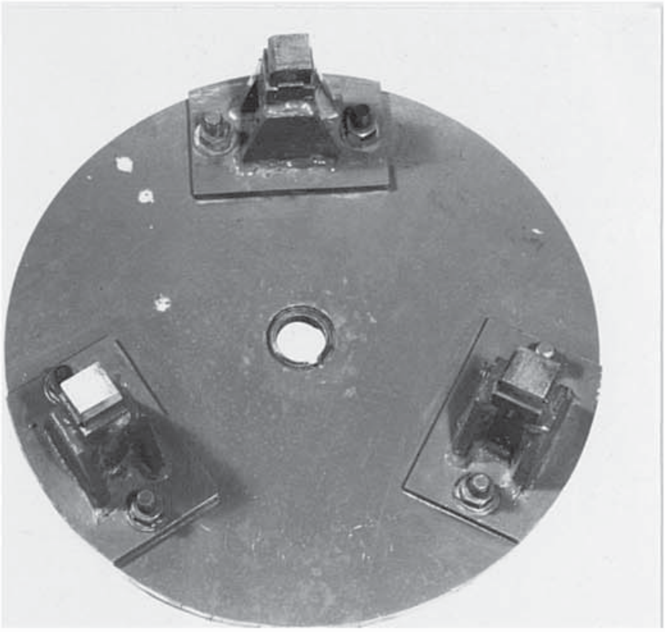


Plate 5.3 The Revolving Pads

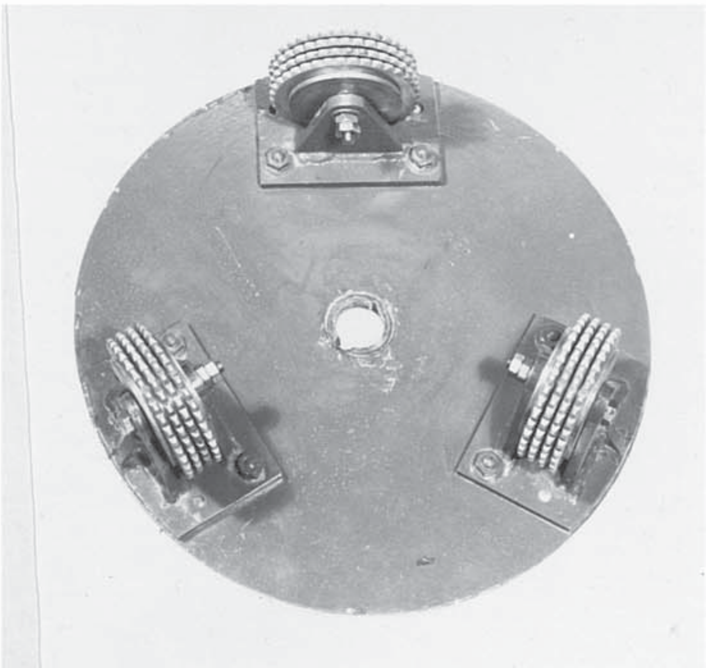


Plate 5.4 The Dressing Wheels

CHAPTER 6

# MACROSTUDY OF ABRASION RESISTANCE OF CONCRETE

## 6.1 Introduction

This chapter describes the laboratory programme designed to study the abrasion resistance of concrete slabs at macro level. The aim of this programme was to investigate the influence on the abrasion resistance of such variables as finishing technique, curing regime and surface treatment. An important feature of this study was the inclusion of those practices which are currently employed for concrete floor construction.

## 6.2 Assessment of current practices

In order to design a laboratory programme which reflects those practices currently being used in the industry regarding finishing techniques, curing regime and surface treatment, it was necessary to conduct an assessment of these current practices. This assessment was conducted in two phases.

### 6.2.1 Mail Survey

A list of 148 companies was compiled from the concrete year book for 1981 using the following , concrete repairs and practices, surface treatment, protective coatings and waterproofing, curing agents, floor covering and finishes. Two standard letters were sent:

(1) A general letter (see Appendix E, Letter A ) to 129 companies, enquiring about the services that they provided for improving the performance of concrete floor slabs, from the standpoint of abrasion resistance.

(2) A specific letter (see Appendix E, Letter B ) to 19 companies

nquiring about the curing agents which they could supply.

The response of this survey was as follows:-

i) 36 of the companies either did not reply, or the original letter was returned.

ii) 48 of the companies who replied provided services which were not considered to be relevant to the present work.

iii) 22 of the responses were from floor contractors.

iv) 42 of the replies were from companies providing curing agents and/or various types of concrete surface treatment.

The products which these companies provided may be summarised as follows:-

(a) Curing agent. Two basic types of liquid membrane-forming curing compounds were promoted- resin based and water based. The resin based compounds were generally supplied at two levels of efficiency, 75% and 90%. There were 14 companies supplying resin based compounds but only 4 companies could supply the water based compounds.

(b) Concrete surface treatment. The main difficulty with this assessment was that each type of product was being supplied by different manufacturers under their own brand name. Furthermore, in some cases, little information was provided regarding the individual ingredients of proprietry or branded treatments. However, it was possible to categorise the various products under the following general headings:-

(1) Surface Hardener. Almost all the companies supplied one or more of these products consisting, generally of aqueous solutions of either sodium silicate or magnesium silico-floride.

(2) In-Surface Seal. These were generally resin based systems which penetrated into the surface of concrete . Most companies supplied at least one product which could be classified as an in-surface seal.

However, there was a wide variety of system available.

(3) Paint. This type of treatment was promoted by most companies, mainly for decorative uses or chemical resistance. These products could be divided into three types of paint system-chlorinated rubber, polyurethane and epoxy resin.

(4) Dry Shake. This type of surface treatment was available in two forms - metallic and non-metallic. Most companies that supplied dry shake offered both types of products.

(5) Floor Topping. The following types of topping were identified- self levelling epoxy, epoxy trowelled, bitumen and polymer emulsion modified cementitious systems. In addition to providing abrasion resistance, the manufacturers claim that these various toppings provide resistance to chemical attack.

From this survey it became apparent that surface hardeners, in-surface seals ,and dry shakes were widely promoted as the means of upgrading the abrasion resistance of concrete slabs and floors. The paints and floor toppings were , however, primarily promoted for decorative purposes and increased chemical resistance.

### 6.2.2 Individual contacts

The second phase of this assessment was carried out by contacting six construction companies specialising in industrial floor construction.

These were :-

1. EVERARD INDUSTRIAL FLOORS (Mr. L. REED)
2. FLOORLIFE-ANDEK LIMILTED (Mr. J. WILSON)
3. I.D.C. (Mr. J. PATEMAN and Mr. B. RUSTON)
4. INDUSTRIAL GRANOLITHIC FLOORING (Mr. L. BEEKETT)
5. JOHNSON FLOOR COMPANY (Mr. F. O'DONAHUE)
6. LACON FLOORS (Mr. J. FITZGERALD)

Enquiries were made regarding the methods used by these contractors for the construction and subsequent curing of industrial floor slabs.

(a) Construction. For simplicity this may be subdivided into a number of stages, and the general procedures are briefly described as follows:-

(i) Placing and Spreading. After the concrete has been placed and spread, it is normally compacted using vibrating pokers.

(ii) Screeding. This involves striking off the surface of the concrete to a predetermined level. It is carried out either manually, using a hand-tamping beam operated by two men, or with machine based methods using vibrating screeds. The number of passes is dependent on the workability of concrete. However, a minimum of two passes was suggested.

(iii) Waiting time. When the above operations have been completed no other operation is performed until the concrete starts to set. This is usually determined by a simple procedure where a visual assessment is made of the foot impression under the weight of an average man. If the impression is less than about 2-4mm then the concrete is ready for the next operation. Some of this waiting time is eliminated when the vacuum dewatering process is used.

(iv) Floating. After the water sheen has disappeared and the concrete can support a man, the next operation is floating. This is carried out using a power float with the planning disc and is only carried out once.

(v) Trowelling. Once the power floating is completed, the concrete surface is power trowelled. The difference between power trowelling and power floating is that, in the former, a series of either three or four blades is used, whereas the latter employs a solid circular disc. The number of trowelling operations was found generally to be variable. Some industrial floors were subjected to only one trowelling operation to produce what was termed a commercial finish. Others were subjected to two or three separate trowelling operations, the final surface being described as high quality finish.

(b) Curing methods. The curing method used most frequently was found to be plastic sheeting, in which the concrete slabs were covered by plastic sheeting immediately after the last trowelling. The plastic sheeting was left on top of the slab for seven days. Liquid, membrane forming, curing compounds were found to be less frequently used than plastic sheeting, whereas, wet burlap was not used by any of the contractors.

## 6.3 Laboratory Programme

A laboratory progrmme was designed to permit the study of the effect of the finishing technique, curing regime and surface treatment on the abrasion resistance of concrete slabs. In order to simulate the site procedures, a mould size of 2.01x1.52x0.1m was selected. It could be internally subdivided, by crack inducers, to produce six test sections 1.0x0.5x0.1m. This mould enabled full use to be made of conventional powered plant. The layout is illustrated in Appendix D, Figure D.3 and can be seen in plate 6.1 .

### 6.3.1 Finishing Techniques

#### 6.3.1.1 Hand Finishing(H.F).

In this method the floating and trowelling operations are carried out using a wooden hand float, and a steel hand trowel respectively. This method of finishing was included in the programme for comparative purposes, since it has been used by most investigators for finishing the concrete surface (see section 2.5.3).

6.3.1.2 Power Finishing(P.F.).

Both the floating and trowelling operations are performed by powered equipment, similar to the practice used on site. These operations are carried out only once, i.e. a commercial finish.

6.3.1.3 Repeated Power Finishing(R.P.F.).

This employs the same powered equipment to that used above, but the trowelling operation is repeated on three separate occasions. This is to produce a high quality finish.

6.3.1.4 Vaccum Dewatering(V.D.).

In this method, the commercial vacuum dewatering process is used, which eliminates the delay before the floating operation can be performed. The floating and trowelling operations are performed similar to section 6.3.1.2 . Since the vacuum dewatering process reduces the water content of the resulting mix, it was decided to include in the test programme a series of concrete mixes whose water content was reduced to a quantity achieved by the vacuum dewatering process. These mixes were again finished by power finishing(P.F.) and are referred to as reduced water content specimens(R.W.C.).

A summary of this programme is provided in Table 6.1 .

6.3.2 Curing Regimes

The curing techniques described below have been included in the programme.

6.3.2.1 Air Curing(A.C.).

In this method the test slabs are left exposed in the laboratory until they are tested.

6.3.2.2 Wet Burlap(W.B.).

Test slabs are enclosed in wet burlop for seven days. This is the curing method which is usually used in the laboratory for large specimens.

6.3.2.3 Plastic Sheeting(P.S.).

Test slabs are wrapped in polythene sheets for seven days. This method was included because it is widely used on site.

6.3.2.4 Liquid Curing Compound.

These were classified as liquid, membrane-forming compounds and a range was selected, in order to reflect the products available on the market. It was decided to include, in the testing programme, the following curing compounds:-

(i) Resin based, 75% efficiency, curing compound(C.C.1).

(ii) Resin based, 90% efficiency, curing compound(C.C.2).

(iii) Water based curing compound(C.C.3).

These products were obtained from one manufacturer, so that their relative performance may be compared without introduction of variables due to differences in manufacture. They were supplied by Fosroc CBP, and their specification is provided in Appendix F, Instructions 1 and 2 .

6.3.3 Surface Treatments

The surface treatments included in the test programme are described in the following paragraphs.

6.3.3.1 Surface Hardener.

Two types of surface hardener have been included, these being representative of the products most widely used in the industry. These are a 20% solution of sodium silicate in water (A) and a 20% solution of magnesium flurosilicate in water(B).

6.3.3.2 In-Surface Seals.

Three types of in- surface seals have been included to again represent the products available in the market under this section. These are:-

(i) 10% solution of fully reacted methyl methacrylate/ethyl acrylate copolymer in aromatic solvents(C).

(ii) 20% solution of low molecular weight aliphatic isocyanate prepolymer based moisture curing polyurethane resin in aromatic solvents(D).

(iii) 30% solution of a bisphenol A/F resin and blended polyamine hardeners in aromatic solvents(E).

The basic chemicals for the above treatments were supplied by SBD Construction Products.

6.3.3.3 Dry Shake Surface Treatment

Two types of commercially available dry shake were included in the programme. These were:-

(i) Metallic Aggregate(D.S.1). This contained iron aggregate.

(ii) Natural Aggregate(D.S.2). This contained quartz aggregate.

These dry shakes were supplied by MASTER BUILDERS and a copy of their specification is enclosed in Appendix F, Instructions 3 and 4 . In addition to the above two types of commercially obtained dry shakes, the following laboratory-prepared dry shakes were also included in the programme:-

(i) Mixture of natural aggregate and portland cement(D.S.3).

(ii) Portland cement dry shake(D.S.4).

These were included so that influence of aggregate and cement could be assessed.

### 6.3.4 Concrete Mix Design

Three concrete mixes were included in the programme. They were selected to cover the expected range of free water-cement ratios, with mix B4(0.44), mix B5(0.52) and mix B6(0.65). Full details of these mixes is provided in Appedix B .

A summary of the experimental design is provided in Table 6.2 .

## 6.4 Specimen Fabrication

A standard procedure was adopted for the production of the concrete slabs, up to the stage where the finishing procedure commenced, at the completion of the waiting period. A summary of this procedure is as follows:-

(1) Reinforcing Bars. In order to prevent breakage and to assist the handling, it was necessary to place reinforcing bars in the slabs. The bars used for each small slab, were two 10mm diameter(Ø) length 950mm, and one 20mm Ø bar length 1050mm. The 20mm Ø bar was placed in the centre of each small slab with 100mm of the bar protruding from the mould as shown in Plate 6.1 . Each of the 10mm Ø bars was placed parallel but 125mm away from the 20mm Ø bar as shown in Figure D.3 of Appendix D . All three bars were placed at mid-depth, 50mm below the surface, in the test slab.

(2) Mixing of Concrete. All the concrete was mixed in a 500 kg capacity laboratory mixer. For each large slabs, two identical mixes were batched. Each mix was dry mixed for 30 seconds before the required water was added, and this was followed by wet mixing for a further two minutes before discharge into wheelbarrows. From each mix three 0.1x0.1x0.1m cubes were taken for the purpose of quality control.

(3) Placing and Spreading. The first mix was transported by

wheelbarrows to the mould, at which time a short-handled square-ended shovel was used to deposit and spread the concrete in the mould avoiding segregation, as shown in Plate 6.2 . The first mix was used to fill the bottom 50mm layer of the mould. The appropriate reinforcing bars were placed on the top of this layer and the second mix was used to fill the mould, adopting a similar procedure.

(4) Compaction. A 50mm diameter CLIPPER vibrating poker, model VP2, was used for compaction. The procedure adopted for compaction involved quickly inserting the tip of the vibrator into the concrete and slowly removing it so as not to leave a void. A constant pattern of 5 vibrator strokes was used for the bottom 50mm layer of each small slab, and 7 vibrator strokes for the top layer.

(5) Screeding. This was carried out using a hand-tamping beam operated by two men as shown in Plate 6.3 . The beam was dropped uniformly on to the concrete, each contact with the concrete to overlap with the previous one. This procedure was carried out twice over the slab. In the final run, or the third pass, the beam was passed over the slab with a sawing motion.

(6) Waiting Time. After the screeding operation was completed, the concrete slabs were not disturbed until the following conditions were met: (i) all the bleeding water and excess moisture had evaporated, (ii) the concrete had sufficiently stiffened for finishing. The methods used to assess if these conditions were satisfied, were (i) visual inspection (ii) foot impression. These methods were found to be subjective and susceptible to error. However, to minimise error, one person's assessment and weight were used throughout the investigation. This waiting time was dependent on the water-cement ratio of the mix and the temperature of the environment. These have been recorded and are provided in Table A.5 of Appendix A .

The above procedure was common to the production of all the concrete slabs except those subjected to the vacuum dewatering process( see section 6.4.4 ) . However,at the end of waiting time, different procedures were employed depending on the variable under investigation. It is, therefore, necessary to discuss these individually.

### 6.4.1 Hand Finished Slabs

This operation was performed by hand using a standard, wooden float for a period of 18 minutes. This operation brought some moisture to the surface, and so a period of time was required for this moisture to evaporate before the trowelling operation was commenced(see Table A.5 of Appendix A ). This was assessed using the procedure detailed above for deciding on the waiting time. The trowelling operations were carried out by hand using a standard, steel trowel for 30 minutes. This operation required considerable skill. This trowelling operation brought more moisture to the surface. However, in this method the floating and trowelling operations were carried out only once.

### 6.4.2 Power Finished Slabs

For this operation a CLIPPER power float/trowel model Gx140 was used. This equipment was driven by a 3.75kw motor. The float plate consisted of a 750mm diameter disc. The trowel head contained four steel blades, each of which were 325x200mm . The blades could be adjusted for choice of pitch.

The floating operation started once the concrete slabs were assessed to be ready. This operation was performed for a period of 8 minutes, with the disc being evenly passed over the concrete surface. This floating operation produced more moisture than the similar hand operation. After the required period of waiting time the trowelling operation commenced . This was performed for a period of 12 minutes, with the rotating blades being evenly passed over the concrete surface. Initially the blades of the trowelling head were used without any tilt while after the first 4 minutes the blades were half tilted, and after the second four minutes the blades were fully tilted. The power trowelling operation needed no skill, as opposed to the hand trowelling.

The floating and trowelling operations were performed only once. The use of power equipment is shown in plate 6.4 .

### 6.4.3 Repeated Power Finished Slabs

In the production of concrete slabs subjected to repeated power finishing, the basic techniques were similar to those described in the previous section. However, after the first trowelling operations, a period of time was allowed for moisture brought out by the trowelling to evaporate before the second series of trowelling started. The second series of trowelling was performed for a similar period as the first series of trowelling but the blades were fully tilted throughout the operation. This series of trowelling brought less moisture to the surface than the first series of trowelling. The waiting time for the next series of trowelling was also less than before.

The third series of trowelling commenced after excess moisture had evaporated. This series of trowelling was performed for 8 minutes. This operation brought some moisture on to the surface, but it was less than with either of the previous series of trowelling. No further trowelling was subsequently undertaken.

### 6.4.4 Vacuum Dewatered Slabs

A Tremix vacuum pump, type E1600(98), and suction mat were used for the vacuum dewatering process. The slabs to be used for the vacuum dewatering were produced according to section 6.4 but, immediately after the screeding operation, the suction mat was placed on the concrete surface. The suction mat consisted of a filter cloth attached to a special lattice with a top cover of plastic sheeting provided with a central suction hose to be connected to the vacuum pump unit. It was necessary to use a little vibration to ensure an intimate contact between the mat and surface of concrete. According to the manufacturers instruction(98) the suction time should be based on one minute per 10mm thickness of slab. Thus, a suction time of 10 minutes was used for each slab, with a vacuum reading of 500mm of mercury, $6.3kP/cm^2$. The water from the concrete surface was sucked into the water collecting tank of the vacuum pump. After the vacuum treatment, the amount of extracted water was measured by emptying the water tank of the pump and the results are given in Table 6.3 . A small quantity of cement was also present in the collected water, this was also measured and these results are also included in Table 6.3 .

When the vacuum mat was removed, the concrete surface was found to be marked similar to the shape of the mat, and it was dry and hard. Immediately after the termination of the vacuum process, the concrete surface was subjected to power floating. After power floating a lapse of time was necessary before power trowelling was commenced. These operations were carried out in a similar manner to that described in section 6.4.2 . The vacuum dewatering process was found to eliminate the waiting time required before the floating operations could commence.

### 6.4.5 Slabs With Reduced Water Content

The purpose of this part of the programme was to construct slabs with free water-cement ratios similar to the resultant water-cement ratio of the vacuum dewatered slabs. The final water-cement ratio of each of these slabs is shown in the Table 6.3 . From this Table, the reduced water content was calculated and is shown in Table 6.4 . The slabs with reduced water content were constructed according to section 6.4, and were finished according to section 6.4.2 . However, during the production of slabs with a free water-cement ratio of 0.4, it was necessary to use 16 vibrator strokes instead of 12, and screeding involved 4 passes instead of the normal 3 passes.

### 6.4.6 Curing of Specimen Slabs

Six different curing regimes were used for those specimens which were subjected to different finishing techniques(see Table 6.2). The large slab was designed so that each of the small slabs could be subjected to different methods of curing as demonstrated in plate 6.5. For each mix the treatment applied to each small slab was selected by a statistically, random method as summarised in Table A.6 in Appendix A . The 100mm cubes were cured under wet burlap for seven days.

The curing regimes were applied as follows:-

(1) Air Curing. After the slabs were demoulded and separated the next morning, they were subjected to air curing and were left exposed in the laboratory.

(2) Wet Burlap. The section which was to receive this method of curing was covered by polythene sheet over night. The following morning, after demoulding, the slab was covered by wet burlap, which was kept wet for seven days. After this period the slab was left exposed in the laboratory until the time it was tested.

(3) Plastic Sheeting. Immediately after the finishing operation the

selected section of the slab was covered by plastic sheet. The next morning , this section was wrapped in polythene sheets for seven days, then, it was unwrapped and left exposed in the laboratory until it was tested.

(4) Curing Compounds. The curing compounds were sprayed on the required section of the slab, immediately after the last finishing operation, according to manufacturers instructions, given in Appendix F Instructions 1 and 2 . A shield was used to prevent contamination of other sections of the slab. The next morning the slabs were demoulded and separated. At this stage, the bottom and sides of these slabs were covered by polythene as shown in plate 6.6 , so that moisture loss from these sections was minimised, thereby simulating site slabs.

### 6.4.7 Liquid Surface Treatment

The slabs which required liquid surface treatments were power finished according to section 6.4.2 . They received air curing for 25 days, mainly to assess the effects of the treatments on poorly cured concrete, after this time they were ready for the application of the various types of liquid surface treatments. These treatments were applied in 2 coats. The first coat was applied by soft brushing the materials into the surface of the slabs, taking care to ensure that no puddles were created. The second coat was applied 6 hours after the first coat in a similar manner. This two coat coverage was approximately 125 millilitre per specimen slab, e.g., 0.5 $m^2$ per 125 millilitre or 4.0 $m^2$ /litre .

### 6.4.8 Dry Shake Surface Treatments

#### 6.4.8.1 Commercially Available Dry Shake

6.4.8.1.1 Metallic Aggregate Dry Shake(D.S.1)

The concrete slabs which were to receive metallic aggregate dry shake were prepared according to section 6.4 . At the end of the waiting time, the procedure adopted was that recommended by the manufacturer, an extract of which is provided in the Appendix F instruction 5. It should be noted that these instructions are identical to the procedure employed for the repeated power finishing given in section 6.4.3 .

The coverage rate for this shake was that recommended for moderate to heavy duty industrial slabs, $7.5kg/m^2$. The manufacturer recommended the use of a curing compound immediately after the last finishing operation. The curing compound used was resin based, with a 90% efficiency, the same curing compound having been included in the main programme, as described in section 6.3.2 .

6.4.8.1.2 Natural Aggregate Dry Shake(D.S.2)

A similar procedure to that described in the previous section was used for slabs which were to receive the natural aggregate dry shake, except that the rate of coverage with the natural aggregate was recommended by the manufacturer to be $4.9kg/m^2$. The application of dry shake is shown in plate 6.7 .

6.4.8.2 Laboratory Prepared Dry Shake

6.4.8.2.1 Laboratory Prepared Natural Aggregate Dry Shake(D.S.3)

The commercially available natural aggregate dry shake was investigated by sieve analysis(see Table A.7 in Appendix A). From the results of this analysis it was determined that approximately 40% by weight of mixture contained cement binder and approximately 60% contained graded aggregate (the aggregates were light in colour and were retained on sieve size between 1.2mm and 150 $\mu m$, while the cement binder was dark in colour and was retained on sieve size 75μm and smaller). From the information provided by this sieve analysis, a blend of natural aggregate (from zone 2 sand) and cement was produced as the laboratory-prepared natural aggregate dry shake. The grading of the aggregate was similar to that of the commercially available dry shake, and 40% of the mixture contained cement .

The above mixture was applied to specimen slabs at a coverage rate of 4.9 $kg/m^2$. Similar procedures as in section 6.4.8.1, were used for the application , finishing and curing of these specimen slabs.

6.4.8.2.2 Cement Dry Shake (D.S.4)

In this part of the programme a cement dry shake was applied to the specimen slabs. The coverage rate used was 1.96 $kg/m^2$. This is the same quantity of cement used in the laboratory-prepared natural dry shake mixture, e.g. 40% by weight of the mixture. The procedure used for application, finishing and curing was similar to that described in section 6.4.8.1 .

## 6.5 Tests Performed

The specimen slabs were subjected to various types of tests, some are presented and discussed in this chapter, while others will be presented in later chapters.

### 6.5.1 Abrasion Resistance Tests

All the specimen slabs were tested for abrasion resistance at 28 days, using the accelerated abrasion test machine with its rolling wheels head. These tests followed the standard procedure developed in chapter 5 . Readings were recorded after 5,10,15 and 30 minutes of exposure to the abrasion machine. It was considered that, recording of the rate of abrasion would be more valuable in assessing the performance of the various finishing techniques, curing regimes, and surface treatments, than measuring only the depth of abrasion after the standard test period of 15 minutes. These results are presented in Figures 6.1 to 6.21 and cover, for mixes B4, B5 and B6, the effects of finishing techniques, curing regimes and surface treatments. Detailed results are given in Tables A8 to A.10 in Appendix A . A summary of the abrasion test results for the standard test and duration is provided in Tables 6.5 to 6.10 .

6.5.2 Strength Tests

6.5.2.1 Cube Tests

The three 100mm cubes, taken from each cast were cured for seven days under wet sacks (except for those taken from the cast used for liquid surface treatment which were air cured similar to the curing regime used for the slabs). Following further storage for 21 days, adjacent to the test slabs, they were tested at 28 days in a grade A testing machine(300 tons AVERY DENSION) in accordance with BS 1881: pt.4: 1970. For each concrete mix, i.e. mix B4, B5 and B6( excluding those used for the liquid surface treatment slabs and those for the reduced water content slab) 48 cubes were crushed( total of 144 cubes). A summary of the results of the cube crushing strength is provided in Table A.11 of Appendix A . Half of these cubes were taken from the concrete used for the bottom part of the specimen slabs, while the other half were taken from the second cast which was used for the top part of the specimen slabs. The results of cube crushing strength for the former were higher than the result of the latter(see Table A.11 in Appendix A ). This is mainly due to the fact that the mixer for the first mix was dry and therefore some of the mix water was used to wet the mixer, thus reducing the water-cement ratio.

However, for the second mix, the mixer was wet and no mix water was used for wetting the mixer. It would have been possible to wet the mixer, by initially mixing a small quantity of grout, but it was felt that this was not necessary since the first mix was not critical.

The values of cube crushing strengths for the three concrete mixes, for both the first and second cast, provided a good representation of normal distribution in each case, similar to that reported by Neville(99). The maximum coefficient of variation was found to be 4.9%. This low value of coefficient of variation indicates that good quality control had been exercised over production of the concrete.

A graph of cube crushing strength against depth of abrasion, as determined for the hand finished slabs, has been provided in Figure 6.22. This graph also includes additional results from the comparative study carried out in chapter 5 .

6.5.2.2 Core Tests

Two 100mm diameter cores were cut from each of the following slabs: power finished, vacuum dewatered and reduced water content slabs, all of which had been cured under wet burlap. These cores were cut using an ATLAS COPCO diamond core cutter. They were tested at 36 days in a grade A testing machine in accordance with B.S 1881: part 120 : 1983 . The estimated in-situ cube strengths are provided in Table A.12 of Appendix A .

## 6.6 Discussion Of Experimental Results

### 6.6.1 Finishing Techniques

In order to evaluate the relative performance of the various finishing techniques and the significance of power trowelling, it was necessary to establish a standard against which the results may be compared. It was decided to use the power trowelling procedure(P.F.) as this standard, since it was similar to the practice followed on the majority of construction sites, and the effects of the other finishing techniques were compared to this standard.

The test results are presented in Table 6.5 and Figures 6.1 to 6.15 . Table 6.5 gives a summary of the abrasion depth results and includes the mean depth of abrasion, the percentage higher or lower than the standard(higher indicates a reduction on abrasion resistance, lower indicates an increase in abrasion resistance) and an indication of whether or not differences are statistically significant. These are based on Student "t" tests, the detailed results being provided in Tables C.9 to C.11 of Appendix C.1 . Figures 6.1 to 6.15 show the rate of abrasion during the tests, the individual values are tabulated in Table A.8 of Appendix A .

For the purpose of assessing the influence of the various types of finishing techniques on the abrasion resistance of concrete, it is important to underestand the influence of the placing, compacting and screeding operations, and the role of the finishing procedure.

During the compaction operation the concrete segregates as a result of vibration. This causes the uppermost part to contain more fines so that the cement content of the surface of concrete is larger than that in the bottom layer(76) and, due to the migration of water, to have a higher water-cement ratio than the interior. The lower section of the concrete on the other hand, contains more coarse aggregate and has a lower water-cement ratio. Furthermore, compaction results in a material decrease in air content and also a decrease in the average size of the air voids(100). However, it has been found (101) that vibration tends to produce a higher air content in the upper portions of the concrete relative to that in the lower layer.

During the waiting time the bleeding process continues (bleeding is a form of segregation), leading to a further increase in the water content of the surface layer, some of the rising water becomes trapped and forms water voids beneath coarse aggregate particles and perhaps even beneath sand particles and immediately under neath the surface. This rising water leaves behind capillaries, and since all the voids are oriented in the same direction, the permeability of the concrete in a horizontal plane may be increased(99). This is verified by the results of the Initial Surface Abrasion Test, given in Table 8.4 in chapter 8. The rising water carries some finer cement particles which result in a layer of laitance. Bleeding continues until the cement paste has stiffened sufficiently to end the process of settlement(99). During the waiting period, the bleed water present on the surface is allowed to evaporate.

The duration of waiting time was found to be variable depending mainly on the water- cement ratio of the mix and secondly on the laboratory temperature. The laboratory temperature together with the duration of waiting-time has been recorded and is presented in Table A.5 of Appendix A . Those mixes with higher water-cement ratio(e.g. mix B6) required longer waiting time than mixes such as B4 with low water-cement ratio. This is clearly due to excess bleed water produced by the wetter mixes.

The method used for assessing the time when the floating operation should commence was found to produce a wide variation in the results, particulary with the assessment of the desired state of hydration of the concrete. It was found that, generally both the requirment for the evaporation of bleed water, and the desired state of hydration coincided. The effectiveness of the various techniques for increasing the abrasion resistance are discussed in the following sections.

6.6.1.1 Hand Finishing Compared To Power Finishing

The abrasion resistance of specimens subjected to the hand finishing (H.F.) technique was generally significantly lower than those subjected to the power finishing (P.F.) technique. The reduction in abrasion resistance for the three water-cement ratios and the six curing regimes were of different magnitude and are given in Table 6.5. The appropriate rate of wear can be seen from the plots given in Figures 6.1, 6.2, 6.6, 6.7, 6.11 and 6.12. Refering to the significance test in Table 6.5 only 3 of the 18 test do not show that hand finishing (H.F.) is inferior to the control power finishing (P.F.). These results have been summarised in Table 6.6 and seem to indicate that the benefits from P.F. are more marked with the denser mixes (B4, B5) than with the relatively wet mix (B6) where H.F. seems to achieve a reasonable performance. Two of the B6 comparisons did not show any significant improvement from power finishing, whereas all six comparisons with mix B4 are shown to be highly significant.

These results clearly demonstrate that the hand finishing technique was unable to perform the finishing task efficiently, thus reducing the abrasion resistance of the specimen slabs. The reasons for reduction in abrasion resistance due to the hand finishing technique, become apparent when the procedure is compared to that of mechanical surface finishing. The main difference between hand finishing and power finishing is that, the latter is capable of applying vibration and more pressure to the surface of the concrete than the former. Furthermore, mechanical surface finishing equipment is capable of producing a smooth surface particularly when the concrete is rather stiff i.e. at the desired state of hydration.

The vibration produced by the power equipment is at a maximum nearest to the surface of the concrete. This vibration is effectively revibration or delayed vibration, since it is applied several hours after the screeding operations. The effect of revibration and delayed vibration on concrete has been studied by a number of investigators(102-109). It is generally agreed that revibration, some 2 to 6 hours after mixing, increases the compressive strength of concrete, compared to the strength of non-revibrated concrete. This is true even for concrete that was initially compacted to an optimum density. This phenomenon may be explained (103,107,108) by the following:-

(i) the closing of microcracks between the paste and aggregates that have been formed due to the restraint offered to the early shrinkage of the cement paste.

(ii) the reduction of pore volume in the revibrated concrete, due to the reduction or elimination of water pockets which may be present under aggregates.

(iii) the structure of cement paste and the hydration process may be influenced by revibration. Indeed, it has been reported(106) that the revibration of neat cement paste may result in strength increase. Strength increases of paste up to 130 percent were reported by Avram et al(108). These high strength increases have been associated with a significant reduction of the water-cement ratio during revibration.

Laboratory investigations have shown that revibration becomes more effective if it is conducted immediately before or shortly after initial set(104,108) and, secondly, it is more effective if the specimen is revibrated while being subjected to a small compressive stress(109). From this body of research it may be postulated that the delayed vibratory disturbance of the power equipment provide additional consolidation through the disruption of the initial gel structure. This vibratory disturbance also allows further compaction by eliminating the voids which result from internal bleeding as the concrete hardens. The extent to which the void content is reduced depends on the length of the delay before vibratory disturbance is applied and on the amount of vibration.

The action of power trowelling (due to application of high uniform pressure) tends to bring particles which are present in the surface matrix into more intimate contact, thus closing up surface pores and microcracks. This is evident by the smooth and "close" texture of the surface finish. Power trowelling may also increase the specific surface of the cement by separating cement particles which are lumped together and by grinding. It has been suggested(82) that an increase in the specific surface of cement results in reduction in the equivalent capillary radius of the hardened cement paste, which reduces moisture gradient, leading to increases in density, strength and abrasion resistance.

Having described the mechanisms by which power equipment is considered to increase the abrasion resistance of concrete slabs, it is appropriate to present an assessment of these mechanisms. This assessment has been carried out by comparing both the observations made during the construction of the specimen slabs using hand and power finishing techniques, and the results of the appropriate abrasion tests.

The following observations were made during the construction of specimen slabs using hand and power finishing techniques:-

(1) After the initial waiting time it was difficult to hand float the specimens with low water-cement ratio (e.g. mix B4).

(2) Little moisture was brought to the surface by the hand floating

process, especially in the case of mix B4 .

(3) The waiting time required after the hand floating operation for the moisture brought to the surface to evaporate and the cement paste to stiffen, was much shorter than with the power finished slabs as can be seen from the data in Table A.5 of Appendix A .

(4) When the hand trowelling operation commenced, it was found extremely difficult to carry out this operation in the case of mix B4 because of the stiffness of the concrete. The resulting surface texture was found to be rather "open" when compared with that of the power finished slabs.

(5) When the power floating disc was used, it was found that this operation brought much moisture to the surface, even for the mixes with low water-cement ratio. This confirms the proposition that entrapped water was released by the vibration.

(6) The waiting time before the trowelling operation could commence was much longer in the case of power floating than that of hand floating. This further indicates that more moisture had been released by the power floating than by hand floating.

(7) Power trowelling operations commenced when the concrete surface began to lose its plasticity i.e. became stiff, similar to the condition of the hand floated specimens. The power trowelling made the surface plastic again, unlike that of the hand trowellled. This indicates further that more moisture has been released.

(8) The pressure exerted on the concrete due to the power trowelling blades, especially when the blades were fully tilted, was much more than that which could be caused by hand trowelling. Furthermore, the power trowelling blades exerted pressure on the concrete surface much more uniformly than that of hand trowelling.

(9) After the trowelling operation, in the case of power trowelling a

thin moisture film was noted on the slab, but in the case of hand trowelling this was not apparent. It is suggested that this thin layer of moisture did not have a detrimental effect on the performance of the slab, since it contained very few fine particles and evaporated, thus further evidence of the reduction in the moisture content of the surface matrix.

(10) In the hand finished method the surface texture of specimens having high water-cement ratio (e.g. mixB6) were generally of better quality, so far as smoothness and closeness of surface texture was concerned, than those with the lower water-cement ratio. This indicated that hand finishing was more effectively applied to the mixes with higher water-cement ratio.

(11) The surface texture of the power trowelled specimens generally appeared to be closed and smoother than that of the hand finished specimens. This is an indication that power trowelling brought the particles present in the surface matrix into more intimate contact.

(12) The specimens which were finished by power equipment were generally of darker colour than those finished by hand. This comparison was made on those specimens which were cured using polythene sheeting. This is a further indication that the surface matrix of the power trowelled specimens, were of lower water-cement ratio than that of the hand finished specimens.

If the experimental results are analysed by considering the total average increase of abrasion resistance (average of abrasion depth for the six curing regimes) due to power finishing for each of the three water- cement ratios, it appears, that the increase in abrasion resistance, with respect to hand finishing, was most pronounced at the lower water-cement ratios with mix B4. According to this hypothesis, which attributes the improved performance to delayed revibration, it was initially considered that mix B6, with the highest water-cement ratio, would show more benefit from power finishing than mix B4 with the lowest water-cement ratio. These wetter mixes have more bleed water and a correspondingly larger pore volume which can be reduced by the vibratory disturbance provided by the power equipment.

Whilst the influences of the individual curing regimes can be seen, the results in Tables 6.5 and 6.6 clearly show, however, that power finishing achieved much greater benefits, over hand finishing, with the specimens from mix B4 than with those from mix B6. With the mix B4 specimens, power finishing produced an average reduction of around 50% in the depth of abrasion whereas , with those from mix B6, this reduction was only some 20% . With the wetter mixes, the workability was such that both power finishing and hand finishing could achieve improvements in the quality of the surface. However, with the drier mixes of lower workability, the low energy supplied by hand finishing could not produce the improvements achieved with much larger energy input provided by power finishing. This is confirmed by the result in Tables 6.5 and 6.6 . This means that, so far as delayed revibration is concerned, the vibratory disturbance of the power equipment was able to reduce the volume of voids present in both high and low water-cement ratio mixes, but the hand finished procedure was only able to reduce the volume of voids present in the high water-cement ratio mix, and even this to only a limited extent.

The experimental results also indicate that the influence on abrasion resistance of the various curing regimes, and of the individual curing compounds were very susceptible to surface texture as is discussed in section 6.6.2 . The results in Table 6.5 indicate that the level of abrasion resistance achieved by each finishing technique was influenced by both the mix design and the curing regimes. It was, therefore, decided to perform a two-way analysis of variance (110), to determine whether the differences in abrasion resistance due to finishing technique were significant, and whether these differences could be attributed to interaction with the two other variables of curing regime and mix design. The analysis is provided in the Appendix C.3, and it shows that the influence of the interaction of these other variables is statistically significant, but that the influence of the main factor, in this case finishing technique, is much more significant. The significance due to the influence of finishing technique, curing regime and mix design were significant at the 0.01% level, whereas the interaction between the three variables were only significant at the 5% level.

Further support for the mechanisms proposed for increasing the abrasion of those specimens finished using mechanical equipment can be obtained from consideration of Figures 6.1, 6.2 ,6.6, 6.7, 6.11, 6.12, which illustrate the rate of wear in the *abrasion tests*. This is evident from the initial slope of these curves, particularly during the initial 5 minutes when the surface matrix is being abraded. With the hand finished specimens, this initial slope is generally steeper than that obtained from specimens produced by power finishing. A steep slope indicates rapid wear, which is indicative of a weak surface matrix, and so these curves clearly indicate how the power finishing technique influences the surface matrix to a major extent. This is even more clearly illustrated by the graphs for the repeated power finishing method (R.P.F.), shown in Figures 6.3 , 6.8 and 6.13 which will be discussed in the next section.

The literature review indicated that there were few research programmes designed to assess the influence of the various finishing techniques on abrasion resistance. The existing data has mainly arisen as supplementors to other investigations, for example, in a programme which investigated the effects of metallic aggregates on concrete floors(48 ) it was found that finishing the concrete with power equipment as compared to hand finishing increased the abrasion resistance by over 60%. This data is not directly comparable with the results of the present study, since it includes the influence of dry shakes. However, this data does confirm that power equipment was able to bring the constituents of the mix in to a more intimate contact than had been achieved with hand finishing, and so confirms the trends of the present study.

The experimental results show that the abrasion resistance of concrete slabs was significantly increased by power finishing. This increase was accounted for by proposing various mechanisms associated with the microstructure of the surface matrix of the concrete, as this is largely responsible for abrasion resistance.

6.6.1.2 Repeated Power Finishing Compared To Power Finishing

As compared with the performance of specimens produced by power finishing, those subjected to repeated power finishing displayed a significant increase in abrasion resistance for all water-cement ratios and all curing regimes. This is evident from the results in Table 6.5 and the graphs in Figures 6.3 , 6.8 and 6.13. During the investigation, the following observations were made on the construction of specimens subjected to repeated power finishing:-

(1) The successive waiting times, before the subsequent trowelling operation commenced, became shorter and shorter, see TableA.5 of Appendix A . This is an indication that the trowelling operations were becoming less and less effective in releasing water.

(2) Each trowelling operation appeared to close the surface structure of the cement-water paste but, after each operation, the surface tended to "open-up" a little, due to release of moisture. This process

was noted to become lessened after each successive trowelling operation.

(3) The surface of each specimen become darker after each successive trowelling operation. The finished surface of each of these specimens was smooth, tight, shiny and almost black. This was very different to the finish achieved on specimens subjected to only a single trowel finish, as can be seen from plate 6.8 .

(4) The specimens with the lower water-cement ratios appeared as dark in colour as those with the high water-cement ratio. Furthermore, the surface texture of all these specimens appeared identical in terms of smoothness, tightness and shine. The dark appearance of the finished slab is mainly due to the reduction of the water-cement ratio of the surface paste, and the grinding effect of power trowelling which changes the usual grey colour of cement particles.

The result of these tests are given in Table 6.5 and it is clear that repeated power finishing brought a significant improvement in abrasion resistance, as expressed in terms of the lower levels of wear. The average decrease in depth of wear, for the three water-cement ratios, ranged between 72%-74%, whereas the average increase in depth of wear, due to the hand finishing technique, ranged between 30%-90% for the three water-cement ratios. This is a further indication that with power equipment, the workability of the three mixes becomes less critical.

The results indicate that, generally, the abrasion resistance of the specimen was enhanced by the use of curing compounds. This effect was most pronounced with the lowest water-cement ratio mix and will be discussed in section 6.6.2 .

In the following analysis, the results obtained with the curing compounds have not been included because:-

(1) The time of application of such compounds has been found by several investigators( 34, 111 ) to influence the efficiency of curing and , with repeated power finishing, the time of application was delayed as compared with the other finishing techniques.

(2) The response of the various curing compounds, was influenced by the individual finishing technique, as can be seen from the data in Table 6.5 .

It appears that the increase in abrasion resistance of the highest water-cement ratio mix was greater than that of lowest water-cement ratio mix. The increase in abrasion resistance of mix B6 was such that it is almost as resistant as that of mix B5, with the intermediate water-cement ratio. This is indicative that the surface matrix is more critical than the concrete mix itself.

The abrasion resistance of the high water-cement ratio mix B6 has been increased by repeated power trowelling so that it is generally, higher than that of the specimens from mix B4, with the lowest water-cement ratio, which were finished by the single power trowel technique. This demonstrates the major influence of repeated power trowelling even on comparatively inferior concrete, for it is interesting to note from the result in Table A.11 of Appendix A, that mix B4 had a significantly higher cube strength than that of mix B6 .

The rates of abrasion, shown in Figures 6.3 , 6.8 , and 6.13 , clearly demonstrate that the surface matrices, produced by repeated power trowelling, were very resistant to the abrasive action of the accelerated abrasion test machine. When these are compared to the equivalent rates of wear of single power trowelling and hand finishing the influence of the surface matrix becomes even clearer. The appropriate rates of wear for the power finished specimens, given in Figures 6.2, 6.7 and 6.12 , and for the hand finished specimens, given in Figures 6.1, 6.6and 6.11 , are much steeper than those for the repeated power finished specimens given in Figures 6.3, 6.8 and 6.13.

The main mechanisms by which the mechanical surface finishing techniques increase abrasion resistance of concrete were discussed earlier in section 6.6.1.1 . The results obtained from the specimens produced by repeated power trowelling further confirm the existence of these mechanisms. The powerful influence of the structure of the surface matrix is, thus, confirmed with these reported significant increases in the abrasion resistance.

In the literature review it was found that both delayed (41,43,50) and repeated (61,73) trowelling increase the abrasion resistance of concrete slabs. The results of these investigations are not directly comparable with the present results, because the magnitude of the increase is very much dependent on : (i) type of trowel used, hand or power, (ii) number of trowelling operations, (iii) the delay between each trowel , (iv) the amount of time trowelling was carried out, (v) type of mix, (vi) type of curing regimes. However, they provide a general trend which the results of the present study confirm.

The mechanism of power trowelling and repeated power trowelling may be broadly stated as compaction and reduction of water-cement ratio of the surface matrix of the concrete. Both the water-cement ratio and the degree of compaction effect the volume of voids in concrete(99). The strength of concrete is influenced by the volume of all the voids, be they due to entrapped air, capillary pores, or gel pores(112). Furthermore, since abrasion resistance is generally influenced by the strength of concrete (29-30,35-38,43) , it is reasonable to suggest that such densification of the surface matrix will improve the abrasion resistance. It is clear that a major factor in this behaviour is the quality and structure of the surface layer. In order to assess the factor influencing the abrasion resistance it is clearly important to assess the microstructure of the concrete, and this aspect will be considered in detail in chapter 7 .

6.6.1.3 Vacuum Dewatering Process

6.6.1.3.1 Vacuum Dewatered slabs Compared To Power Finished Slabs

The experimental test results, as summarised in Table 6.5 and plotted in Figures 6.4, 6.9 and 6.14, indicate that the abrasion resistance was significantly higher for all the vacuum treated concrete(V.D.) as compared with the control specimen produced by power finishing. The average increases in abrasion resistance were 55% ,50% and 33% for concrete mixes B6, B5 and B4, respectively. During the investigation the following observations were made concerning the vacuum dewatering process:-

(1) The water extracted from the concrete mixes was proportional to the original water content of the mix, as is clear from the data in Table 6.3 .

(2) After the removal of the vacuum mat, the resulting surface was very stiff with all the three concrete mixes. It would not have been possible to float the surface by hand.

(3) The waiting time required before commencing the trowelling operation was shorter than with the P.F. specimens, and the differences between the three concrete mixes were reduced. This is apparent from Table A.5 of Appendix A.

(4) The extracted water carried a small quantity of cement fines, the values being given in Table 6.3 . This is an indication of the migration of cement fines to the surface of concrete during the vacuum process. It is interesting to note that the quantity of extracted cement fines was greatest in the wetter mixes, B6, and not in those

mixes with the higher cement content, mix B4 .

From these observations it appears that vacuum processing caused a considerable reduction in the water content of the concrete. The reduction was greater at the surface and least at the bottom, because the efficiency of the vacuum process was highest close to the surface and gradually diminished towards the base. This, together with the fact that there was also some migration of the cement fines towards the processing surface, leads to a considerable decrease in the surface water-cement ratio. The resulting lower water content, and higher cement content, together with the action of mechanical surface finishing equipment accounts for the increase in abrasion resistance of the vacuum processed concrete slabs.

In terms of the reduction in the depth of wear, the mix that exhibited the largest improvement in abrasion resistance was the mix with highest initial water content. This was mainly due to the fact that more water was extracted from it than from the other mixes, resulting also in a greater redistribution of the cement toward the surface of this mix, and lead to larger relative decrease in water-cement ratio of this mix. Thus, the final surface layer achieved with all three mixes became very similar. This is reflected in the similarity between the results obtained with the three mixes, for each curing regime.

Abrasion shown in Figures 6.4, 6.9 and 6.14, confirms that the surface matrix of the vacuum dewatered specimens were much more resistant to the abrasion forces than was that of power finished slabs.

The results of the present study confirm the findings of previous investigators ( 56,73-79) that the abrasion resistance is increased by the vacuum dewatering process. However, as suggested in the literature review, the absolute increases in abrasion resistance, due to this process, differ drastically from investigator to investigator. This may be attributed to variations in water-cement ratio of the particular concrete mixes and also, to the various finishing technique that were employed. For example, in one investigation (77) the vacuum dewatered specimens were finished by power equipment whereas the unprocessed, comparative specimens were finished only by hand, and not suprisingly, it was claimed that a 95% reduction in the depth of abrasion was achieved by vacuum dewatering. In view of these poorly designed experiments, it has been decided that the results in this study will not be compared with those from other investigators involving vacuum dewatering .

The test results giving the crushing strengths of the cores taken from both vacuum dewatered slabs and non-vacuum dewatered slabs(e.g. P.F. slabs) are shown in Table A.12 of Appendix A . The crushing strength of the former were greater than those of the latter, the average increase being around 10% . When the cores were being crushed, very few voids were detected in the unprocessed cores, but some were apparent on the cores removed from the processed slabs. More of these voids were detected on the cores from the wetter mixes, mix B6.

It has been reported(113) that the compressive strength of vacuum dewatered specimens was less than that of unprocessed concrete with the same initial water-cement ratio. In this work(113), the unprocessed samples had been fully compacted by vibration, whereas the vacuum dewatered concrete was only vibrated when it was placed in the mould, with no further vibration during or after processing. It is suggested that the lower strength of the processed specimens can be attributed to the presence of voids, which were noted above in the cores, resulting from the inability of the concrete to adjust itself completely to the reduction in volume due to the extraction of water. This has been confirmed by Malinowski and Wenander(82) and others(114) who report that the volume of extracted water by vacuum dewatering was generally larger than the reduction in volume of treated concrete. As this volume differential results in an increase in the air pore volume, there is therefore, increased porosity. Thus, the crushing strength of the processed cores should be less than that of the unprocessed cores. However, when processed samples are vibrated, either during or after vacuum dewatering, the compressive strength has been found (115) to be more than that of an unprocessed concrete with the same initial water-cement ratio. These findings indicate that the increases recorded in crushing strength of the processed cores has been brought about by vibration. The only vibratory disturbance which was applied to the slab after the dewatering operation, was the application of power equipment for the purpose of finishing the surface. The vibratory disturbance must be of such magnitude that not only has it been capable of eliminating the pores immediately beneath the surface, but also it has been able to reduce the air voids created by the action of vacuum processing. This clearly demonstrates the large amount of work that is done to the concrete by power trowelling.

Researchers investigating(56,73-79) the performance of vacuum dewatered slab, generally conclude that the compressive strength of the processed slab is greater than that of unprocessed slab with the same initial water-cement ratio.

The preceding discussion provides further confirmation of the mechanisms involved in increasing abrasion resistance of concrete due to the application of mechanical surface finishing equipment.

6.6.1.3.2 Vacuum Dewatered Slabs Compared To Reduced Water Content Slabs

In all cases, the vacuum dewatered slabs recorded higher abrasion resistances than the equivalent reduced water content slabs(R.W.C.), as can be seen from the results in Table 6.7 . In the majority of cases the "t" tests, summarised in Table 6.7, indicate that the decreases in abrasion depth, due to the use of vacuum dewatering process, were statistically significant. From these results it is suggested that generally the abrasion resistance of a vacuum treated concrete slab will be significantly higher than that of a non-processed mix with the same final water-cement ratio as the vacuum processed specimens. This increase in abrasion resistance was most pronounced with the wetter mixes, such as B6. A similar trend was found when the performance of the vacuum treated slabs was compared to that of the specimens with the same initial water-cement ratio as that of vacuum processed samples.

The results of the core crushing test are provided in Table A.12 in Appendix A. These results indicate that the crushing strengths of cores, taken from the unprocessed slabs with the same water-cement ratio as the final water-cement ratio of vacuum treated slab, were substantially greater, the only exception being the lowest water-cement ratio mix B4. It is possible that this unprocessed slab was not fully compacted due to the low workability of the mix, even though the vibration period was increased.

When the performance of vacuum treated slabs was compared to that of unprocessed slabs of the same initial water-cement ratio as the processed specimens, the increase in abrasion resistance was attributed mainly to the reduction of water content. The results obtained for this section, however, demonstrate that the reduction in water content of the unprocessed slabs does not increase the abrasion resistance of concrete to the same level as the vacuum processed slabs. This may be explained by the following:-

(1) The reduction in water content of the vacuum treated slabs was not evenly distributed, more water being extracted adjacent to the processing surface(113). With the unprocessed slab, the reduction in water content was evenly distributed through the body of concrete. It is suggested, therefore, that the water content at the surface of the vacuum treated specimen was lower than that throughout the unprocessed slab(R.W.C.).

(2) The cement content of the unprocessed slabs(R.W.C.) was not varied and remained constant with the vacuum dewatered specimens. The process produced considerable redistribution of the aggregate and cement within the concrete, the result being that the concrete next to the processing mat contained more cement and fines than the concrete at some distance away from the mat(115). This resulted in the cement content at the surface of the processed slab being higher than that throughout the unprocessed surface.

(3) the detrimental effect of the vacuum dewatering process (e.g., increased porosity) was eliminated or reduced nearest to the surface by the use of mechanical surface finishing equipment. This was also able to bring the extra cement, present on surface, into more intimate contact with the other constituent of the surface matrix.

The higher core crushing strength of the unprocessed slabs can be accounted for by:-

(a) The reduction in water content is evenly distributed in these specimens.

(b) No redistribution of the constituents takes place, apart from the normal effect of segregation which is caused by compaction, thus resulting in a more homogeneous final condition.

(c) There is a reduction in porosity due to a reduction of the water-cement ratio.

From Figures 6.4, 6.9 and 6.14 it is clear that the rates of wear for the vacuum treated slabs were low, due to the very resistant surface matrix. If these curves are compared with those for the unprocessed slabs with the reduced water-cement ratio, shown in Figures 6.5, 6.10 and 6.15, it is clear that the vacuum dewatered slabs are much more resistant to the action of the accelerated abrasion machine.

No published data has been found which compares the abrasion resistance of a vacuum dewatered concrete slab with that of an unprocessed concrete slab whose water-cement ratio is the same as the final "apparent" water -cement ratio of the vacuum treated slab. However, research data exist(115) which compares the compressive strength(as measured by cube crushing) of vacuum treated cubes, fully vibrated, with the compressive strength of unprocessed cubes of the same water-cement ratio as the final water-cement ratio of the vacuum treated cubes. The compressive strength of the latter was found to be greater than the former(115), which is consistent with the findings of the present study. In conclusion, it can be stated that the results of this series of tests further confirms the proposed mechanisms by which the vacuum dewatering process increases the abrasion resistance of concrete.

### 6.6.2 Curing Regimes

In concrete, water is present in three distinct phases, these being gel water, chemically combined water, and capillary water. Of these, the capillary water can be readily lost from the matrix, the rate being dependent upon air temperature, relative humidity, and wind speed (116). The main aim of curing is to maintain these capillary spaces in a saturated state to provide an ideal environment for the hydration of cement. In order to compare the efficiency of various curing regimes in achieving this objective and, also, to assess the influence of curing on the abrasion resistance of concrete, it is necessary to use a standard by which results of the various curing regimes can be assessed. In section 6.2.2 it was stated that the method of curing which is most frequently used on site for slabs is plastic sheeting. In view of this, and the fact that it is less susceptible to error than other possible methods, this technique was selected as the standard for comparison.

The test results are summarised in Table 6.8, and include the mean depth of abrasion, the percent higher or lower than the standard(higher indicates a reduction in abrasion resistance, lower indicates an increase in abrasion resistance) and an indication as to whether these differences are statistically significant based on student's "t" tests . The details of this statistical analysis are provided in Table C.12 to C.14 in Appendix C.1 . The rate of abrasion for the various regimes are given in Figures 6.1 to 6.15, these being plotted from data presented in Table A.8 of Appendix A .

The two-way analysis of variance, given in Tables C.26 and C.27 of Appendix C.3, was carried out to determine whether the variation due to the curing regimes was significantly different to that which may be caused by the interaction of the finishing techniques and the mix design. It shows that the influence of these variables was statistically significant, but the influence of curing was highly significant, i.e. at the 0.01% level, whereas the interaction of the finishing technique and mix design were only significant at the 5% level.

6.6.2.1 Air Curing

The results both in Table 6.8 and in Figures 6.1 to 6.15, clearly indicate that curing was of paramount importance. The decrease in abrasion resistance due to the inefficient air curing was statistically significant in all three concrete mixes, irrespective of the finishing technique. The results suggest that curing becomes more critical as the water-cement ratio of the concrete mix increases. The average decrease in abrasion resistance was 62%, 76% and 109% respectively for mixes B4, B5 and B6. The results of the reduced water content concrete mixes(R.W.C) also suggest that the curing become more critical with the higher water content mixes.

The reason why curing becomes more critical for concrete mixes at higher water-cement ratio is best explained by considering the structural development of concrete paste. The strength of a cement paste is mainly derived from the bonds formed between the very small particles that compose the cement gel and the greater the number of such particles, and so the denser the gel structure, the stronger will be the resulting paste(117). The amount of pore space that has to be filled is a function of the initial water content, whilst the amount of gel that can potentially develop is a function of the relative amount of cement present. It follows that in a higher water-cement ratio mix, there is more pore space to be filled with hydration products than with a lower water-cement ratio mix. Thus there is a greater need for adequate curing to ensure that sufficient gel product are produced to fill these pores. In addition, the rate of evaporation from the low water content mixes will be lower than with the wetter mixes, due to the less porous nature of this paste. The rapid loss of water from the wet mixes (B6) led to a rapid reduction in the degree of saturation in the pore space and so hydration rapidly ceased. With the drier mixes, the paste is denser and so the hydration continued for a longer period in these slabs.

When the results of those specimens cured by curing compounds are discounted, it appears that, next to the water-cement ratio, the mode of curing has the greatest influence on the abrasion resistance of concrete. This is logical and consistent with the above explanation of the structural development of cement paste, since both water-cement ratio and degree of hydration influence the porosity of the paste(117). It is interesting to note that, in a recent investigation(118) it has been found that the zone affected by the poorest curing condition extended only some 30mm below surface of the sample, this sample being a cement paste with a water-cement ratio of 0.5 . This demonstrates the importance of curing on the structure of the surface matrix and , therefore, its influence on the abrasion resistance of the concrete slabs. This is reflected in the rates of abrasion shown in Figures 6.1 to 6.15 , from these it is clear that the surface matrix of the air cured sample offered very little resistance and was rapidly penetrated by the abrasion forces. Once this surface matrix was penetrated it is evident that more resistance was developed due to the aggregate/paste structure. With the other curing regimes the surface matrices provided much more resistance to the abrasion forces, and in some cases this matrix was not penetrated.

These results confirm the general conclusions reached by other investigators (29,43,50,61,92) that adequate curing is important in controlling abrasion resistance and that , in particular, it is of prime importance with the higher water-cement ratio mixes(29,92).

#### 6.6.2.2 Wet Burlap Curing

The results of the wet burlap curing method summarised in Table 6.8, clearly demonstrate that by promoting effective hydration of cement, through proper curing, the abrasion resistance of the concrete slabs was substantially increased. Generally, no statistically significant differences were found between the results achieved with wet burlap curing and those with the plastic sheeting method . However, it should be noted that in the mixes with very low water-cement ratios, the abrasion resistance of some of the specimens cured by the wet burlap method were greater than those cured by the plastic sheet method. A typical example of this behaviour are the results from the following B4 mixes - R.P.F. , V.D. and R.W.C. However, none of these differences was found to be statistically significant. With mixes B6 and B5, with the higher water-cement ratios, the situation was reversed with the abrasion resistance of those specimens cured by the plastic sheeting being greater than those cured by wet burlap. Again these differences were generally not statistically significant. It is suggested that these variation in relative behaviour may be due to interactions between several factors.

Mixes with water-cement ratios below 0.5 are susceptible to self-desiccation(99). In the lower water-cement ratio mixes, where they were cured by the plastic sheeting, no external moisture was available to compensate for any loss of moisture due to evaporation or absorption, and so the relative humidity within the paste decreased. As the gel can only form in water-filled space, this loss of water reduced hydration and, if the internal relative humidity drops below about 80%, hydration ceases(119). This effect is rather unlikely to have been the cause of variation in the results since the surface of the concrete was effectively covered immediatly after the last finishing operation.

Both the temperature and the relative humidity influence the rate of water loss by evaporation from the surface of concrete(116). This variation in temperature and relative humidity was found to influence the waiting time for the finishing operations. These variations were, however, of small magnitude, as can be seen from Table A.5 of Appendix A and additionally the surface of concrete was covered immediatly after the finishing operations. The variation in the results are, therefore, unlikely to have been caused primarily by such variations in temperature and relative humidity.

The wet burlap curing method can only be effective if correctly and rigidly controlled. This method was found to require constant surveillance to prevent the burlap from drying. The main difficulty arose during weekend period, although measures were taken to prevent the burlap from drying. Over the weekends the wet burlap was covered by a plastic sheet. However, this was not always effective. Intermittent wetting and drying at early age can cause more damage than not curing at all(120). Furthermore, it has been reported(121) that the top 6mm of an uncured concrete surface falls below 80% relative humidity within one day of casting and the top 20mm within 7 days. This suggests that, if the burlap is allowed to dry the surface matrix will be rapidly affected, with a consequent effect on the abrasion resistance. A further factor arising with the wet burlap is the positive movement of water from the wet burlap into the top of slab. With the wet mixes this is unlikely to have a major influence due to the high, initial water content of these mixes. However, with the dryer mixes, the transfer of water into the surface layer of the slab would stimulate further hydration thereby improving the abrasion resistance of the slab cured with wet burlap. This is borne out by the results given in Table 6.8 for mix B4, where the wet burlap slabs appear superior to those cured with plastic sheeting. Thus, the variation in the results may have been the effect of moisture movements between the surface layer of the slabs and the wet/dry burlap.

Curing with plastic sheeting required little attention once the specimens had been effectively wrapped in the plastic sheet. This method of curing is considered to provide a relatively more constant curing environment for the surface matrix of the concrete. In addition it is less susceptible to error and this is supported by the low variability in the results of abrasion tests undertaken on these slabs.

Few investigators have investigated the relative performance of the wet burlaps and plastic sheeting curing methods, particularly in terms of the abrasion resistance of concrete. Very recently Senbetta and Schaler(118) found no significant difference between these two methods, when used for curing cement paste with a water-cement ratio of 0.5. They included an abrasion test in their investigation. This conclusion appears to be in general agreement with the present finding.

6.6.2.3 Curing Compounds

The results of this part of the programme are also included in Table 6.8 and they indicate, in general, that the curing compounds were particularly effective in increasing the abrasion resistance of concrete. However, they were found to be very sensitive to the surface texture of the concrete to be cured. When the concrete was finished by hand, particularly the drier mix B4, the surface was open textured and not perfectly smooth, as described in section 6.6.1.1 . The application of curing compound to these slabs resulted in a reduction in abrasion resistance, some of these reductions being significant at the 5% level as indicated in Table 6.8. In contrast, the slabs subjected to repeated power finishing were very smooth with a close texture, and the application of curing compounds significantly increased the abrasion resistance of these slabs, as typified by the results for mix B4 (R.P.F.).

The performance of the three curing compounds may be summarised as follows:-

(1) The resin based, 75% efficiency curing compound(C.C.1). With the majority of surface finishes, no statistically significant difference were found between the abrasion resistance of the specimens cured with this curing compound and that of those cured using the plastic sheeting method. However, in most cases, the abrasion resistance was increased by the use of curing compound, i.e., the depth of wear was reduced.

(2) The resin based, 90% efficiency curing compound(C.C.2). The use of this curing compound was found to increase the abrasion resistance in almost every case, the exception being with the mix B4 slab subjected to hand finishing. In the majority of these cases, the increase in abrasion was statistically significant. The use of this curing compound was found to be consistently more effective in increasing the abrasion resistance than either of the other two curing compounds.

(3) Water based curing compound (C.C.3). The application of this type of curing compound was found, generally, to increase the abrasion resistance of concrete. In the majority of cases, however, these increases were not found to be statistically significant.

It is necessary to consider any factors that could account for this variation in test results. The first factor is concerned with the rate of application. Whilst this was carried out at the rate recommended by the supplier, it was found very difficult to spray a uniform coat of the curing compound. It has been demonstrated(121) that the rate and uniformity of application of a curing compound greatly influences its moisture retention properties. It is suggested, therefore, that some of the variation in the results may be due to non-uniform application of curing compound.

The curing compound systems have very low viscosities so that a compound, when applied, tends to run off any "peaks" in the profile of the concrete surface and forms thicker layers in the "valleys" (122). This results in a situation where the "peaks" tend to create thin or open spots through which moisture is lost and so reduces the efficiency of the curing compound. This effect also explains the sensitivity of curing compounds to surface texture. In the hand finished method particularly with mix B4, the surface texture was open and not smooth, with many high and low points and so the efficiency of the curing compound would have been greatly reduced. Repeated power finishing resulted in a surface that was very smooth and close, with few high and low points. Thus, there would only be a few thin or open spots through which moisture could have been lost, leading to a greater efficiency from the curing compound.

The application of curing compound led to the formation of a thin film on the concrete surface which according to the suppliers should have degraded after several weeks. The process depends on the type of compound, the initial membrane thickness and the degree of exposure to ultra violet light. With both of the resin based curing compounds the surface film had largely disappeared at the time of abrasion test at 28 days. The film formed by the water based curing compound produced a waxy finish which was still evident after 25 days. Attempts were made to remove this, using white spirit, before the abrasion tests commenced. If any trace of curing compound was in existence on the test surface at the time of abrasion test, this would influence the abrasion test results. The variation found in the results of specimens cured by the water based compound is suggested to have been largely caused by this effect. Generally this variation can be seen in the rate of abrasion shown in Figures 6.1 to 6.15 for the samples cured by C.C.3 . Typical behaviour for these slabs can be seen from the plot in Figure 6.8 . During the first few minutes (10 minutes) the rate of wear was very low and then, suddenly, this rate increased, but the plot achieved with the other curing compounds are more uniform. This suggests that a thin film of curing compound may have remained on the surface, and this resisted the abrasion forces. Once this was penetrated the rate of abrasion greatly increased as concrete was again being tested.

From the results in Table 6.8, it is clear that the use of curing compounds, generally, increased the abrasion resistance of all the concrete mixes. This increase may be accounted for by the efficient curing of the specimens. In the plastic sheet method, the plastic sheet covering the surface of the specimen was removed after 7 days while, for the curing compounds, the surface of the specimens were covered by the curing film for several weeks. These specimens were, therefore, effectively cured for the longer periods. It has been found (29) that extension of curing period from 7 to 28 days has a marked improvement on abrasion resistance. The curing compounds may also have acted as liquid surface treatment, apparently sealing the surface of the concrete. It is probable that this sealing quality was temporary, and that after a few months loses its effect. However, no long term tests were performed to investigate this aspect.

There is very little comparative performance data available relating curing compounds to other curing methods. Many investigators have used different curing compounds without specifying the type and the efficiency of the individual compounds. This has resulted in a situation where one investigator(50) has found that curing compounds are more effective than moist curing, while other investigators(118) have found curing compounds to be as ineffective as air curing. However, neither give the type and efficiency of the curing compounds used. The criteria adopted to evaluate the performance of the various curing methods have been very varied. They have included, for example, the moisture-retention properties, strength, volume changes, and the surface condition. The results of the present study are in agreement with the general conclusion reached by Fentress(50) that curing compounds are more effective than moist curing.

### 6.6.3 Surface Treatments

#### 6.6.3.1 Liquid Surface Treatments

This phase of investigation examined the abrasion resistance of five liquid surface treatments for concrete, these were two types of concrete surface hardeners based on aqueous solution of sodium silicate and magnesium flurosilicate, and three types of concrete in-surface seals based on various resin systems. The test results are summarised in Table 6.9, and associated rates of abrasion are shown in Figures 6.16 to 6.18. Table 6.9 includes the mean depth of abrasion, the percent higher or lower than the standard (higher indicates a reduction in abrasion resistance, lower indicates an increase in abrasion resistance) and an indication as to whether these differences are statistically significant based on Student's "t" test. In these analyses, the standard referred to a non-treated slab of the same mix subjected to the same construction and curing procedures. The details of the statistical analyses are provided in Table C.15 of Appendix

C.1. The rates of abrasion given in Figures 6.16 to 6.18 are plotted from the results which are given in Table A.9 of Appendix A .

All five treatments increased the abrasion resistance of the concrete surfaces. All the increases in the abrasion resistance of the specimens were statistically significant, with one exception, that being the specimen from the mix B6 that was treated with surface treatment B, magnesium flurosilicate. The increases due to the three in-surface seals were highly significant, as can be seen from the values tabulated in Table 6.9 .

From a study of the curves in Figures 6.16 to 6.18 , it would seem that differences can be detected between the effects of hardeners and the in-surface seals. The application of both sodium silicate and magnesium flurosilicate reduced the rate of abrasion of the concrete surfaces by varying degrees, during the standard 15 minutes test cycle. However, between 15 and 30 minutes, the reinforced surface matrix was gradually penetrated and the rate of abrasion increased and, in some cases, this rate was greater than that of the control specimens. The implication of this being that the surface hardeners are only partially effective and, their influence is dependent on the quality of the concrete slab.

Generally there was very little difference between the performance of the two concrete surface hardeners. This was to be expected since, they both rely on a similar principle for increasing abrasion resistance, the reaction with the free lime to fill the pores. Both concrete hardeners were most effective on mix B4, with a water-cement ratio of 0.44, and least effective on the higher water-cement ratio mix B6, with a water-cement ratio of 0.65 . It is suggested that in the higher water-cement ratio mix, there was a greater volume of pores to be filled. The air curing of these wet slabs markedly reduced hydration and so there was only a relatively small quantity of free lime available to react with the solution, thus some of the pores will be filled with unreacted powder or remain empty. In the lower water-cement ratio mix B4, there was only a limited volume of smaller pores to be filled.

The application of the three concrete in-surface seals greatly reduced the rate of abrasion in all the three concrete mixes, during the standard 15 minutes test. Indeed, the impregnation of these polymer solutions, appears to have reduced the influence of the concrete mix on the performance of the surface matrix in resisting abrasion forces during the first 15 minutes of the test. When applied to the concrete the individual resin systems formed surface films, the strength of these films is mainly responsible for resisting the abrasion forces. Once the layer which has been impregnated was ruptured the abrasion forces would be resisted solely by the plain concrete. A clear example of this is provided by the rate of abrasion curves for treatments C, D and E with mix B6. As can be seen from Figure 6.18, the abrasion forces were not able to penetrate the concrete surface reinforced by treatment D, almost no wear occuring during the final 15 minutes of the test. However, with treatments C and E, whilst they provided resistance to the abrasion forces up to the end of the first 15 minutes test cycle, during the remaining 15 minutes the reinforced surface matrix was penetrated and the rate of abrasion increased as the forces were acting on the plain, base concrete. The observation that the abrasion forces were able to penetrate through the surface treated by C and E, in concrete mix B6, but not in concrete mix B4 and B5, demonstrates that the characteristic of the concrete mix is also partly responsible for resisting the abrasion forces, and also indicates that the reaction of a given treatment is influenced by the concrete to which it is applied.

The moisture curing polyurethane type of surface treatment, treatment D, was found, overall, to be the most consistently effective of all the treatments. This is illustrated by the rate of abrasion graphs, where it is clear that the abrasion forces were unable to penetrate through the reinforced surface matrix even after 30 minutes of exposure to the accelerated abrasion test machine. This being apparent with all three mixes. The average, percentage increase in the abrasion resistance at the standard 15 minutes test duration, due to the application of the in-surface seals for the three concrete mixes, ranged between 80% to 83%. This narrow range implies that the in-surface seals were as effective in high water-cement ratio mixes as they were in the low water-cement ratio mixes. This further supports the hypothesis that the abrasion forces were being resisted by the in-surface seals which penetrated into the surface matrix, rather than by a modified cemented matrix.

In the literature review it was found that researchers (37,40,43,61) who have investigated the effects of concrete surface hardeners have indicated that these treatments do generally have a beneficial effect on the abrasion resistance. The results of the present study are not directly comparable with these results since the effectiveness of the surface hardeners is very much influenced by the surface texture of concrete, the fineness of the material used particularly with Magnesium flurosilicate and the concentration of the basic material used for the treatment. Most of these investigators (37,40,43,61) have also used hand finished samples. However, the results of the present study confirm the general conclusion that surface hardeners increase the abrasion resistance of concrete. The presentresults also confirm the conclusion reached by Smith(37), when testing the effect of Magnesium and Zinc flurosilicates, that these treatments were most effective on concrete with water-cement ratios around 0.5 . Other investigators(40,43) have been mainly concerned with the relative performance of surface hardeners on cured and uncured specimens. They have found that the effects of surface hardeners are far less pronounced on cured specimens. No published data has been found which may be compared with the results obtained with the in-surface seals.

In the present programme no longer-term tests were undertaken to assess the influence of time on the performance of the various types of liquid surface treatments, i.e. determining the abrasion resistance of the samples at 28 days, 3 months, 6 months and 1 year. It is interesting to note that the application of surface hardener did not generally compensate for lack of curing (as compared to the plastic sheeting method ), but application of the in-surface seals had far more influence on the abrasion resistance than did the mode(s) of curing. Clearly such treatments could be employed to reduce the influence of poor curing.

6.6.3.2 Dry Shake Surface Treatment

The specimens to which the dry shake treatments were applied were finished by the repeated power finishing method (R.P.F.), and the subsequent curing was achieved by spraying with the resin based, 90% efficiency, curing compound(C.C.2). Thus, to assess the influence of the four types of dry shake surface treatments included in the programme, it was necessary to compare their results with those of repeated power finished(R.P.F.) specimens cured using the same compound(C.C.2).

The test results are summarised in Table 6.10, which includes the mean depth of the abrasion, the percent higher or lower than that standard (higher indicates a reduction in abrasion resistance, lower indicates an increase in abrasion resistance) and an indication of whether or not differences are statistically significant based on student's "t" tests. The details of this statistical analysis are presented in Tables C.16 and C.17 in Appendix C.1. The rates of abrasion for the various treatments are given in Figures 6.19 to 6.21, these being plotted from the detailed results presented in Table A.10 of Appendix A.

6.6.3.2.1 Metallic Aggregate Dry Shake

The application of this treatment increased the abrasion resistance of the concrete slabs as can be seen from the results in Table 6.10. These increases were statistically significant, as compared to the standard, and to the other dry shake surface treatments included in the programme. The calculations are provided in Tables C.16 to C.17 of Appendix C.1. The results in Table 6.10 indicate that the use of the metallic dry shake improved the concrete surface to such an extent that the depth of abrasion, for the high water-cement ratio mix, was very close to that of the low water-cement ratio mix. For example, with mix B6 the abrasion depth was 0.04 mm, and for mix B4 it was 0.01mm, so that they both exhibit excellent abrasion resistance. It is interesting to note that the increases in abrasion, although statistically significant, are nonetheless very small in magnitude especially with mixes B4 and B5. In the former, the abrasion depth was reduced from 0.03mm to 0.01mm, and in the latter it was reduced from 0.06mm to 0.03mm.

From the rate of abrasion shown in Figures 6.19 to 6.21, it is clear that the abrasion forces were unable to penetrate through the reinforced surface matrix. To assess the resulting thickness of the metallic dry shake, three 100mm diameter cores were taken from the treated concrete slabs. The metallic dry shake was visible, due to the sparkles of metal present. Each core had a band some 3 to 5mm thick which was darker, due to the increased cement content, and sparkled. It was observed that the dry shake had become intimately mixed with the surface of the concrete, and it was an integral layer at the top of the concrete surface. The action of the repeated power trowelling was largely responsible for incorporating the metallic dry shake within the normal structure of the concrete surface.

The present results confirm the finding of the other investigators(43-44,48,50,53) that the application of metallic dry shakes significantly increase the abrasion resistance of concrete slabs. Direct comparisons between results are not possible because most of these investigators have used hand finishing and different test methods. It has been suggested(44) that the increase in abrasion resistance is mainly due to the ductility of metallic aggregate, which tends to be flattened out and compacted with wear rather than to break down as would natural aggregates. However, the present study has clearly established the importance of finishing techniques and it is now suggested that high abrasion resistance is only partly due to the introduction of metallic aggregate and cement to the surface layer. The additional role of the finishing technique is discussed in the subsequent sections.

#### 6.6.3.2.2 Natural Aggregate Dry Shake

To assess their effect on abrasion resistance, the results obtained with both natural dry shakes, commercial and laboratory-prepared, were compared with those obtained with the control slabs, repeated power finished cured with C.C.2 . The significant tests are summarised in Table 6.10, the detailed values are given in the Tables C.16 and C.17 in Appendix C.1. These show that there were no significant differences between the results from the control and of those from either type of dry shakes. Most investigators(43,50) have reported that the application of natural aggregate dry shakes to the surface increases the abrasion resistance of concrete slabs. The results of the present study do not seem to support this conclusion. Several reasons can be suggested for this apparent deviation and these also suggest that this finding is quite consistent with the earlier discussion.

From literature review no correlation was found, for high strength concrete, between the quality of the aggregate and the abrasion resistance(38,66). However, with concrete of lower strength, the influence of the aggregate becomes apparent. This is very similar to the effect observed in the present programme with the influence of finishing technique. Repeated power finishing was able to reinforce the surface matrix of both the treated and untreated specimens to such an extent that the influence of the increased aggregate and cement content were not apparent. Once the abrasion forces had penetrated through this surface layer the rate of abrasion would change, depending on the layer encountered. This occurred with both the natural aggregate and the cement dry shakes.

Investigators(43-44,48,50,53) of the influence of dry shakes on abrasion resistance have invariably used the hand finished method. The increased abrasion resistance noted with the treated specimen by these investigators was mainly due to the increase in aggregate and cement contents at the surface. Such results will not , therefore, be comparable with those obtained in the present study. The influence of the dry shake would have been evident if repeated power finishing had not been employed, and the surfaces of all the specimens had been finished by hand finishing. This was not carried out as the suppliers had recommended power finishing and, at the start of the programme, the critical influence of repeated power finishing had not been realised.

From the rates of abrasion, apparent in Figures 6.19 to 6.21, it is clear that the abrasion forces were unable to penetrate through the surface matrix, with the maximum depth of wear being only 0.22mm after 30 minutes of testing. These curves are very similar to those of the untreated specimens shown in Figures 6.3, 6.8 and 6.13, for R.P.F. cured with C.C.2 . This is a further indication that it is the surface matrix that resisted the abrasion forces and, again, reflects the influence of the finishing technique. One, 100mm diameter core, was taken from each of the six treated slabs. On each of these cores there was a 2-4mm thick band of darker appearance, this was similar to the cores taken from the slabs treated with the metallic aggregate, but without the sparkles.

Based on the results of this programme, it is suggested that the suppliers of natural aggregate dry shake surface treatments sell a finishing technique rather than the material, for increasing the abrasion resistance of the concrete slab.

#### 6.6.3.2.3 Cement Dry Shake

The abrasion resistance of the specimen treated with the cement dry shake was not significantly different from that of the untreated standard specimen, as can be seen from Table 6.10. No significant differences were found between the cement dry shake and that of the natural aggregate dry shakes, see Tables C.16 and C.17 in Appendix C.1 .

It is generally believed that the application of dry cement to the surface will result in shrinkage and crazing, crazing being a pattern of fine cracks resembling crushed eggshell which is formed by surface shrinkage. This was not observed on the specimens treated in the present programme, mainly because it was used as a dry shake rather than as a "drier". The difference between these concepts may be summarised as follows:-

(1) "Driers" are used to enable earlier and easier finishing, and to produce a smoother, more visually attractive surface.

(2) "Driers" are applied to soak-up the bleed water and be immediately, and gently, floated to give a smooth finish.

(3) The cement dry shake is sprinkled on the surface at a much later stage than "driers", after bleeding has ceased and surface water evaporated.

(4) The finishing technique used on the cement dry shake ensures that it is intimately combined with the other constituent of the surface matrix, rather than remaining on the top of the surface.

The main reason that no significant difference was observed between the abrasion resistance of treated and untreated slabs has been explained in section 6.6.3.2.2 . It may be added that the untreated specimen was naturally cement rich on the surface(99), and the action of repeated power finishing combined this cement with the other constituents of the surface matrix. One, 100mm diameter core, was taken from each of the three treated slabs. There was a darker band near the surface, similar to the cores taken from natural and metallic aggregate dry shake specimens, but the band was significantly thiner than those achieved with the other dry shakes and so was difficult to measure.

### 6.6.4 Influence Of Mix Design

The results of the cube tests from this programme, together with those from the comparative study given in Tables A.4 and A.11 of Appendix A , may be used to demonstrate the influence of crushing strength on the abrasion resistance of concrete slab. The water-cement ratios of these mixes have been recorded and so all the results may also be used to assess the relationship between water-cement ratio and abrasion resistance. Only the results obtained with the hand finishing and wet burlap cured samples have been used for this analysis. These are comparable with the results from the comparative study and , furthermore, minimise the influence of the other variables. The depth of abrasion has been plotted against crushing strength, and water-cement ratio in Figures 6.22 and 6.23 . These clearly demonstrate that abrasion resistance varies directly with the crushing strength and inversely with the water - cement ratio. These findings confirm the conclusions of other investigators (29,30,35-36,38,43). However, it is important to note that the influence of finishing technique and surface treatment, reduces the dependence of abrasion on water-cement ratio and compressive strength of the concrete mix as has been seen from the results in Tables 6.5 to 6.10 . These results also demonstrate that compressive strength cannot be used as the sole indicator of the quality of slab, so far as its abrasion resistance is concerned.

### 6.6.5 Relative Performance

From the results of this programme it is possible to rank the relative performance of abrasion resistance of concrete surface due to the various finishing techniques and surface treatments. With such an analysis, it is necessary to use only data obtained from a single, controlled curing regime. The only common regime that covered both finishing techniques and the dry shake surface treatment was the resin based, 90% efficiency, curing compound. These results have been used and are summarised in Table 6.11 which gives the ratings from the analysis. It should be noted that the specimens treated by the liquid surface treatments have also been included, but they were air cured.

The application of the metallic dry shake clearly provided the highest abrasion resistance in all the three concrete mixes. The results for the other dry shakes have not been included in Table 6.11, because no significant differences were found between them and the specimen slabs finished by the repeated power finish method. The least resistant surface was provided by the hand finished method. It is interesting to note that the repeated power finishing method was more effective than the in-surface seals. This conclusion is still valid when due account is taken for air curing as can be seen from the appropriate results in Table 6.8 .

If the results of air cured specimens are used, then the Table 6.12 shows that the surface which was reinforced by the in-surface type of surface treatments provided the most resistant concrete surface, and the least resistant surface was that of the specimens finished by hand. The repeated power finished specimens are now ranked as the second best in this Table. From the results in Table 6.11 and 6.12 , it can also be demonstrated that adequate curing was more effective in increasing the abrasion resistance, than was the application of the surface hardener types of surface treatments.

## 6.7 Summary

This chapter has mainly been concerned with the abrasion resistance of concrete surfaces at macro-level. The work may be summarised as follows:-

(1) A survey was undertaken of current construction practices of

concrete floor slabs.

(2) The influence of finishing techniques, curing regimes and surface treatments, on the abrasion resistance of concrete slabs, was investigated.

(3) The influence of these preceding variables on abrasion resistance has been accounted for by various mechanisms.

(4) By considering all the abrasion test data, it has been possible to present a rating system for assessing the influence of finishing techniques, curing regime and surface treatment on abrasion resistance.

It should be noted that the mechanisms, which have been proposed to account for the influence of the various variables, are mainly related to the microstructure of the concrete nearest to the surface layer. However, since this chapter does not include any data relating to the examination of this microstructure, the proposed mechanisms must be considered as tentative requiring further investigation.

| FINISHING TECHNIQUE | FLOATING (No.of Application) | | TROWELLING (No.of Application) | |
|---|---|---|---|---|
| | HAND (Wood Float) | POWER PLANING DISC | HAND (Steel Trowel ) | POWER TROWELLING BLADES |
| H.F | 1 (18 min) | - | 1 (30 min) | - |
| P.F | - | 1 (8 min) | - | 1 (12 min) |
| R.P.F | - | 1 (8 min) | - | 3 (32 min) |
| V.T | - | 1 (8 min) | - | 1 (12 min) |
| R.W.C | - | 1 (8 min) | - | 1 (12 min) |

Note: TIME given in minutes (min)

TABLE 6.1 Programme for Surface Finishing

| Test Set | Parameter | Variable | Constant | No.of Cast | No.of Large Slabs (2.01 x 1.52 x 0.1m) | No.of Test Slabs (1.0 x 0.5 x 0.1m) |
|---|---|---|---|---|---|---|
| 1 | Finishing technique | H.F | Surface treatment (None) | 6 | 3 | 18 |
| | Curing regimes | A.C, W.B, P.S, CC1, CC2, CC3 | | | | |
| | Concrete mix | B4, B5, B6 | | | | |
| 2 | Finishing technique | P.F | DITTO | 6 | 3 | 18 |
| | Curing Regimes | A.C, W.B, P.S, CC1, CC2, CC3 | | | | |
| | Concrete mix | B4, B5, B6 | | | | |
| 3 | Finishing technique | R.P.F | DITTO | 6 | 3 | 18 |
| | Curing regimes | A.C, W.B, P.S, CC1, CC2, CC3 | | | | |
| | Concrete mix | B4, B5, B6 | | | | |
| 4 | Finishing technique | V.D | DITTO | 6 | 3 | 18 |
| | Curing regimes | A.C, W.B, P.S, CC1, CC2, CC3 | | | | |
| | Concrete mix | B4, B5, B6 | | | | |
| 5 | Finishing technique | R.W.C. | DITTO | 6 | 3 | 18 |
| | Curing regimes | A.C, W.B, P.S, CC1, CC2, CC3 | | | | |
| | Concrete mix | B4, B5, B6 | | | | |
| 6 | Surface treatment | A, B, C, D, E, O | Curing regime (Air) | 6 | 3 | 18 |
| | Concrete mix | B4, B5, B6 | Finishing technique(P.F) | | | |
| 7 | Surface treatment | D.S.1 | Curing regime (CC2) | 3 | 3 (half of slab to be used) | 9 |
| | Concrete mix | B4, B5, B6 | Finishing technique(R.P.F) | | | |
| 8 | Surface treatment | D.S.2 | DITTO | 3 | 3 (half of slab to be used) | 9 |
| | Concrete mix | B4, B5, B6 | | | | |
| 9 | Surface treatment | D.S.3 | DITTO | 3 | 3 (half of slab to be used) | 9 |
| | Concrete mix | B4, B5, B6 | | | | |
| 10 | Surface treatment | D.S.4 | DITTO | 3 | 3 (half of slab to be used) | 9 |
| | Concrete mix | B4, B5, B6 | | | | |

| MIX NO. | Free W/C Ratio | Quantity of Water in the mix* (L) | Quantity of Cement in the mix (Kg) | Quantity of Water Extracted (L) | Quantity of Cement and Fine Particles Extracted + Non-evaporable Water (gm) | % Reduction in Water Content | Final W/C Ratio |
|---|---|---|---|---|---|---|---|
| B4 | 0.44 | 30.84 | 69.16 | 3.50 | 60.6 | 11.10 | 0.40 |
| B5 | 0.52 | 34.66 | 65.74 | 5.21 | 66.1 | 14.8 | 0.45 |
| B6 | 0.65 | 37.58 | 57.00 | 6.67 | 70.2 | 17.6 | 0.54 |

* Assuming 90% of water which has been allowed for absorption has been absorbed i.e. Free water + 10% of absorption water

TABLE 6.3 Reduction of Water-Cement Ratio due to Vacuum-Dewatering Process

| MIX NO. | Absorption Water (L) | Normal Water Content (L) | | Cement Content (Kg) | Final Free Water-Cement Ratio | Reduced Water Content (L) | |
|---|---|---|---|---|---|---|---|
| | | Mix Water | Free Water Content | | | Free Water Content | Mix Water |
| B4 | 4.37 | 34.77 | 30.40 | 69.16 | 0.40 | 27.66 | 32.03 |
| B5 | 4.62 | 38.82 | 34.20 | 65.74 | 0.45 | 29.58 | 34.20 |
| B6 | 5.26 | 42.31 | 37.05 | 57.00 | 0.54 | 30.78 | 36.04 |

TABLE 6.4 Water-Cement Ratio for the Reduced Water Content (R.W.C.) Specimens

| Type of Curing Regimes | Analysis | MIX No. | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MIX B4 | | | | MIX B5 | | | | MIX B6 | | | |
| | | Type of Finishing | | | | | | | | | | | |
| | | Standard (P.F) | H.F. | R.P.F | V.D. | Standard (P.F) | H.F. | R.P.F | V.D. | Standard (P.F) | H.F. | R.P.F | V.D. |
| A.C | Mean (mm) | 0.47 | 0.83 | 0.18 | 0.35 | 0.90 | 1.10 | 0.35 | 0.47 | 1.29 | 1.68 | 0.38 | 0.63 |
| | % diff. | | +77 | -62 | -26 | | +22 | -61 | -48 | | +30 | -70 | -51 |
| | Level of signif. | | 1% | 0.2% | 5% | | No | 0.1% | 0.1% | | 5% | 0.1% | 0.2% |
| W.B | Mean (mm) | 0.31 | 0.57 | 0.09 | 0.18 | 0.56 | 0.68 | 0.20 | 0.25 | 0.82 | 0.89 | 0.27 | 0.31 |
| | % diff. | | +84 | -71 | -42 | | +21 | -64 | -55 | | +8 | -67 | -62 |
| | Level of signif. | | 1% | 0.1% | 1% | | 5% | 0.1% | 0.1% | | No | 0.1% | 0.1% |
| P.S | Mean (mm) | 0.30 | 0.46 | 0.10 | 0.23 | 0.48 | 0.61 | 0.18 | 0.25 | 0.66 | 0.84 | 0.17 | 0.27 |
| | % diff. | | +53 | -67 | -23 | | +27 | -62 | -48 | | +27 | -74 | -59 |
| | Level of signif. | | 1% | 0.1% | 5% | | 5% | 0.1% | 0.2% | | 5% | 0.1% | 0.1% |
| CC1 | Mean (mm) | 0.25 | 0.49 | 0.05 | 0.16 | 0.44 | 0.62 | 0.14 | 0.20 | 0.58 | 0.65 | 0.16 | 0.30 |
| | % diff. | | +96 | -80 | -36 | | +41 | -68 | -54 | | +12 | -72 | -48 |
| | Level of signif. | | 0.1% | 0.1% | 1% | | 1% | 0.1% | 0.1% | | No | 0.1% | 1% |
| CC2 | Mean (mm) | 0.22 | 0.57 | 0.03 | 0.14 | 0.41 | 0.61 | 0.06 | 0.20 | 0.60 | 0.74 | 0.14 | 0.24 |
| | % diff. | | +159 | -86 | -36 | | +49 | -85 | -51 | | +23 | -77 | -60 |
| | Level of signif. | | 0.1% | 0.2% | 5% | | 1% | 0.1% | 0.2% | | 5% | 0.1% | 0.1% |
| CC3 | Mean (mm) | 0.26 | 0.58 | 0.02 | 0.15 | 0.45 | 0.66 | 0.04 | 0.23 | 0.58 | 1.03 | 0.13 | 0.28 |
| | % diff. | | +123 | -76 | -42 | | +47 | -91 | -48 | | +78 | -77 | -52 |
| | Level of signif. | | 0.1% | 0.1% | 1% | | 5% | 0.1% | 1% | | 1% | 0.1% | 0.2% |

Note: Each mean is the average of 3 abrasion tests
Level of significance based on paired 't' tests

TABLE 6.5 Summary of Finishing Technique Test Results

| Level of Significance / MIX No. | No | 5% | 1% | >1% |
|---|---|---|---|---|
| B4 | 0 | 0 | 3 | 3 |
| B5 | 1 | 3 | 2 | 0 |
| B6 | 2 | 3 | 1 | 0 |

TABLE 6.6 Summary of the Results of Significance Test on Hand Finished and Power Finished Specimens

| Type of Curing Regime | Analysis | MIX NO. | | | | | |
|---|---|---|---|---|---|---|---|
| | | B4 | | B5 | | B6 | |
| | | TYPE OF FINISHING TECHNIQUE | | | | | |
| | | Standard (R.W.C.) | V.D. | Standard (R.W.C.) | V.D. | Standard (R.W.C.) | V.D. |
| A.C | Mean (mm) | 0.40 | 0.35 | 0.53 | 0.47 | 0.98 | 0.63 |
| | % diff. | | -12 | | -11 | | -36 |
| | Level of Signif. | | No | | No | | 1% |
| W.B | Mean (mm) | 0.24 | 0.18 | 0.39 | 0.25 | 0.60 | 0.31 |
| | % diff. | | -25 | | -36 | | -48 |
| | Level of Signif. | | 5% | | 1% | | 1% |
| P.S | Mean (mm) | 0.28 | 0.23 | 0.41 | 0.25 | 0.51 | 0.27 |
| | % diff. | | -18 | | -39 | | -47 |
| | Level of signif. | | 5% | | 0.2% | | 0.2% |
| CC1 | Mean (mm) | 0.22 | 0.16 | 0.27 | 0.20 | 0.57 | 0.30 |
| | % diff. | | -27 | | -26 | | -47 |
| | Level of signif. | | 5% | | 5% | | 1% |
| CC2 | Mean (mm) | 0.18 | 0.14 | 0.28 | 0.20 | 0.46 | 0.24 |
| | % diff. | | -22 | | -29 | | -48 |
| | Level of signif. | | No | | 5% | | 0.2% |
| CC3 | Mean (mm) | 0.20 | 0.15 | 0.30 | 0.23 | 0.49 | 0.28 |
| | % diff. | | -25 | | -23 | | -43 |
| | Level of Signif | | 5% | | No | | 1% |

Note: Each mean is the average of 3 Abrasian Tests
Level of Significance based on paired "t" tests.

TABLE 6.7 Summary of R.W.C and V.D Test Results

Table 6.8 Cont.

| MIX No. | Type of Finishing Techniques | Analysis | TYPE OF CURING REGIMES | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Standard (P.S) | A.C. | W.B. | CC1 | CC2 | CC3 |
| B4 | H.F | Mean (mm) | 0.46 | 0.83 | 0.57 | 0.49 | 0.57 | 0.58 |
| | | % Diff. | | +80 | +24 | +6 | +24 | +26 |
| | | Level of signif. | | 1% | No | No | 5% | 5% |
| | P.F | Mean (mm) | 0.30 | 0.47 | 0.31 | 0.25 | 0.22 | 0.26 |
| | | % Diff. | | +57 | +3 | -17 | -27 | -13 |
| | | Level of signif | | 5% | No | No | 5% | No |
| | R.P.F | Mean (mm) | 0.10 | 0.18 | 0.09 | 0.05 | 0.03 | 0.02 |
| | | % Diff. | | +80 | -10 | -50 | -70 | -80 |
| | | Level of signif. | | 0.2% | No | 1% | 0.2% | 0.2% |
| | V.D | Mean (mm) | 0.23 | 0.35 | 0.18 | 0.16 | 0.14 | 0.15 |
| | | % Diff. | | +52 | -22 | -30 | -39 | -35 |
| | | Level of signif. | | 1% | No | 5% | 1% | 1% |
| | R.W.C | Mean (mm) | 0.28 | 0.40 | 0.24 | 0.22 | 0.18 | 0.20 |
| | | % Diff. | | +43 | -14 | -21 | -36 | -28 |
| | | Level of Signif. | | 1% | No | 5% | 1% | 5% |

Cont....

Table 6.8 Cont.

| MIX No. | Type of Finishing Techniques | Analysis | TYPE OF CURING REGIMES | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Standard (P.S) | A.C. | W.B. | CC1 | CC2 | CC3 |
| B5 | H.F | Mean (mm) | 0.61 | 1.10 | 0.68 | 0.62 | 0.61 | 0.66 |
| | | % Diff. | | +80 | +11 | +2 | 0 | +8 |
| | | Level of Signif. | | 1% | No | No | No | No |
| | P.F | Mean (mm) | 0.48 | 0.90 | 0.56 | 0.44 | 0.41 | 0.45 |
| | | % Diff. | | +88 | +17 | -8 | -15 | -6 |
| | | Level of Signif. | | 0.2% | No | No | No | No |
| | R.P.F | Mean (mm) | 0.18 | 0.35 | 0.20 | 0.14 | 0.06 | 0.04 |
| | | % Diff. | | +94 | +11 | -22 | -67 | -78 |
| | | Level of Signif. | | 0.2% | No | No | 0.1% | 0.1% |
| | V.D | Mean (mm) | 0.25 | 0.47 | 0.25 | 0.20 | 0.20 | 0.23 |
| | | % Diff. | | +88 | 0 | -20 | -20 | -8 |
| | | Level of Signif. | | 0.1% | No | No | 5% | No |
| | R.W.C | Mean (mm) | 0.41 | 0.53 | 0.39 | 0.27 | 0.28 | 0.30 |
| | | % Diff. | | +29 | -5 | -34 | -32 | -27 |
| | | Level of Signif. | | 5% | No | 1% | 1% | 5% |

Table 6.8 cont...

Table 6.8 Cont.

| MIX No. | Type of Finishing Techniques | Analysis | TYPE OF CURING REGIMES | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Standard (P.S) | A.C. | W.B. | CC1 | CC2 | CC3 |
| B6 | H.F | Mean (mm) | 0.84 | 1.68 | 0.89 | 0.65 | 0.74 | 1.03 |
| | | % Diff. | | +100 | +6 | -23 | -12 | +23 |
| | | Level of signif. | | 0.2% | No | 5% | No | No |
| | P.F | Mean (mm) | 0.66 | 1.29 | 0.82 | 0.58 | 0.60 | 0.58 |
| | | % Diff. | | +95 | +24 | -12 | -9 | -12 |
| | | Level of Signif. | | 0.2% | No | No | No | No |
| | R.P.F | Mean (mm) | 0.17 | 0.38 | 0.27 | 0.16 | 0.14 | 0.13 |
| | | % Diff. | | +123 | +59 | -6 | -18 | -24 |
| | | Level of signif. | | 0.1% | 1% | No | No | 5% |
| | V.D | Mean (mm) | 0.27 | 0.63 | 0.31 | 0.30 | 0.24 | 0.28 |
| | | % Diff. | | +133 | +15 | +11 | -11 | +4 |
| | | Level of Signif. | | 0.1% | No | No | No | No |
| | R.W.C | Mean (mm) | 0.51 | 0.98 | 0.60 | 0.57 | 0.46 | 0.49 |
| | | % Diff. | | +92 | +18 | +12 | -10 | -4 |
| | | Level of signif. | | 1% | No | No | No | No |

| MIX No. | Analysis | TYPE OF LIQUID SURFACE TREATMENT | | | | | |
|---|---|---|---|---|---|---|---|
| | | Standard (O) | A | B | C | D | E |
| B4 | Mean (mm) | 0.54 | 0.4 | 0.38 | 0.08 | 0.07 | 0.12 |
| | % diff. | | -26 | -30 | -85 | -87 | -78 |
| | Level of signif. | | 5% | 5% | 0.1% | 0.1% | 0.1% |
| B5 | Mean (mm) | 0.78 | 0.51 | 0.48 | 0.12 | 0.14 | 0.22 |
| | % diff. | | -35 | -38 | -85 | -82 | -72 |
| | Level of signif. | | 5% | 5% | 0.1% | 0.1% | 0.1% |
| B6 | Mean (mm) | 1.18 | 0.89 | 1.00 | 0.26 | 0.14 | 0.28 |
| | % diff. | | -25 | -15 | -78 | -88 | -76 |
| | Level of signif. | | 5% | No | 0.1% | 0.1% | 0.1% |

Note: For the key to Type of Surface Treatment refer to Section 6.3.3

TABLE 6.9 Summary of Liquid Surface Treatment Test Results

| MIX No. | Analysis | TYPE OF DRY SHAKE SURFACE TREATMENT | | | | |
|---|---|---|---|---|---|---|
| | | Standard (R.P.F) | D.S.1 | D.S.2 | D.S.3 | D.S.4 |
| B4 | Mean (mm) | 0.03 | 0.01 | 0.02 | 0.03 | 0.03 |
| | % Diff. | | -67 | -33 | 0 | 0 |
| | Level of signif. | | 0.1% | No | No | No |
| B5 | Mean (mm) | 0.06 | 0.03 | 0.08 | 0.07 | 0.05 |
| | % diff. | | -50 | +33 | +17 | -17 |
| | Level of signif. | | 1% | No | No | No |
| B6 | Mean (mm) | 0.14 | 0.04 | 0.13 | 0.16 | 0.15 |
| | % diff. | | -71 | -7 | +14 | +7 |
| | Level of signif. | | 0.1% | No | No | No |

Note: For the key to Type of Surface Treatment refer to Section 6.3.3

TABLE 6.10 Summary of Dry Shake Surface Treatment Test Resul

| Type of Finishing Technique or Surface Treatment | MEAN DEPTH OF ABRASION(mm) | | | RANKING* |
|---|---|---|---|---|
| | Mix B4 | Mix B5 | Mix B6 | |
| H.F | 0.57 | 0.61 | 0.74 | 7 |
| P.F. | 0.22 | 0.41 | 0.60 | 5 |
| R.P.F | 0.03 | 0.06 | 0.14 | 2 |
| V.D | 0.14 | 0.20 | 0.24 | 4 |
| Surface hardener | 0.38 | 0.48 | 0.89 | 6 |
| In-surface seal | 0.07 | 0.12 | 0.14 | 3 |
| Metallic Dry Shake | 0.01 | 0.03 | 0.04 | 1 |

* 1 = Best 7 = Worse

TABLE 6.11 Relative Performance of Finishing Technique and Surface Treatment Results for C.C.2 Cured Specimens

| Type of Finishing Technique or Surface Treatment | *MEAN DEPTH OF ABRASION(mm)* | | | *RANKING** |
|---|---|---|---|---|
| | *Mix B4* | *Mix B5* | *Mix B6* | |
| H.F | 0.83 | 1.10 | 1.68 | 6 |
| P.F | 0.47 | 0.90 | 1.29 | 5 |
| R.P.F | 0.18 | 0.35 | 0.38 | 2 |
| V.D | 0.35 | 0.47 | 0.63 | 3 |
| Surface hardener | 0.38 | 0.48 | 0.89 | 4 |
| In-surface seal | 0.07 | 0.12 | 0.14 | 1 |

* 1 = Best 6 = Worse

TABLE 6.12 Relative Performance of Finishing Technique and Surface Treatment Results for Air Cured Specimens

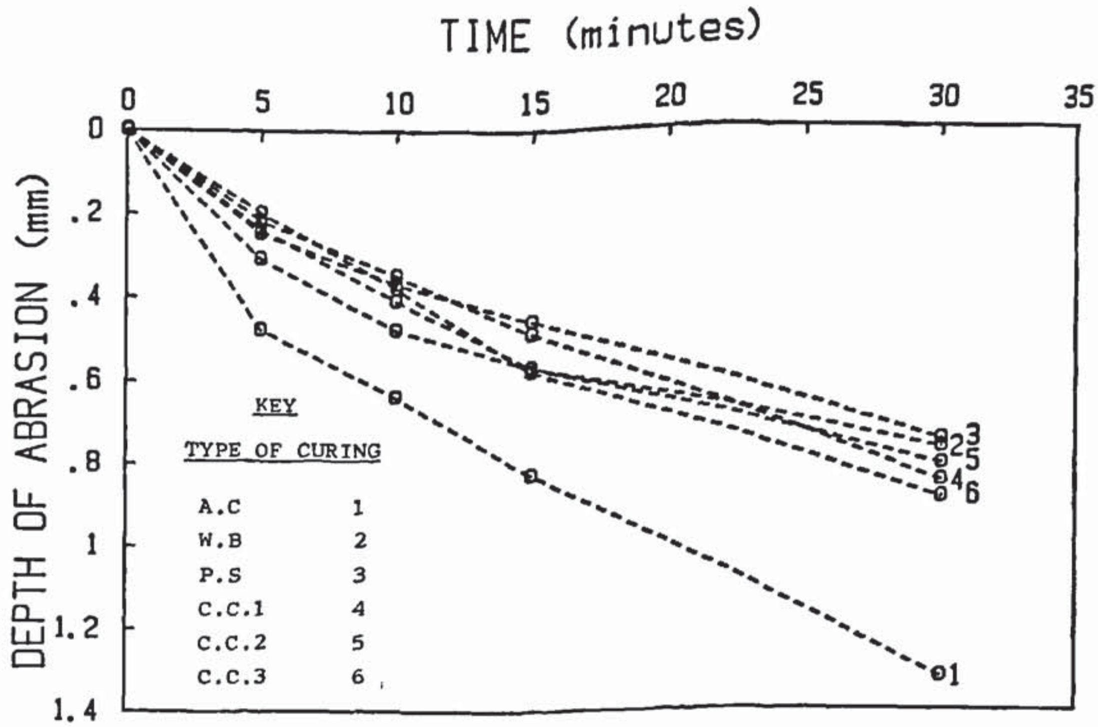



FIGURE 6.1 Rate of Abrasion for Mix B4 H.F

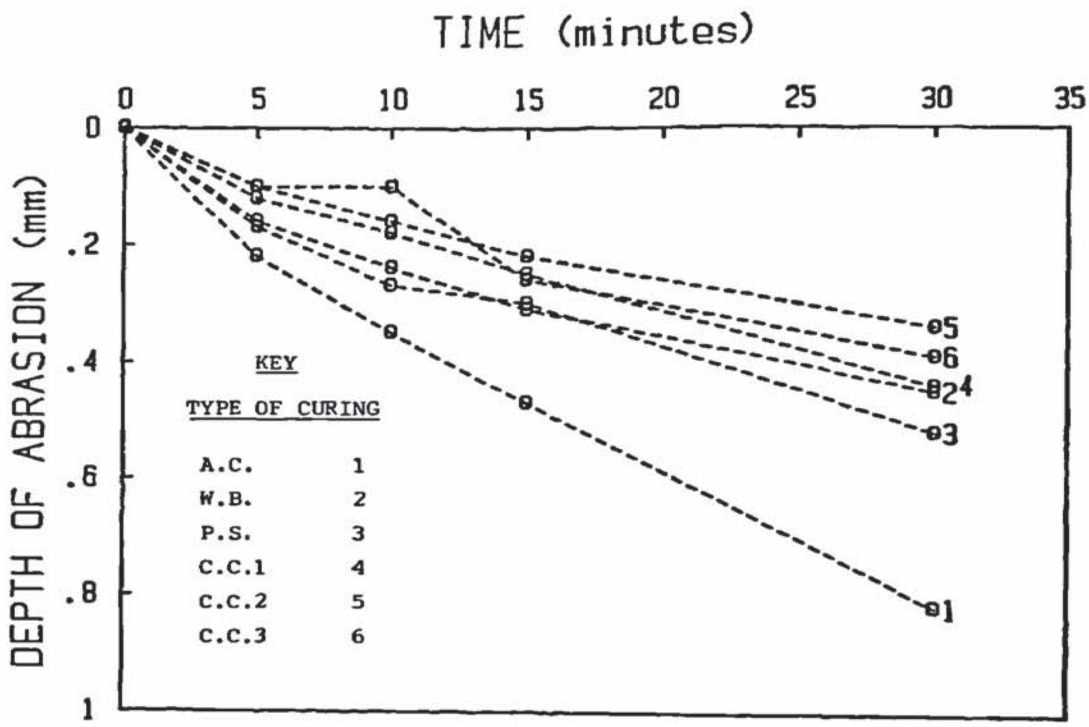



FIGURE 6.2 Rate of Abrasion for Mix B4 P.F

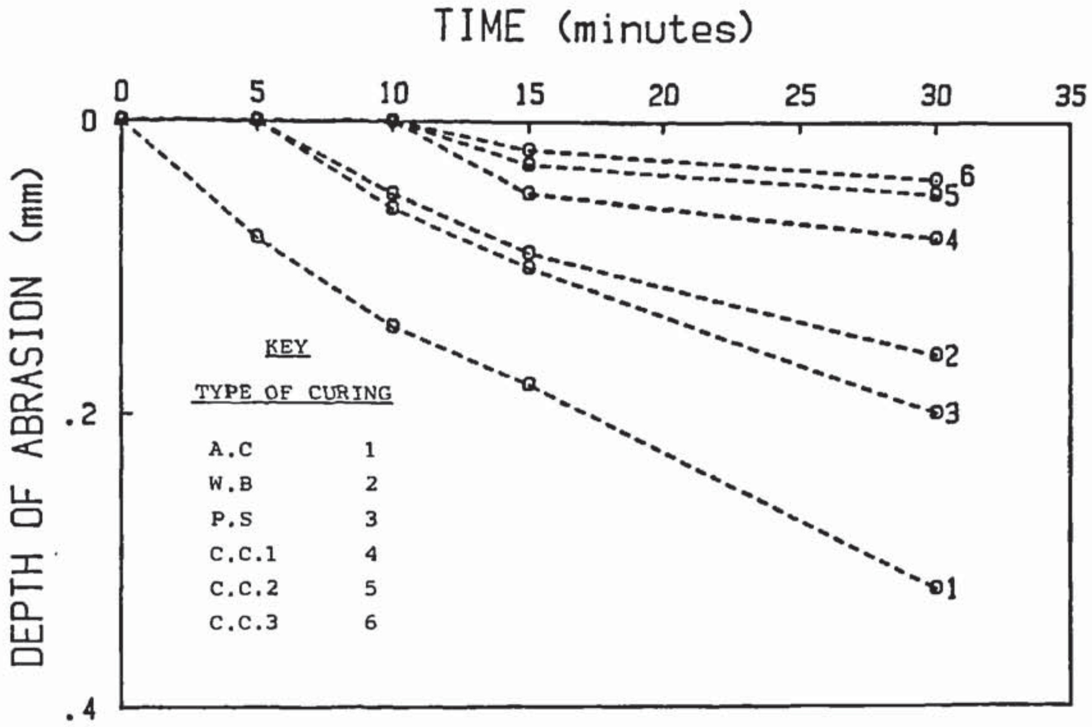



FIGURE 6.3 Rate of Abrasion for Mix B4 R.P.F

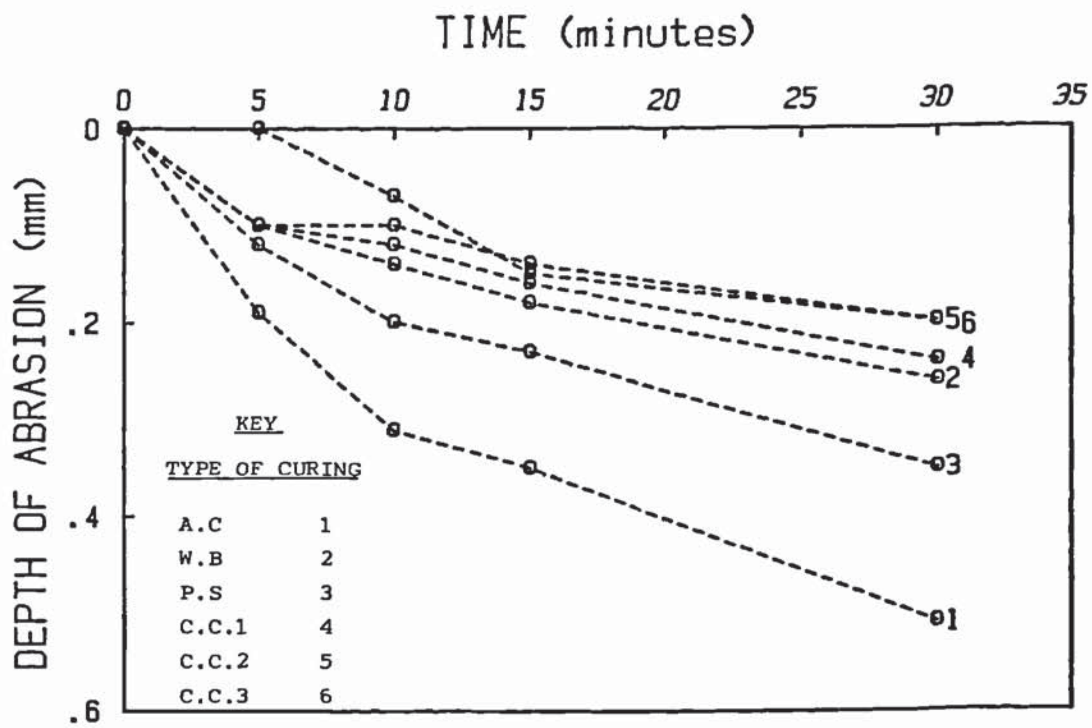



FIGURE 6.4 Rate of Abrasion for Mix B4 V.D

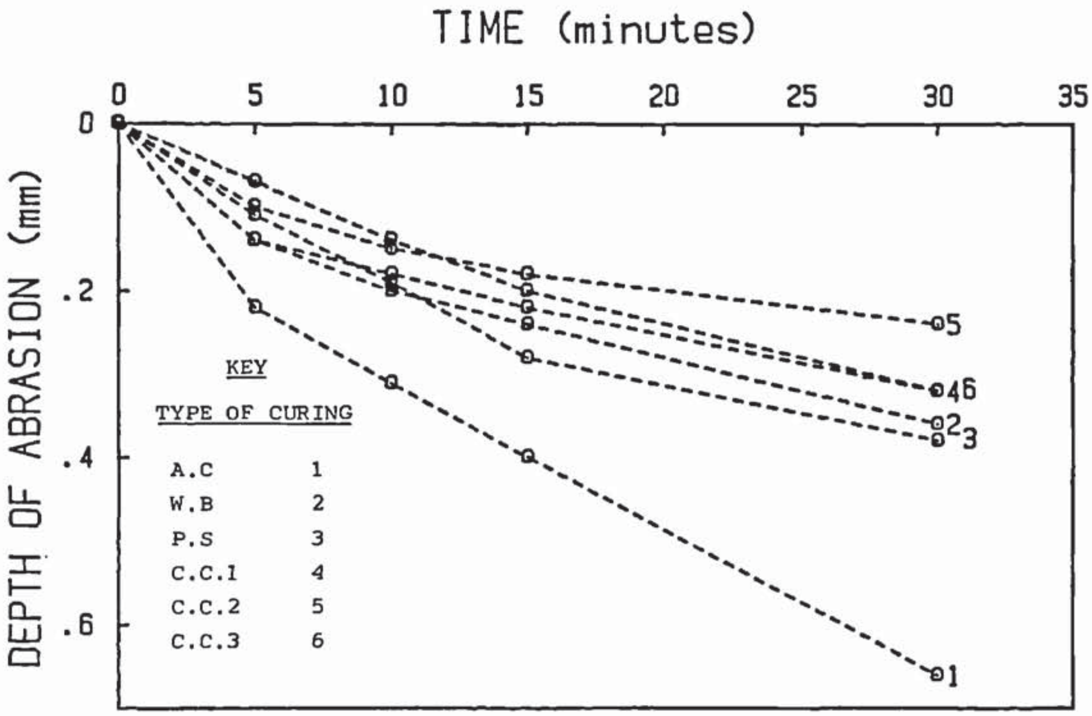



FIGURE 6.5 Rate of Abrasion for Mix B4 R.W.C

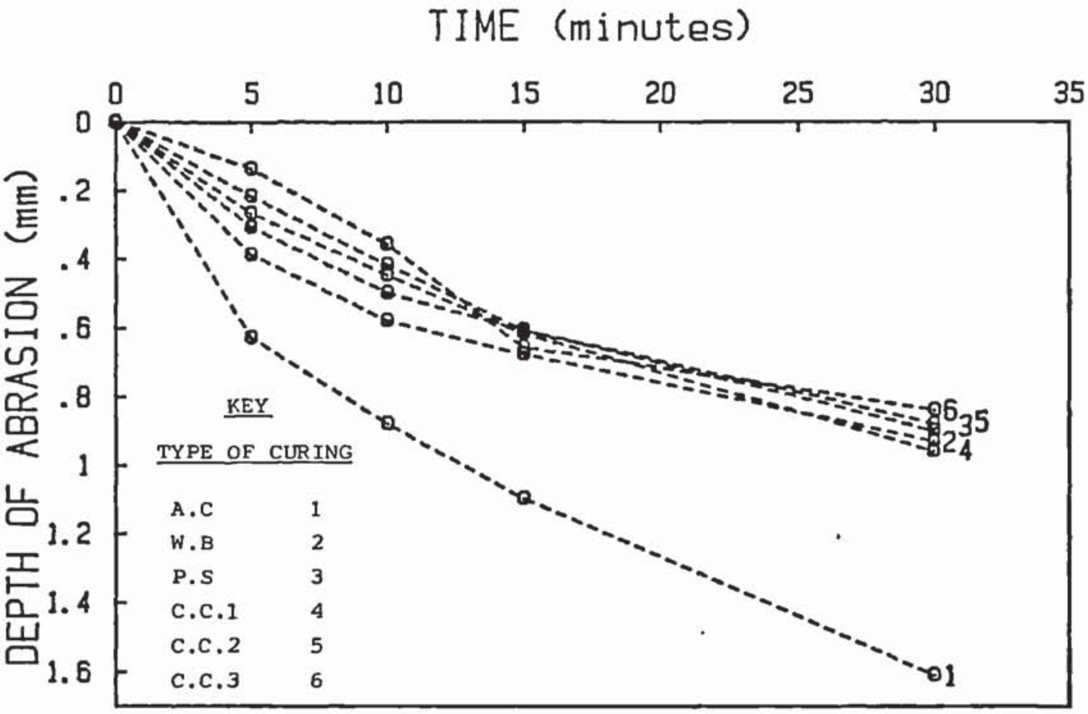



FIGURE 6.6 Rate of Abrasion for Mix B5 H.F

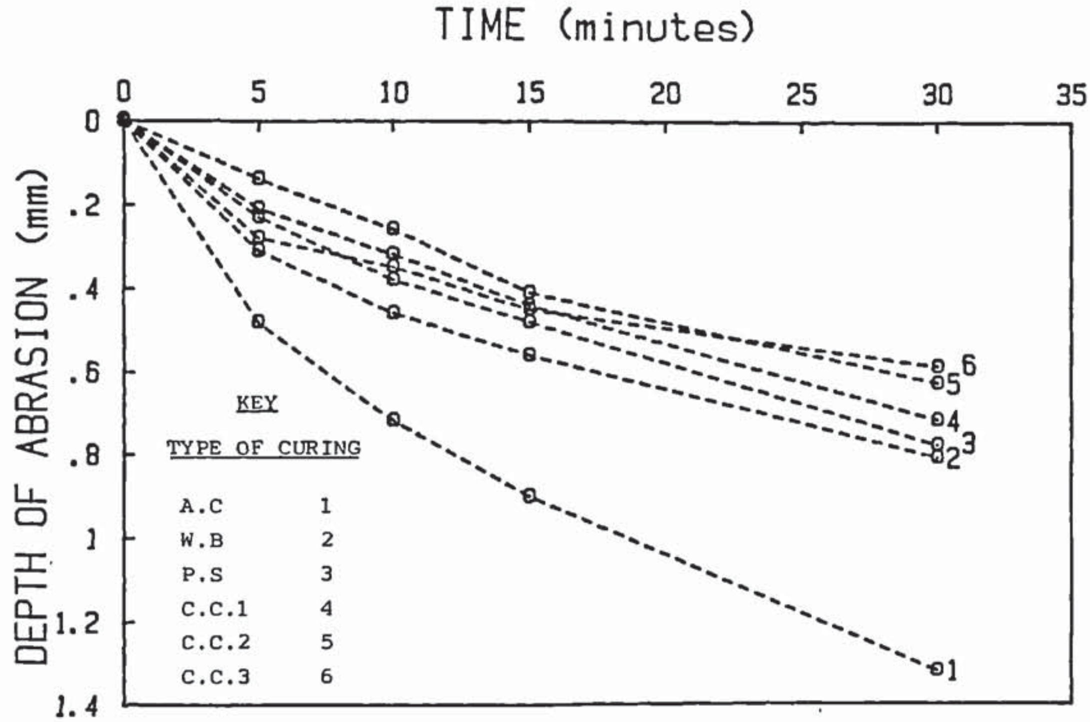



FIGURE 6.7 Rate of Abrasion for Mix B5 P.F

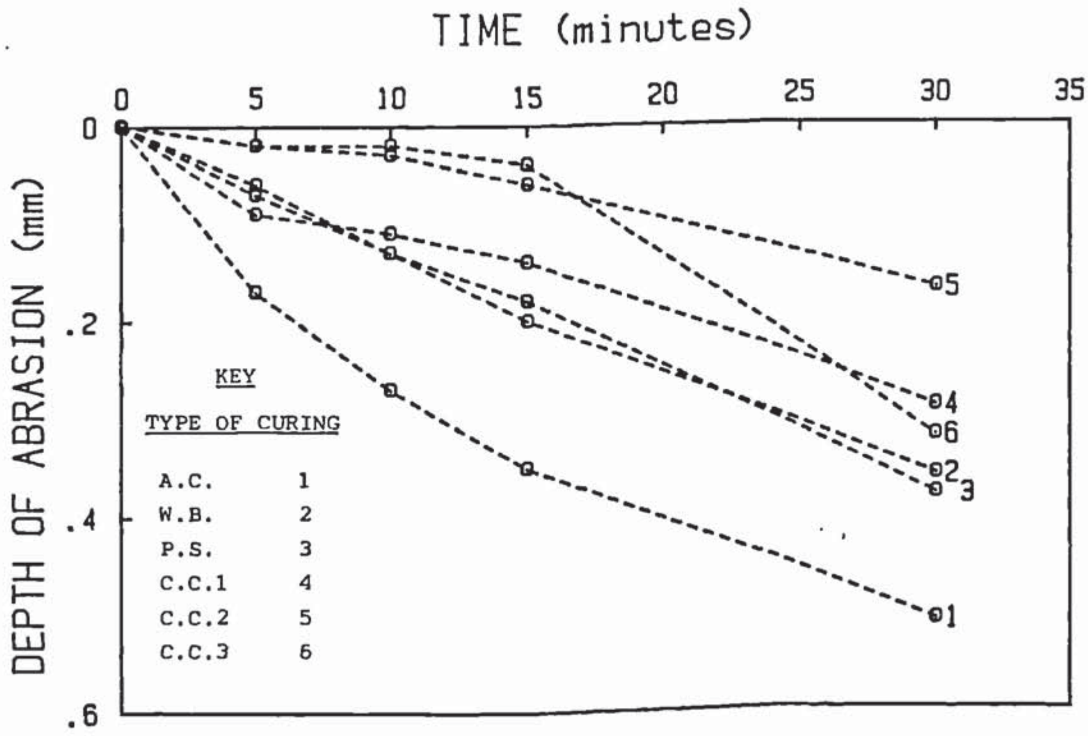



FIGURE 6.8 Rate of Abrasion for Mix B5 R.P.F

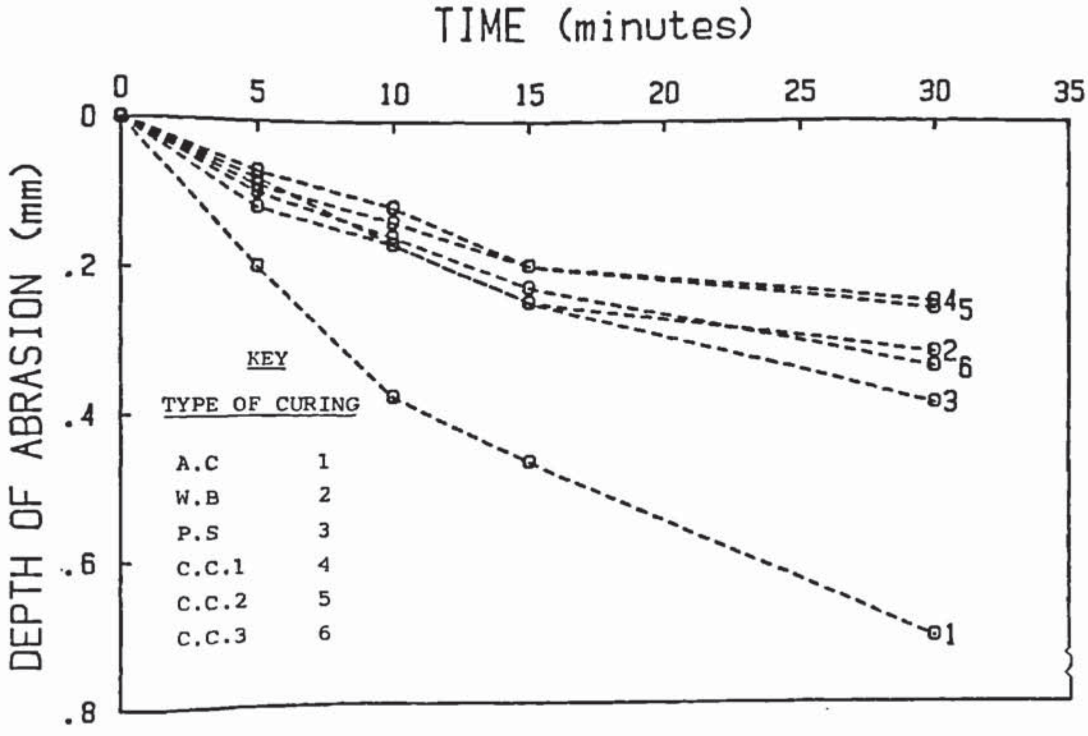



FIGURE 6.9 Rate of Abrasion for Mix B5 V.D

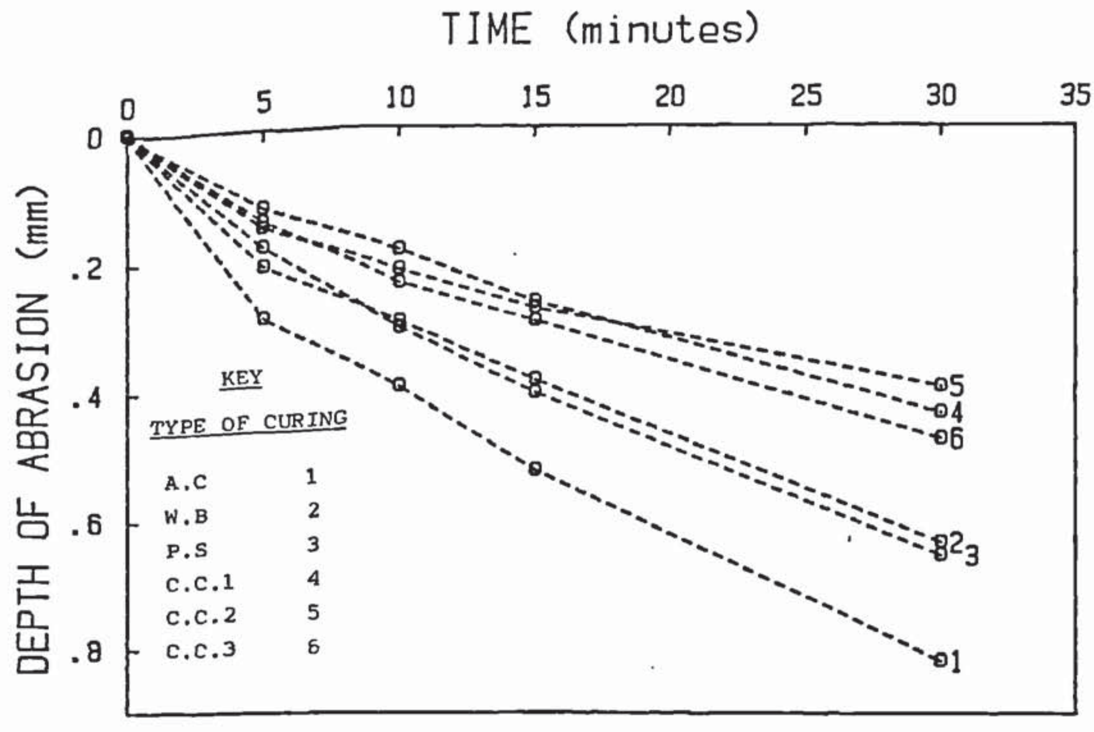



FIGURE 6.10 Rate of Abrasion for Mix B5 R.W.C

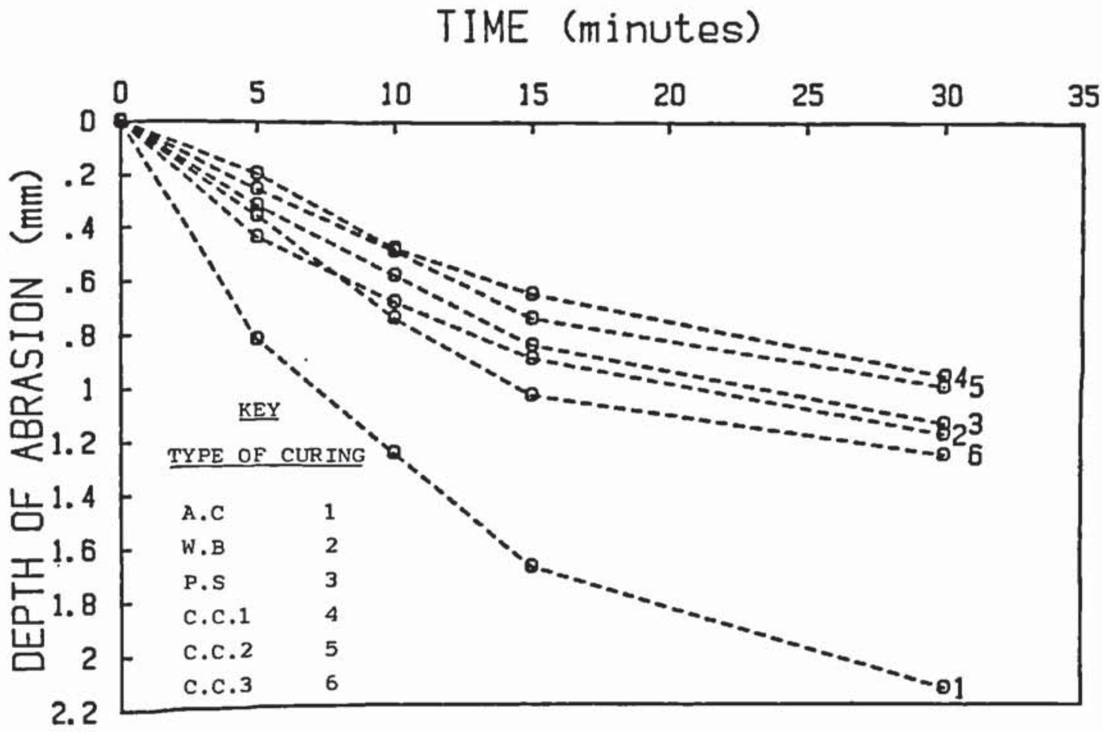



FIGURE 6.11 Rate of Abrasion for Mix B6 H.F

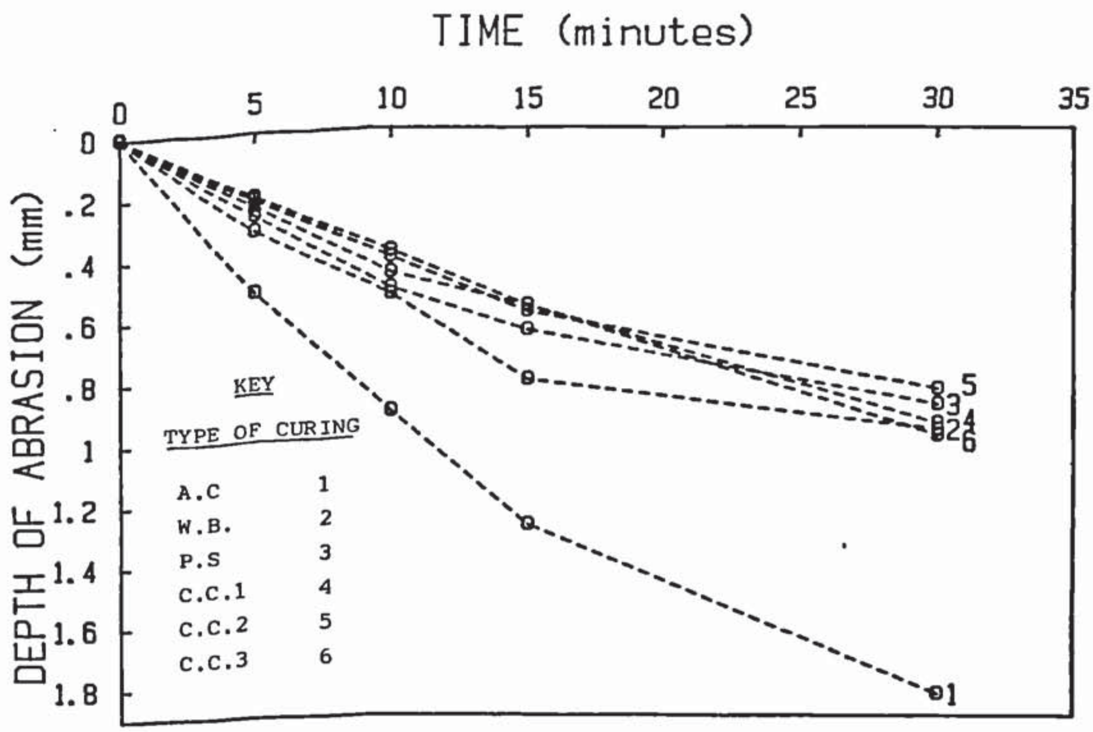



FIGURE 6.12 Rate of Abrasion for Mix B6 P.F

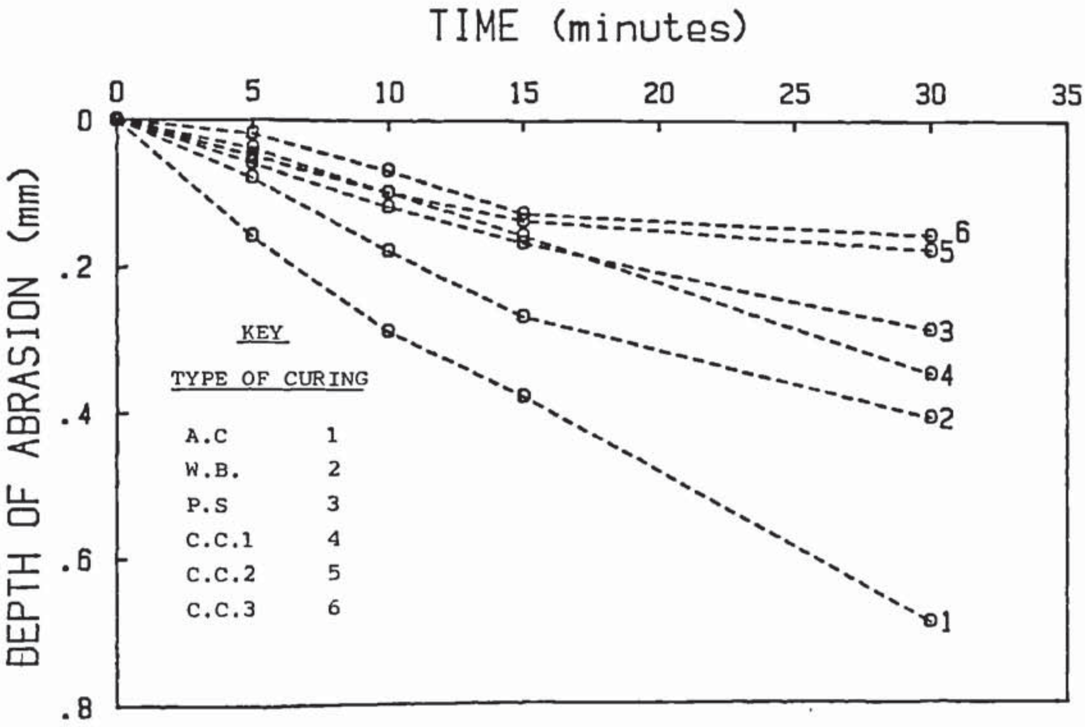



FIGURE 6.13 Rate of Abrasion for Mix B6 R.P.F

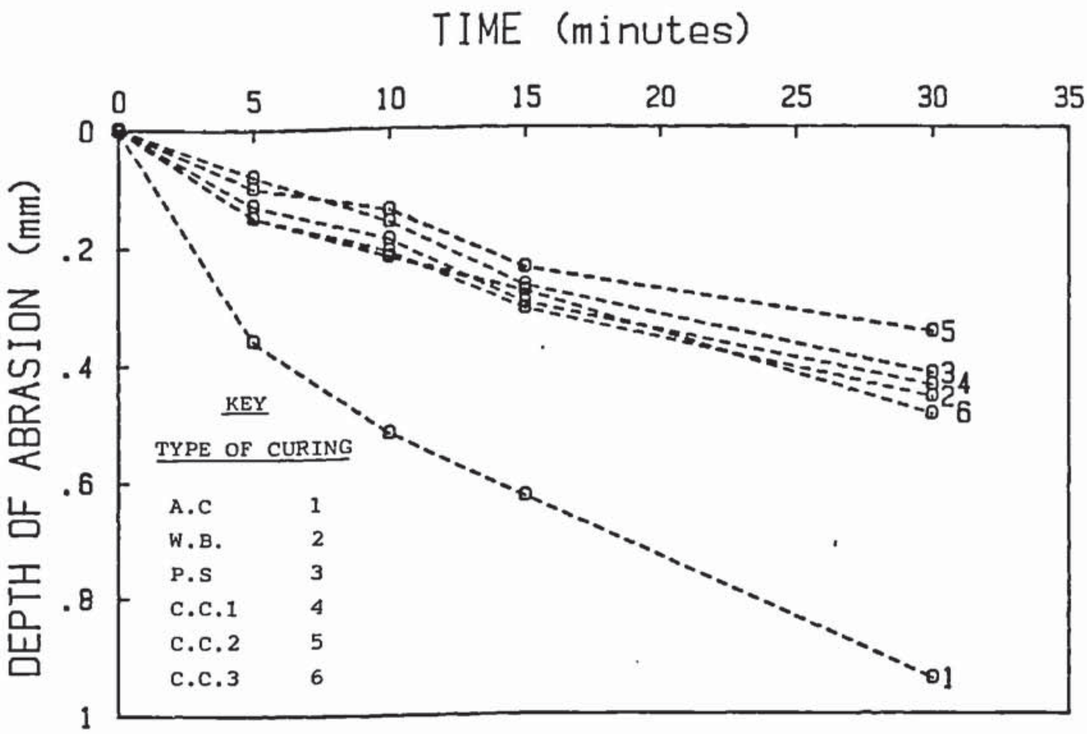



FIGURE 6.14 Rate of Abrasion for Mix B6 V.D

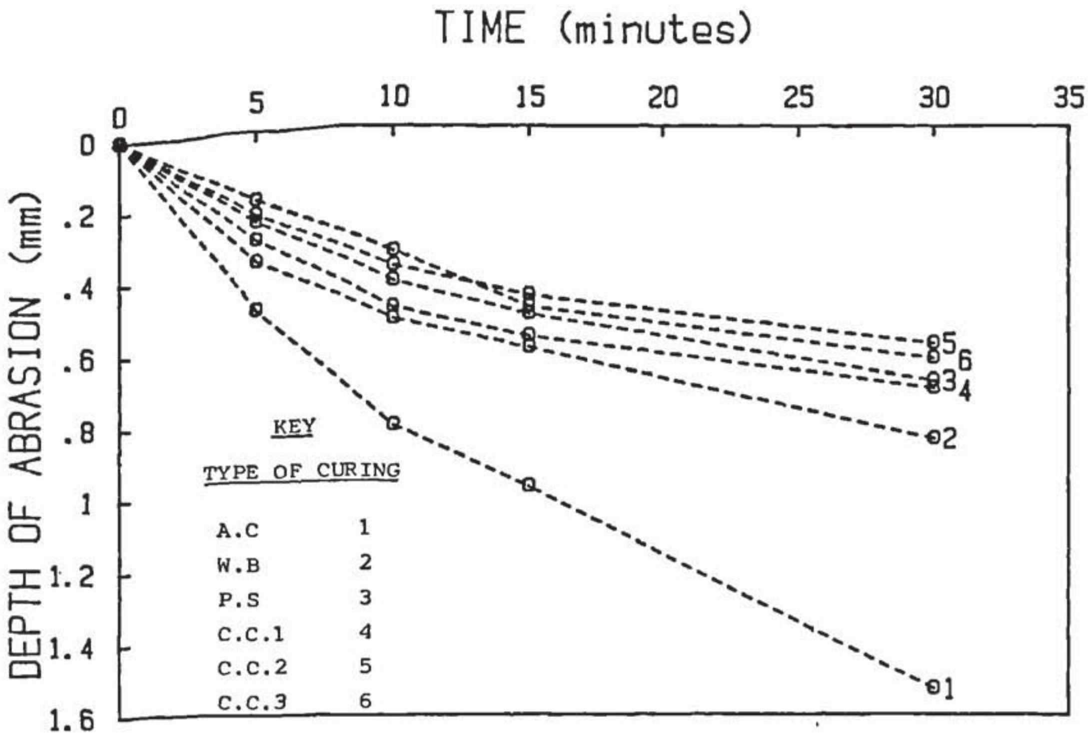



FIGURE 6.15 Rate of Abrasion for Mix B6 R.W.C.

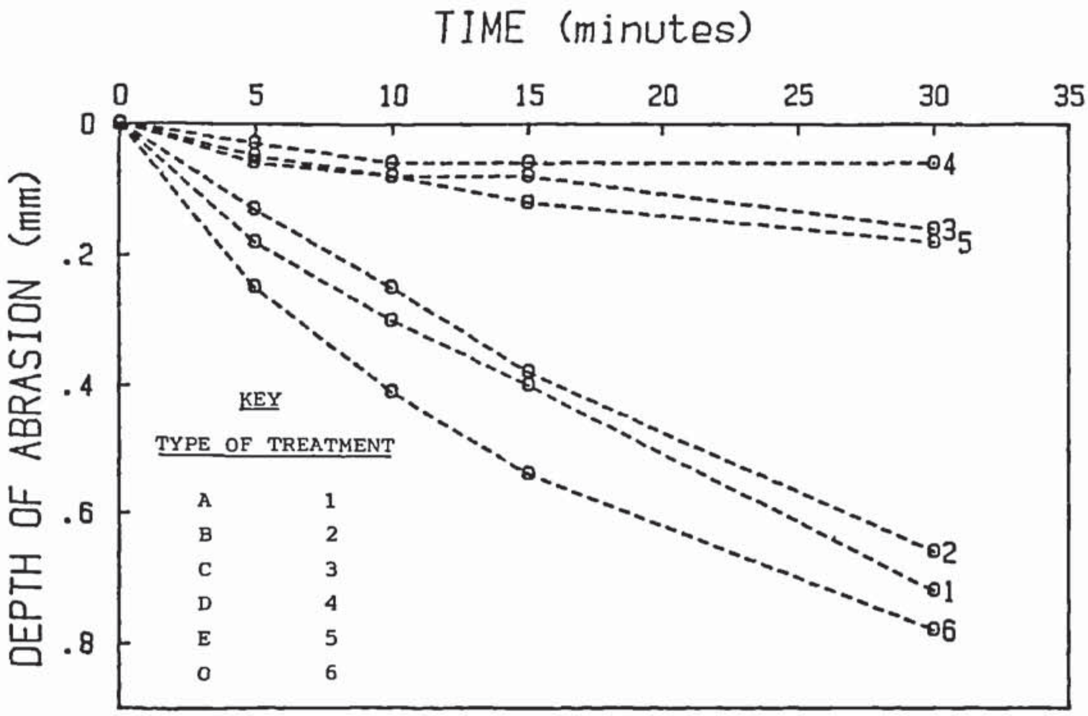



FIGURE 6.16 Rate of Abrasion for Liquid Surface Treatment Mix B4

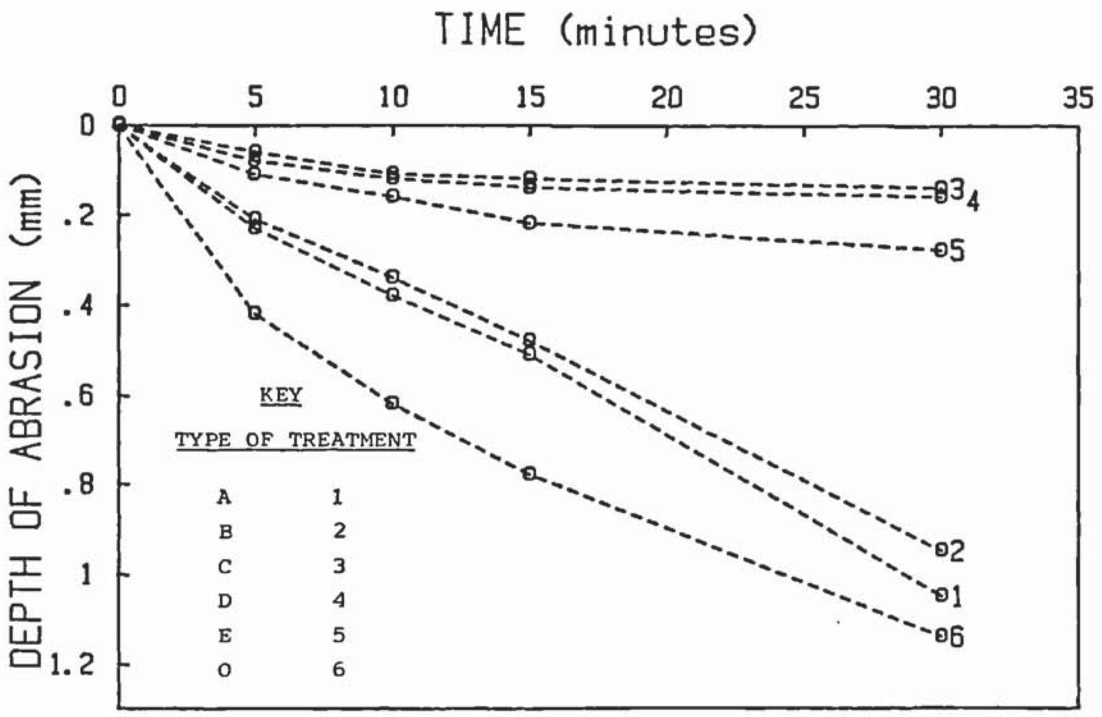



FIGURE 6.17 Rate of Abrasion for Liquid Surface Treatment
Mix B5

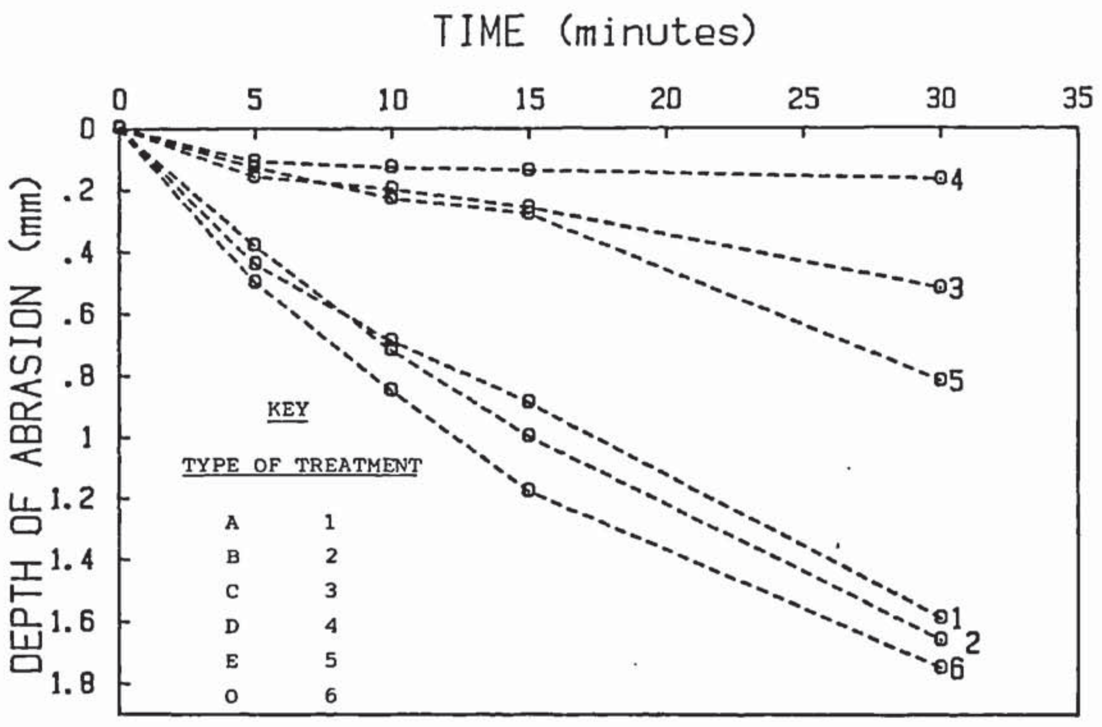



FIGURE 6.18 Rate of Abrasion for Liquid Surface Treatment
Mix B6

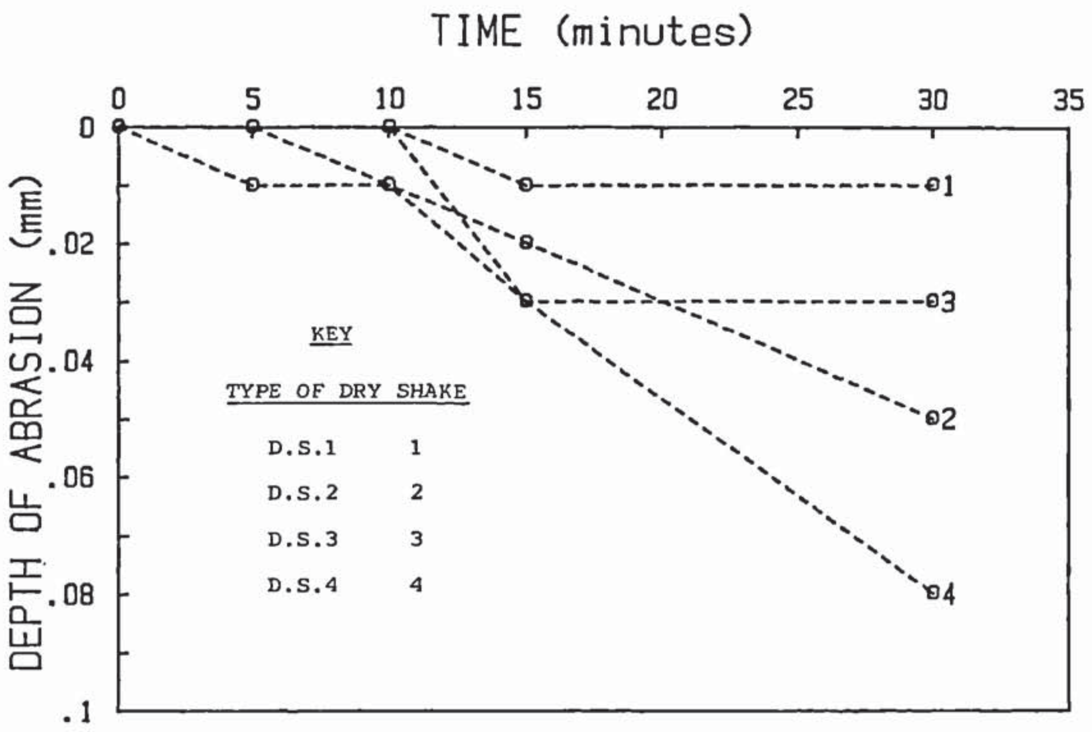



FIGURE 6.19 Rate of Abrasion for Dry Shake Surface Treatment
Mix B4

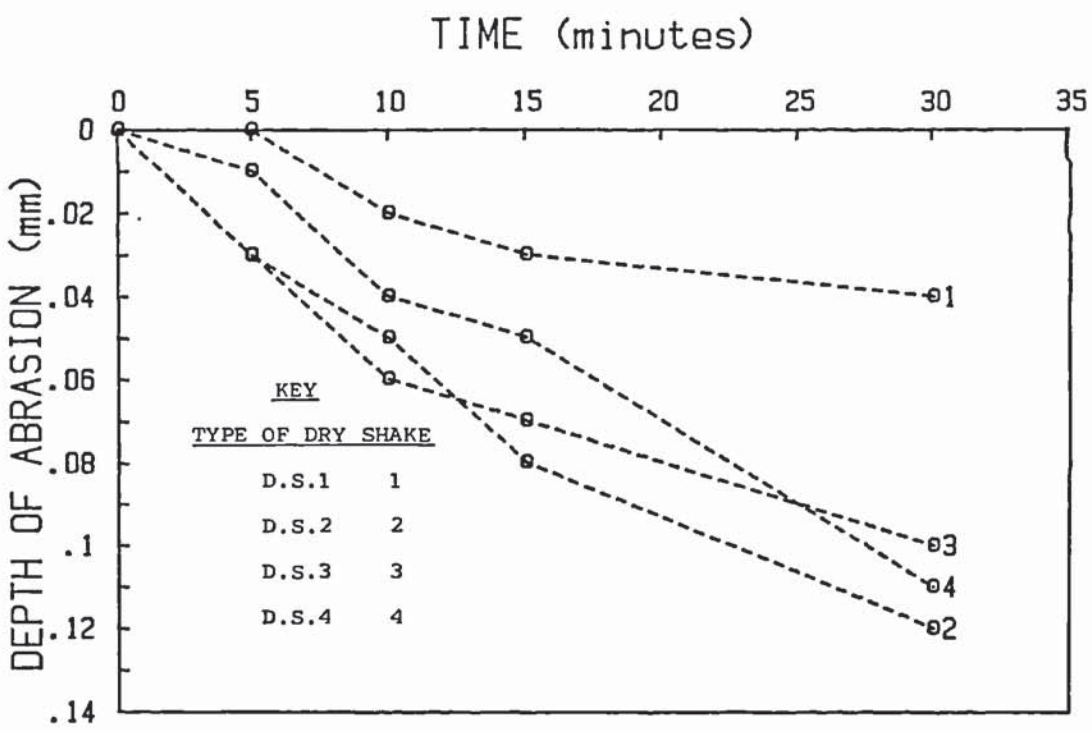



FIGURE 6.20 Rate of Abrasion for Dry Shake Surface Treatment
Mix B5

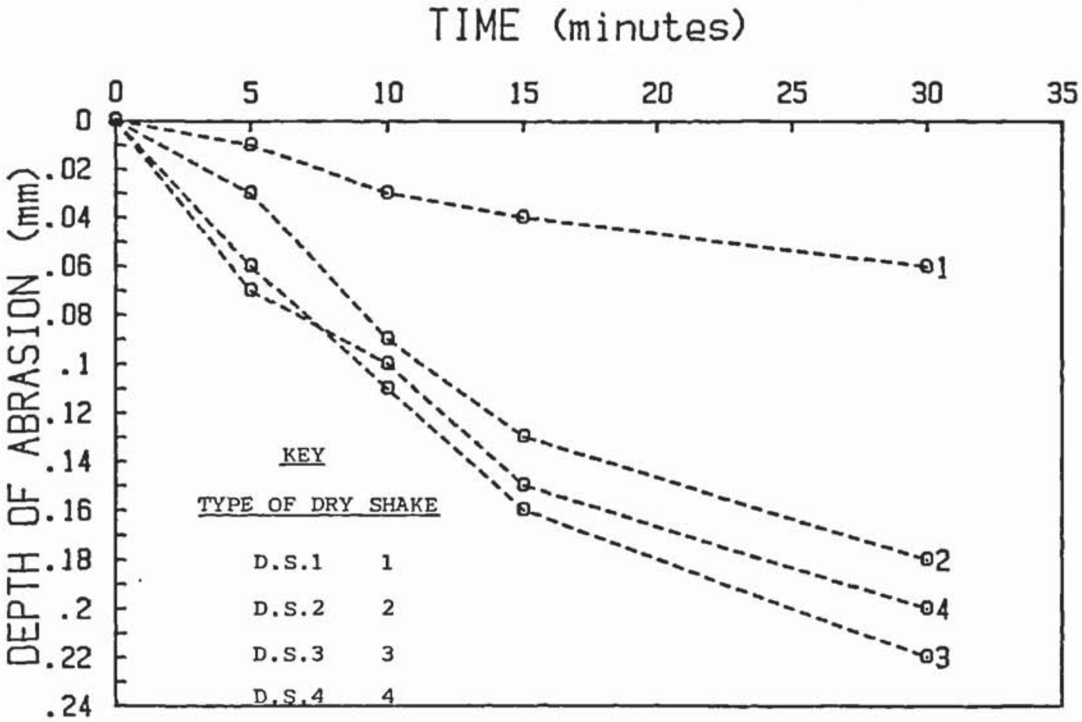



FIGURE 6.21 Rate of Abrasion for Dry Shake Surface Treatment Mix B6

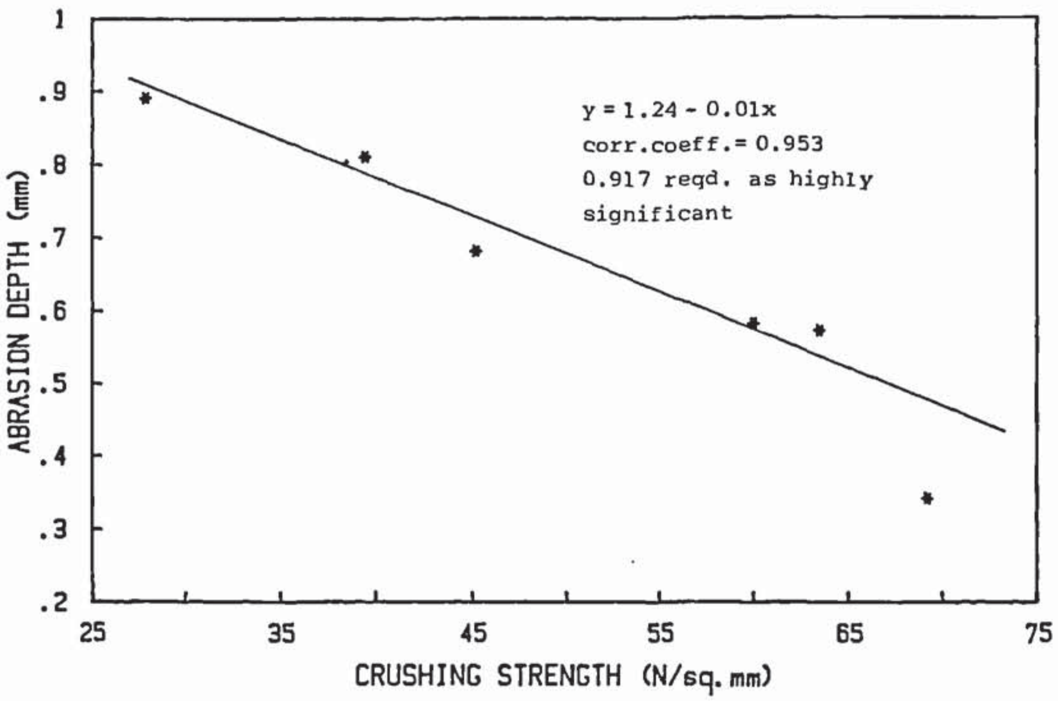



FIGURE 6.22 Abrasion Depth V's Crushing Strength

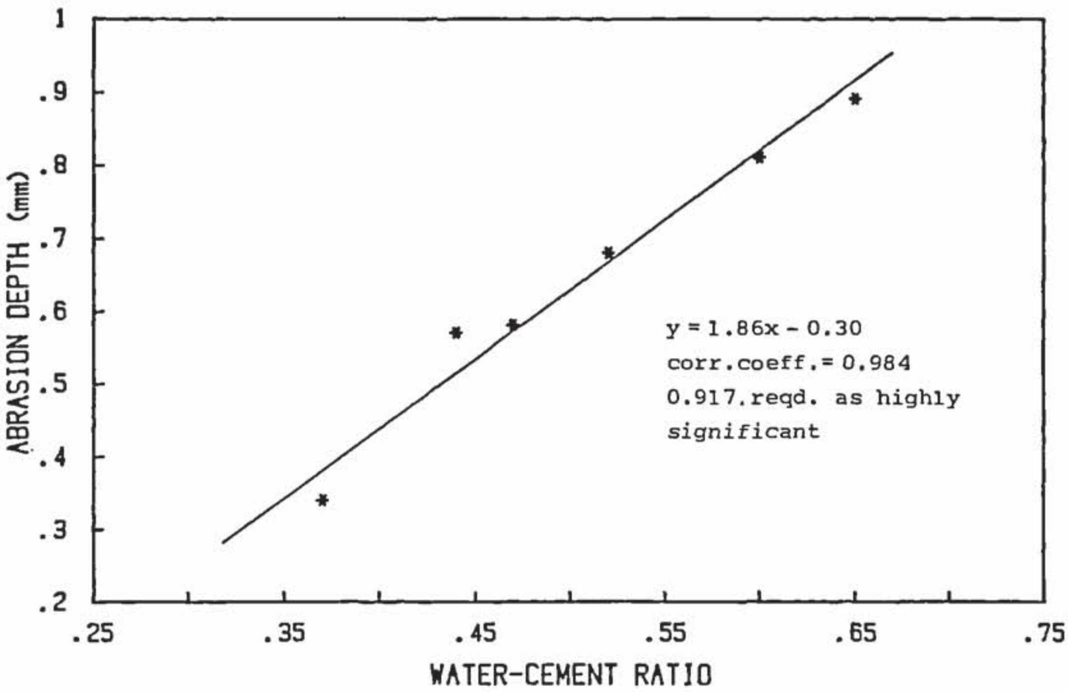



FIGURE 6.23 Abrasion Depth V's Water-Cement Ratio

Plate 6.1 Empty Mould Internally Subdivided into Six Sections, and 20 mm $\theta$ reinforcing bars in position

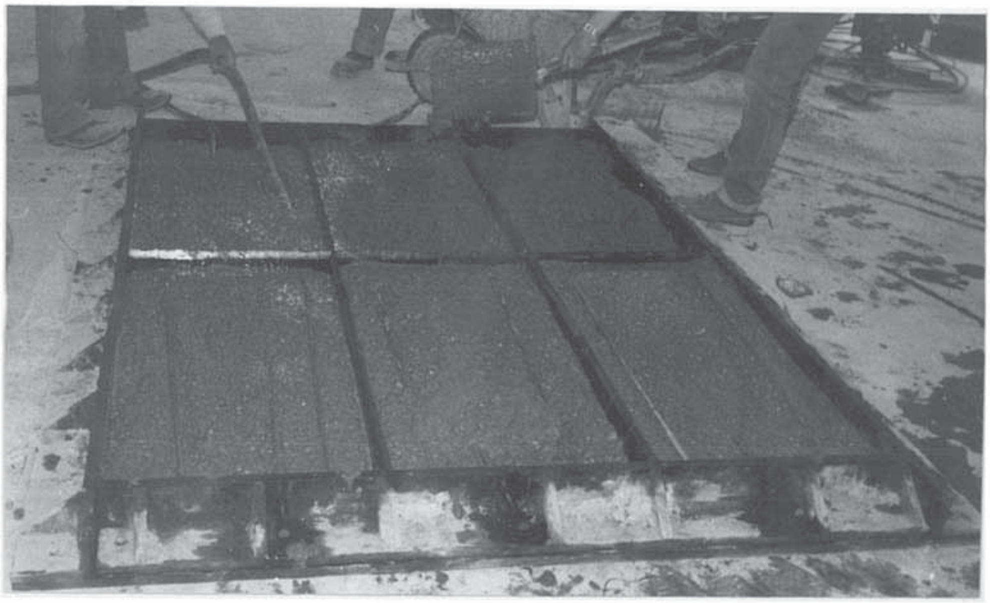


Plate 6.2 Concrete is Being Placed in the Mould and Vibrating Poker is Used for Compaction

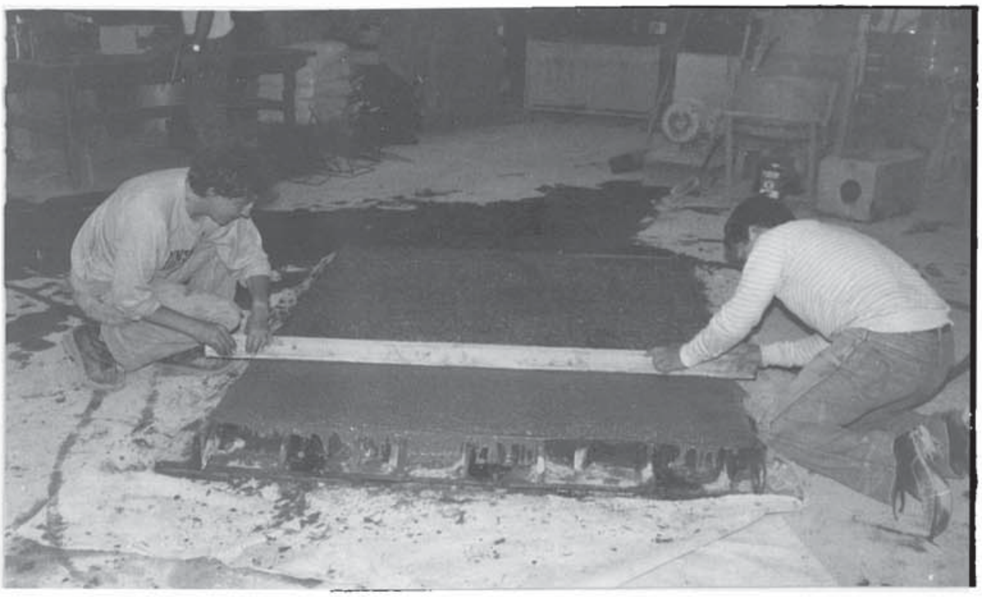


Plate 6.3 Screeding being performed by Hand-Tamping Beam Operated by Two Men

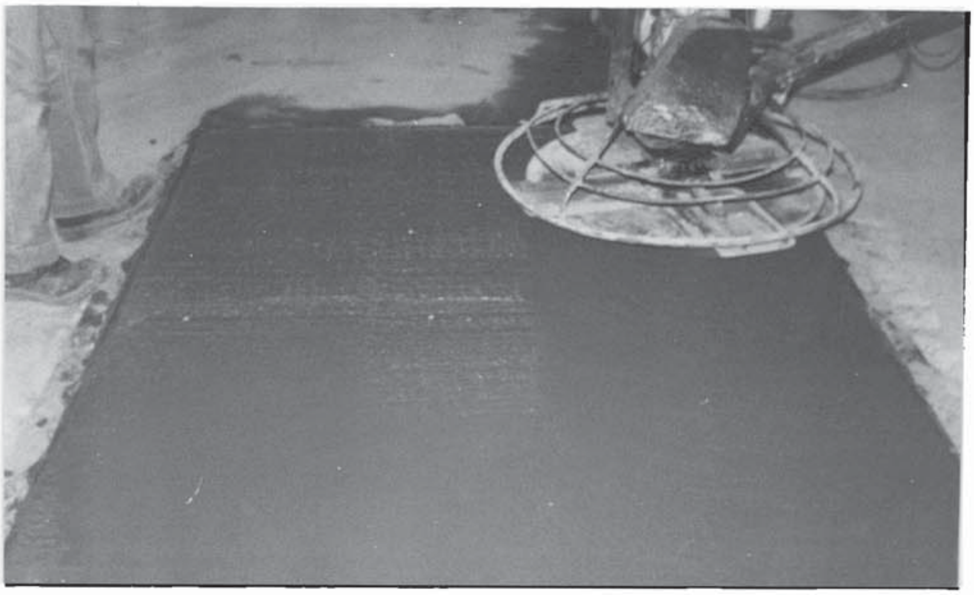


Plate 6.4 Concrete Slab is Being Floated Using Power Equipment

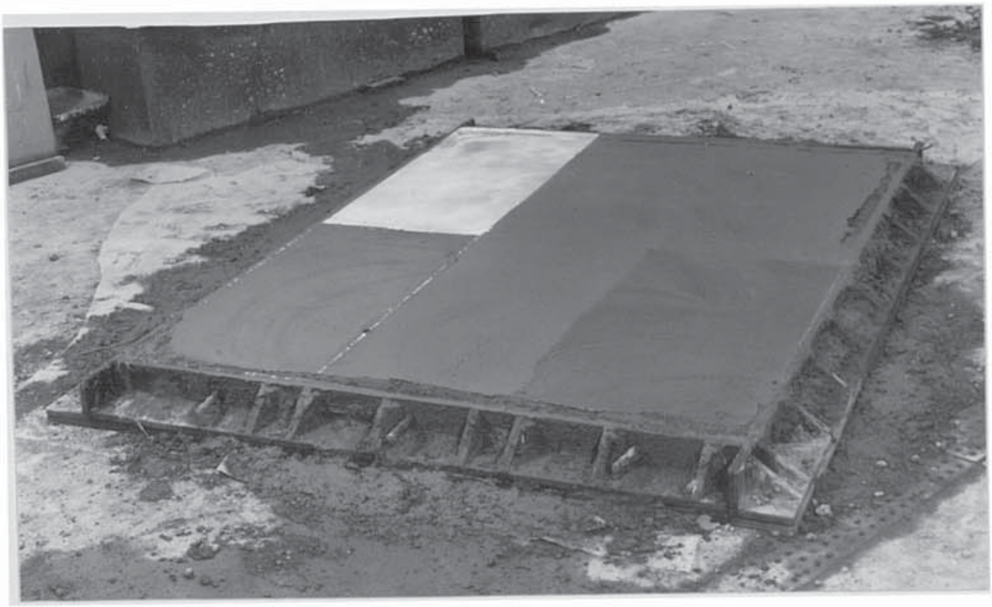


Plate 6.5 Different Curing Regimes on Each of the Six Small Slabs

Plate 6.6 Plastic Sheets Covering Edge and Bottom of Small Slabs, Ready for Storage

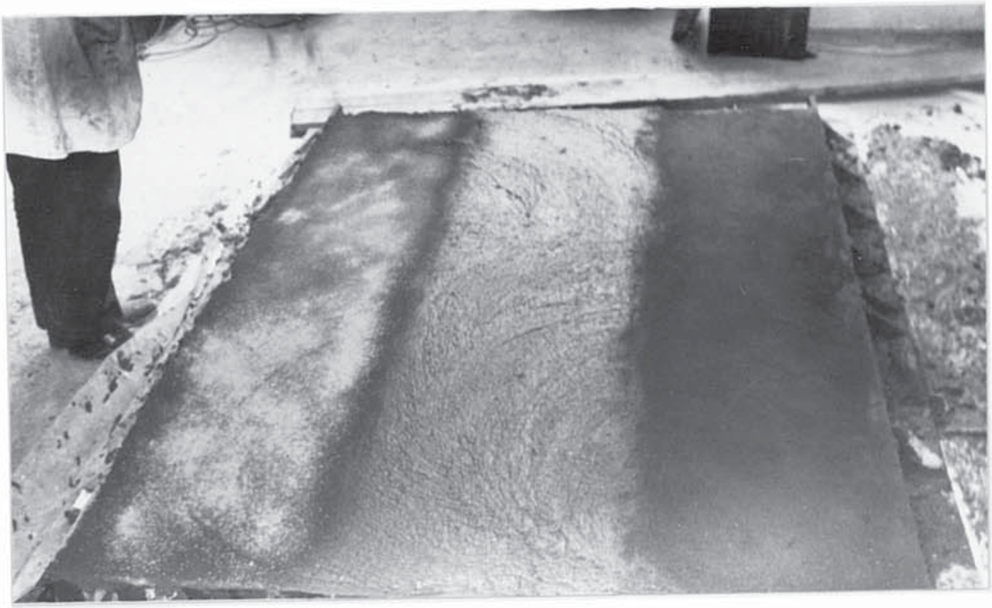


Plate 6.7    Application of Dry Shake Surface Treatment

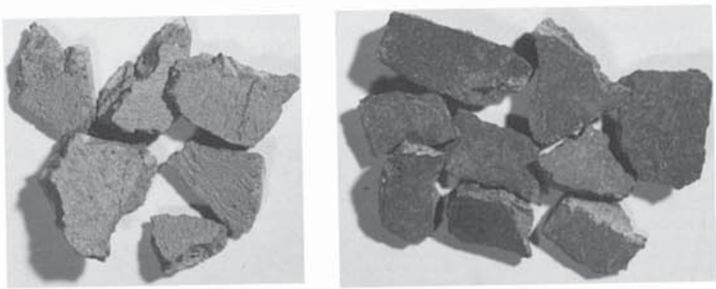


Plate 6.8    Difference Between Colour of R.P.F. and P.F. Samples

CHAPTER 7

# MICROSTRUCTURAL STUDY OF ABRASION RESISTANCE OF CONCRETE

## 7.1 Introduction

The previous chapter demonstrated that finishing technique, curing regime, and surface treatment, all influence the abrasion resistance of concrete slabs. Various mechanisms were proposed to explain the influence of these variables on the abrasion resistance. These mechanisms were related directly to the microstructure of the concrete nearest to the surface. To substantiate these mechanisms it is, therefore, necessary to examine the microstructure of the affected concrete. This was undertaken using the following methods and techniques:-

(1) Mercury Intrusion Porosimetry

(2) Microhardness Examination

(3) Scanning Electron Microscopy

(4) Petrographic Examination

(5) Differential Thermal Analysis

## 7.2 Mercury Intrusion Porosimetry Method

The determination of the pore-size distribution (PSD) of a porous solid is an important step in the investigation of the microstructure. Various techniques, including mercury intrusion porosimetry (MIP), have been used by many investigators to determine and compare the PSDs of porous materials (123-132). This programme utilized a porosimeter, Model 900/910 series supplied by the Micrometrics Instrument Corporation, which operated to a maximum pressure of 50000 psi ($350N/mm^2$). Throughout this work all the data is expressed in psi as the equipment is calibrated in psi and produces the results in this format. This was used to study the effect of finishing technique, curing regime and surface treatment on the microstructure of the concrete, particularly that of the surface layer. The MIP technique relies on the physical principle that a non-wetting liquid, forming a contact angle of more than 90 degrees with a given solid material, will penetrate the pores of the solid material only under sufficient pressure. The pressure required depends on the contact angle between the non-wetting liquid and the solid, and the surface tension of the liquid opposing its entrance into the given opening. If a cylindrical pore shape is assumed, then the pressure at which mercury enters a pore of given size can be calculated by Washburn's pressure displacement equation (133):-

$$P = -4 \gamma \cos \theta / d$$

Where $P$ = absolute pressure ($N/mm^2$)

$\gamma$ = surface tension of Mercury (N/mm)

$\theta$ = contact angle between Mercury and the material

$d$ = pore diameter (mm)

The derivation of the equation is given in Appendix G.1.

The technique involves determining the volumes of mercury that may be forced into the interstices of the material to be examined under various pressures. Firstly, the system is evacuated to remove any gases or vapours so that the mercury is free to penetrate without additional impediment. The amount of mercury which penetrates the pores is proportional to the pore size and pressure applied.

The porosimeter consists of a pressure generator, a means for determining the volume of the mercury intruded, a vacuum pump and vacuum indicator. A sample cell and reservoirs for the mercury and the pressure transmitting fluid complete the basic elements of the equipment. Further details of the equipment are given in Figure D.4, in Appendix D, and the procedure for operating the equipment is fully described in the instruction manual (134).

The main limitations for the MIP techniques may be summarised as follows:-

(1) The Washburn (133) equation assumes that the pores are all circular in cross-section but, in reality, this is not usually the case. However, the effect of this limitation should not be significant in the present study, since it only affects the calculated diameter, the shape of the PSD curve should not be appreciably different. Furthermore, the results are required for comparative purposes, with the main interest being in changes rather than the absolute values.

(2) The presence of "ink-bottle" pores, or other shapes, with constricted "necks" opening into a large void volume (124, 130) can lead to large errors in the shape of the PSD. The pore diameter calculated by the Washburn (133) equation is not truly indicative of the effective diameter of such pores, with the diameter of capillaries being too small.

(3) The compressibility of the material under test. This is particularly important for materials which have pores that do not connect with the surface, e.g. cork, as this compressibility would increase the measured pore volume.

(4) The compressibility of the mercury with increasing pressure can produce errors, and this is usually eliminated by carrying out a blank run.

(5) The assumption of a constant value for the surface tension of mercury ($\gamma$) and for the angle of contact of mercury ($\theta$). According to Rootare (135), the most reliable value for the surface tension of mercury has been obtained by Roberts (136) who reported a value of $485 \times 10^{-6}$ N/mm. The correct value for the contact angle is a matter of some debate, with the contact angles between mercury and a large

variety of materials ranging from about 112 degrees to 142 degrees (124). The value used in the present programme was 117 degrees. This value is considered to be appropriate for oven dried cement pastes (125). It should be noted that the use of an incorrect contact angle does not significantly affect the results when a porous material of the same type is being compared, as is the case in the present work.

In considering these limitations of the MIP method, it is essential to appreciate that the term "diameter" refers to what should be termed the "pore entry diameter". At the outset of a mercury intrusion test the sample is surrounded by mercury and, as pressuring proceeds, mercury flows from the surface towards the centre through whatever pores are available. Where the path that the mercury must follow, to reach a particular internal pore, is smaller in diameter than the internal pore itself, that internal pore will only be intruded after sufficient pressure is applied to intrude the narrower pathway (125). Finally, isolated pores having no communication with the exterior of the sample cannot be measured, regardless of the applied pressure. Whilst the MIP method is not perfect, it provides results which are consistent with those from other methods such as capillary condensation technique. In addition, it appears to yield more meaningful data (126,132) on the capillary pore system for cement paste than can be revealed by the scanning electron microscopy studies.

### 7.2.1 Specimen Under Investigation

#### 7.2.1.1 Finishing Technique

This study was confined to specimens cured by plastic sheeting for each concrete mix (e.g. mix B4, B5 and B6), since the results of abrasion tests, given in Chapter 6, showed that this method achieved the most constant curing conditions. Specimens removed from slabs subjected to the following finishing techniques were examined:-

(1) Hand Finishing (H.F.)

(2) Power Finishing (P.F.)

(3) Repeated Power Finishing (R.P.F.)

(4) Vacuum dewatering (V.D.)

From each of these slabs, two samples were removed for study, one from the surface matrix and one from the middle of the slab (i.e. 50mm from the top). A total of 24 MIP tests were carried out for this part of the programme.

It should be noted that 6 preliminary tests were carried out to investigate the type of sample required for the test, and to assess the reproducibility of the technique as applied in this programme.

7.2.1.2 Curing Regime

In this series of tests, the following curing conditions were included, from mixes B4 and B6, i.e. low and high water-cement ratio mixes:-

(1) Air curing (A.C.)

(2) Wet burlap curing (W.B.)

(3) Resin based, 75% efficiency, curing compound (C.C.I)

(4) Resin based, 90% efficiency, curing compound (C.C.2)

(5) Water based curing compound (C.C.3)

For each condition, samples were taken from the surface matrix of the slabs. The total number of MIP runs carried out for this part of the programme was 10. The plastic sheeting method of curing was not included as the appropriate results from Section 7.2.1.1. were used, these being for the power finished specimens cured by plastic sheeting.

7.2.1.3 Liquid Surface Treatment

As with the previous section, this was limited to specimens for mixes B4 and B6. Samples were taken from the surface matrix of surfaces subjected to the following treatments:-

(1) 20% solution of Sodium Silicate in Water (A).

(2) 20% solution of Magnesium Fluorosilicate in Water (B).

(3) 10% solution of fully reacted Methyl methacrylate/ethyl acrylate copolymer in aromatic solvents (C).

(4) 20% solution of low molecular weight aliphatic isocyanate prepolymer based moisture curing polyurethane resin in aromatic solvent (D).

(5) 30% solution of a bisphenol A/F resin and blended polyamine hardners in aromatic solvent (E).

(6) Untreated surface (O)

A total of 12 MIP runs were carried out for this part of the programme.

### 7.2.2 Experimental Procedures

The following is a summary of the procedures used for determining the PSD of the samples under investigation.

A 100mm diameter core was taken from each test slab. A 2mm thick section was sliced from the surface matrix of each of these cores using a diamond cutting wheel. These slices were broken by hand into small chunks, approximately 2-4mm wide and 5-8mm long. A special effort was made to remove as many aggregate particles as possible from these chunk samples. A similar procedure was used with the samples taken from the middle of the slab. The 100mm diameter cores were cut in half and a 2mm thick section was sliced from the bottom of the top half of the core. The size and the shape of the samples were suitable for both the adopted drying method and the size of the cell. If small samples were to be used, then considerable care would be needed in interpreting the results because interparticle void space would be included as well as the true porosity (137). However, it has been found (128) that the PSD curve for small samples is closest to the true PSD function, and so the selection of the appropriate sample size will be a compromise.

The chunk samples were oven dried for three days at a temperature of 105 degrees C. The samples were removed from the oven 30 minutes before commencing the experiment and transferred to a $CaCl_2$ desiccator, where they could cool to the room temperature in a dry atmosphere. The cool,dry chunks samples were then placed into a porosimeter cell of known weight and the complete cell weighed to the nearest 0.0001 gm in order to determine the sample weight. The porosimeter cell was able to accommodate samples of 5-6 gm. The cell was then placed in the pressure chamber. The samples and the system were evacuated for at least one hour at a pressure of 20 μm Hg to remove any gases and, subsequently, mercury was allowed into pressure vessel until it was full. A sufficient air pressure was admitted into the chamber to permit the mercury outside the sample cell to drain out. The pressure vessel was evacuated again and the sample was then ready for testing.

The pressure was gradually increased to atmospheric and the volume of mercury penetrating the sample was measured with a digital counter which was transferred into volume as shown in Appendix G.2. The system was filled with a pressure transmitting fluid and a pressure above atmospheric was applied using compressed air. Errors due to the compressibility of the mercury were corrected by carrying out a blank run using only mercury.

### 7.2.3 Results and Discussion

The PSD data are presented in the form of cumulative pore-diameter distribution curves, shown in Figures 7.1 to 7.11. In these the pore volume (volume of penetrated mercury), expressed in millilitres of pore per gramme of oven dried sample, is plotted against the applied pressure, expressed in psi. Using the Washburn equation, this pressure can be converted to a pore diameter, expressed in microns. It is usual practice to represent the applied pressure/pore diameter on logarithmic scale. This is for convenience, since, with pressure ranging from 1 to 50000 psi, the diameters range from a few tens of Angstroms to several micrometres. The logarithmic abscissa has, therefore, no influence over the data processing or the resulting PSDs. It is possible to present the data in other forms, such as the plot of differential distribution function d(volume)/d(diameter) against diameter. No real advantage results from presenting the results in this form, and there may be some disadvantages. With a differential presentation, distortion may result when the range of diameters covers several orders of magnitude as it vastly overemphasises the apparent importance of the finest pore sizes at the expense of the coarser sizes (125). The advantage of the cumulative distribution curve is that it readily reveals:-

(a) Total volume of mercury intruded.

(b) The pore volume in any pore range.

(c) The median pore diameter, the diameter for which 50% of the pore volume is greater and 50% is smaller.

(d) The mode pore diameter, corresponding to the region of steepest slope.

The cumulative distribution curve also show the "threshold diameter", which is defined (125) as the diameter above which there is comparatively little intrusion into the sample, and immediately below which the greatest portion of intrusion commences.

The PSD curves include the distribution of both voids and pores. The void space is included since the measured volume necessarily includes that of any space existing between the components of the test samples. It is, therefore, suggested that for pressures below 100psi, the PSD may be distorted by this void space and so should be discarded. Furthermore, this factor makes it very difficult to determine the initial pore entry diameter.

In the preliminary work two forms of samples were investigated, the chunk sample (as described in Section 7.2.2.) and slice samples. The slice samples were 2mm thick, 5mm wide and some 10-15mm long. With the chunk samples, efforts were made to remove any visible aggregate particles but, with the slice samples, no effort was made to remove the aggregate. The resulting PSD curves, given in Figure 7.1, indicate that with the chunk samples there was an increase in the indicated pore volumes. This can be attributed to a reduction of aggregate in the chunk samples and, additionally, to the slice samples being too large to reveal all the pores due to some of the pores not having an external opening. The PSD curves have been obtained from single samples representing each condition under investigation. It was decided to only test single samples as work by other investigators (125,131) had demonstrated that the test is reproducible. The preliminary work and the results of the main investigation show, Figures 7.1 to 7.11, that the MIP technique produces results which are consistent. This confirms the findings of other researchers (125,131) investigating cement paste.

The samples were subjected to MIP tests at approximately 120 days after the slabs were cast. During this period the slabs had been stored in the laboratory. This exposure to the atmosphere could have influenced the PSDs due to carbonation. Although this was not checked, it is suggested that all the samples were affected in a similar manner. It is also recognised that the particular drying process would cause some modification to the pore structure and this is discussed further in Section 7.2.3.2. An example calculation of

PSD is given in Appendix G.2. Detailed discussion of these results is considered in the following section, under the appropriate headings.

#### 7.2.3.1 Finishing Technique

The PSD curves obtained from the 24 samples are illustrated in Figures 7.2 to 7.5, for each mix - B4, B5 and B6 - the curves for the hand finishing, power finishing and repeated power finishing samples are provided in one graph, Figures 7.2 to 7.4, for ease of comparison. In each of these graphs there are six PSD curves, three are for the samples from the surface matrix (top 2mm) and three for the samples from the middle of the slabs, and they cover the three finishing techniques. The PSD curves for the vacuum dewatered samples for the three mixes are shown in Figure 7.5. This graph also includes six curves, three for samples from the surface matrix (top 2mm) and three for samples from the middle of the slabs.

The following observations have resulted from examining the general form and appearance of the PSD curves shown in Figures 7.1 to 7.4:-

(1) There is a systematic change in the PSD curves of the surface samples with the general distribution shifting to the right with the application of mechanical surface finishing equipment (e.g. P.F.and R.P.F Samples), that is, the pores become increasingly finer.

2) The PSD curves of the samples taken from the middle of the slabs of a given mix, are generally very similar, indicating that the pore structure of the middle of the slab has not been influenced by the application of mechanical surface finishing equipment. On this basis, it also indicates that the MIP method produces reproducible results.

(3) The PSD curves for hand finished (H.F.) samples were generally very similar to those of the samples taken from the middle of the slabs, this indicates that hand finishing did not significantly

influence the pore structure at the surface.

(4) The total pore volume intruded decreased with the application of mechanical surface finishing equipment, Table 7.1.

(5) The initial pore entry diameter generally decreased with the application of the mechanical surface finishing equipment. This is shown most clearly in the samples subjected to repeated power finishing.

(6) These curves indicate that the "threshold diameter", was displayed in all cases but was lowest in the repeated power finished samples, e.g. see Figures 7.2, 7.3, 7.4, Curve No. 6 in each case.

(7) The median and mode pore diameter for the repeated power finished sample are less than those of either power finished or hand finished samples in all three concrete mixes.

(8) The application of repeated power finishing (R.P.F.) appears to have reduced both the coarse and fine pores in the surface matrix of the concrete slab.

(9) The PSD curves for the samples taken from the middle of the slabs clearly show that mix B6, with the highest water-cement ratio, had both the highest total pore volume, and the coarsest PSD. In comparison, mix B4, with the lowest water-cement ratio, has the least total pore volume with the pores becoming increasingly finer. This confirms the findings of other investigators (125,126,129) that the PSD is a function of water-cement ratio. However, it is apparent that this distinction between the curves from the three mixes was not so marked with the samples taken from the surface matrix due, largely, to the application of the individual finishing techniques. Indeed, the PSD curves for the repeated power finished samples for all three mixes are generally very similar both in form and in the total pore volume intruded.

These results have been used to prepare Figure 7.12, which shows the relationship between total pore volume and abrasion depth for the three finishing techniques and the three concrete mixes. It is clear from this relationship that the abrasion resistance varied directly with total pore volume. This supports the hypothesis presented in chapter 6 to explain how the application of the finishing technique improved the abrasion resistance.

The cumulative distribution curves for the vacuum dewatered samples are shown in Figure 7.5. These were compared with each other and with those of Figures 7.2 to 7.4 and the following observations may be made:-

(1) The PSD curves for samples taken from the middle of the vacuum dewatered slabs displayed larger total pore volumes (see Table 7.1) and initial pore entry diameters, than the equivalent slabs which were not processed by the vacuum dewatering technique (e.g. power finished samples). Furthermore, it is clear that there are more coarser pores present in the processed slabs, which indicates that vacuum dewatering increased the porosity of the middle section of the slabs.

(2) It is clear that both the total pore volume and the initial pore entry diameter of the surface matrix of the processed slabs are smaller than those from the middle of the slab. This suggests that the mechanical finishing equipment was able to eliminate most of the pores created in the surface matrix by the vacuum dewatering process. However, this vibratory disturbance does not appear to have been as effective in reducing the pores created by vacuum dewatering at the middle section of the slab.

(3) A comparison of the curves obtained from the surface matrices of the processed and unprocessed slabs (e.g. P.F.) shows that the total pore volume and the initial pore entry diameter of the processed slabs are significantly lower than those of the unprocessed slabs. This

suggests that the application of power finishing equipment eliminated the detrimental effects of vacuum dewatering and enhanced its primary purpose of reducing the water content.

(4) The PSD curves of the samples taken from the surface matrix of the processed slabs for the three different types of concrete mixes are generally very similar to each other. This indicates that the structure of the surface matrix of the specimen slabs of the three mixes become very similar after the finishing treatment, implying that, at the surfaces their resultant water-cement ratios were of similar magnitude.

It was noted that the total pore volume of the middle of the processed slabs was generally greater than those of the unprocessed slabs, but in Chapter 6 the results of the core crushing tests indicated that the crushing strength of the processed cores was higher than those of the cores from the unprocessed slabs. These results are not consistent with the accepted view that increased porosity reduces compressive strength. It is suggested that the action of power equipment reduced the porosity of the sections which were most affected by the vacuum processing (maximum being at the surface and minimum being at the bottom of the slab). The porosity of the processed slab near the surface was, therefore, less than that of the unprocessed slab, but near the middle of the slab the porosity of the processed slab was greater than the unprocessed slab, while near the bottom the porosity of both slabs would be very similar. It is, therefore, suggested that the overall porosity of the unprocessed slabs was greater than that of the processed slabs. This suggests that the results obtained are consistent with the fact that porosity controls compressive strength. However, further investigations are required to determine the distribution of porosity throughout the slab, due to vacuum treatment.

The results in Figures 7.2 to 7.5, together with the experimental observations, confirm generally the validity of the hypothesis presented in the previous chapter, suggesting that:-

(a) The abrasion resistance of concrete is controlled by the pore structure of its surface matrix.

(b) Finishing techniques influence the pore structure of the surface matrix of the concrete slabs.

Further study is necessary to confirm these results and to determine the thickness of the surface layer of concrete which is influenced by the different finishing techniques.

7.2.3.2 Curing Regime

The cumulative distribution curves for the six curing regimes and two concrete mixes are shown in Figures 7.6 to 7.7. From these curves the following observations have been noted:-

(1) The PSD curves are similar in form and very close together.

(2) The air cured samples exhibit greater total pore volume and higher initial pore entry diameter than those from the other curing regimes.

(3) The P.S. and W.B. samples show both the least total pore volume and the lowest volume of fine pores in mix B6 but, in mix B4, the P.S. sample shows high initial pore entry diameter and higher volume of coarser pores, while the W.B. sample again shows both the lowest total pore volume and initial pore entry diameter.

(4) The samples cured with curing compounds generally display a lower content of coarser pores and a low initial pore entry diameter, as compared with the air cured sample. However, they also contain relatively large amounts of the finer pores and have higher total pore volumes than the P.S. and W.B. samples, the exception being mix B4,

(5) The PSD is a function of degree of hydration (125) and so it was expected that the variation in the PSD curves, due to different curing regimes, would have been much more pronounced than reported in the present study, particularly with the air cured samples.

The total pore volumes have been abstracted from Figures 7.6 and 7.7 and are presented in Table 7.2, together with the abrasion resistance results. As reported in Chapter 6, the specimens treated with the curing compounds generally exhibited lower abrasion depths than the specimens cured by wet burlap and plastic sheeting, but the curing compound samples also display higher total pore volume than either the wet burlap or plastic sheet cured samples. The abrasion test results may have been influenced by traces of the curing compounds remaining on the specimen slabs at the time of abrasion test, and this was commented on in Chapter 6. Furthermore, the procedure used in the MIP method may have influenced the results. The main reasons that the MIP method was not as sensitive to variation in curing conditions as it was to variation in finishing techniques may be summarised as follows:-

(1) The surface samples were taken from the top 2mm of the slab. Those samples treated with curing compounds may have been contaminated with the particular curing compound and, therefore, this would have influenced the results of both the MIP tests and the abrasion tests.

(2) The drying technique used would have influenced the pore structure. This would not have a major influence on the relative results of the finishing technique samples since only one type of curing regime was used (i.e. P.S. method). In the present part of the study, however, different curing regimes were used and the drying technique may have influenced the various samples in different ways.

(3) Contamination due to the curing compound and the drying technique may have affected the contact angle θ which could have influenced the MIP results. As suggested previously, the value of θ is not important for comparative purposes, as was the case in the finishing technique samples, but in this case, and also for the liquid surface treatment samples, the various chemicals may have affected the contact angle in different ways.

The sensitivity of the MIP method may be increased for studying curing conditions if:-

(a) The MIP test is carried out soon after the abrasion test.

(b) The top 1mm of the surface matrix is ignored and the next 2mm of the matrix is used as a sample.

(c) A vacuum drying technique (138) is used for preparing the samples.

If the results of the specimens cured by curing compounds were to be ignored, then it is suggested that the MIP method, although suffering from procedural deficiencies, was capable of describing the microstructure of the surface matrix of the samples, and these results were generally consistent with those of the abrasion tests. In conclusion, it is suggested that the results of the MIP method show promise, and that there is a need for further study to confirm and substantiate the trends found in the present investigation.

7.2.3.3 Liquid Surface Treatments

The PSD curves obtained from the 12 samples subjected to the MIP test in this phase of the work are shown in Figures 7.8 to 7.11. In addition, Table 7.3 provides values of the maximum penetration volume, together with the abrasion depth results for these surface treated samples. From the PSD curves in Figures 7.8 to 7.11, the following observations have been noted:-

(1) Generally, the PSD curves for the samples treated with the in-surface seal - treatments C, D and E - appear to have lower proportions of both the coarse and fine pores, and lower total pore volumes, as compared to the control sample.

(2) The PSD curves of the samples treated with surface hardeners - treatments A and B - do not appear to follow a general trend. With mix B4, the sample treated by the solution of sodium silicate (A), a higher volume of both coarse and fine pores than the control sample was observed, while the sample treated with the solution of magnesium fluorosilicate (B) has a PSD curve very similar to that of the control sample. However, with mix B6, both of the treated samples display reductions in the volume of fine pores, but with similar distribution of coarse pores, compared with the control sample.

From Table 7.3, it is clear that the various liquid surface treatments have influenced the abrasion resistance of the slabs much more sigificantly than they have influenced the total pore volume. A similar observation was recorded with the curing regimes in the previous section. Furthermore, the total pore volume of the samples treated by the in-surface seals are in general agreement with the abrasion resistance results, with a reduction in the total pore volume being accompanied by an increase in the abrasion resistance. This trend, however, is not apparent with the samples treated with surface hardeners.

As with the MIP test carried out in the previous section, these results may also have been influenced by the particular test procedures. It is suggested that the following factors need to be considered:

(1) The specimen slabs were treated by the various liquid surface treatments 25 days after casting, but the MIP tests were carried out

approximately 120 days after casting. During this time the effectiveness of the various surface treatments may have been reduced, this being particularly so with the surface hardeners, the results of which were very inconsistent.

(2) The drying process may have influenced the chemical components of the treatments, and so other drying techniques would have been more appropriate, such as vacuum drying mentioned in the previous section.

(3) The test samples, although only 2mm thick, may have been too thick to detect changes in the pore structure of the surface matrix arising from the individual treatments. It is suggested that, where the penetration depth was only very limited, the 2mm samples may have been insensitive to changes in the pore structure which would only have influenced a very thin layer. Thus, thinner sections, taken at various depths below the surface, may reveal more valuable information.

The trend of the present results appears to indicate that the pore structure of the surface matrix of samples treated with in-surface seals have been modified by such treatments. However, there is little consistent evidence to suggest that the pore structure of the surface of samples treated with surface hardener was appreciably modified. It is concluded from these observations that further, extensive investigations are necessary to substantiate the trends identified in the present results.

#### 7.2.3.4 General Discussion

It must be appreciated that the results of this study should not be considered as conclusive, since the PSD curves were obtained from single samples. Even so, the results clearly demonstrate that the MIP method can be a valuable technique for investigating the abrasion resistance of concrete. Due to the pioneering use of the MIP method in this field and the limitations on time, it was not possible to re-design the test procedure to make it more appropriate for the particular investigation. For example, these could have included using different sample thicknesses at different depths below the surface, and different drying tehniques. However, the findings point to modified procedures which may be fruitful in future investigations.

The most important conclusion is clearly that the MIP technique is capable of detecting quantitatively the influence of factors which affect the abrasion resistance of concrete. The implication of this being that, it is possible to determine quantitatively the extent and the depth to which various factors influence the surface matrix of the concrete slab. The results obtained clearly show that porosity is the major factor in controlling abrasion resistance, and that the abrasion resistance may be related to the total porosity. This could be developed to provide a means of predicting the pore volume and abrasion resistance.

## 7.3 Microhardness Technique

This technique has been used by many investigators, both for the study of metals (139), and non-metallic materials (21-22,140-144). The general approach has been to relate microhardness to various physical properties of the individual material. In particular, the microhardness of cement paste has been shown (142-144) to correlate with the strength, modulus and porosity of hydrated cement. Other investigators, (21-22), have been able to correlate the microhardness with the wear resistance of aggregates. In view of these findings, and the implication that microhardness could be used to compare the microstructure of different concrete specimens, this method of investigation was included in the programme.

The indentation hardness is defined (145) as the ratio of the applied load, in Kg, to the surface area of the indentation, in $mm^2$. In this method, a diamond indenter is depressed into the surface of the material being tested, under a given load. The size of the resulting indentation is measured and the microhardness expressed as the ratio of the load to the superficial area of the impression, in $Kg/mm^2$. The particular equipment was a Vickers M12, a microhardness tester, which consisted of a square-based pyramid of diamond, the included angle between opposite faces being 136 degrees. The shape of a perfect Vickers impression was thus that of a square, and the superficial area of the four faces of the impression is $d^2/2 \sin 68^o$, where d is the indentation diagonal of the square in microns,

$$\text{Hardness, } H = \text{Load/Area}$$

Then Vickers microhardness number $H_v = \frac{2 \sin 68^o P}{d^2}$

Where P is the applied load in gm.

The indentation diagonal was measured by means of an optical system provided within the microhardness instrument. Standard tables, prepared by the manufacturers, were used to determine the Vickers microhardness number.

### 7.3.2 Specimens under Investigation

The results of the MIP analysis clearly indicated that the finishing technique influenced the PSD of the concrete in the surface matrix of the slabs. It was considered that microhardness profiles, from the surface matrix into the core of the concrete specimens, could provide further insight into the mechanisms by which the individual finishing techniques increased the abrasion resistance. A detailed study was, therefore, undertaken of the microhardness profiles produced by the following finishing techniques:-

(1) Hand finishing (H.F.)

(2) Power finishing (P.F.)

(3) Repeated power finishing (R.P.F.)

Samples were taken from three concrete mixes, B4, B5 and B6, all of which had been cured by plastic sheeting (P.S.). Three samples were taken from each slab to produce a total of 27 samples to be investigated.

Due to the results of the MIP analysis, and the time limitations, it was possible to undertake only a preliminary microhardness study of the surface treated specimens. In this study, one sample was taken from each slab for the microhardness investigation so 6 samples were tested.

In order to determine the microhardness profiles, indentation readings were recorded at the following locations below the surface of the samples: 0, 0.25, 0.50, 0.75, 1.00, 1.50, 2.00, 3.00, 5.00, 8.00, 12.00 and 16.00 mm.

### 7.3.2 Experimental Procedures

The 100mm diameter cores taken for the MIP investigation also provided the samples for this study. Three samples were cut, using a diamond cutting wheel, from each core. Each sample was cut from different locations in the core, these being selected on the basis that they should contain a minimum of exposed aggregate area. The samples were cut parallel to core axis from the top 20mm section of the core. The face area of each sample was approximately 20 mm by 20 mm and they were 5mm thick. Each sample was embedded in Araldite resin Hy 753 and Hardener H 951. The embedded samples were polished using the rotating lap and grit (grit size 400 to 1200), similar to the polishing procedure described by Barringer (146).

Concrete may be considered as porous and heterogeneous and so the microstructure involves a wide range of particle sizes and pore sizes.

For the microhardness measurement to be representative it must include a significant number of particles and pores, and so it was decided to test three samples from each slab. Earlier studies (147) have concluded that the error in microhardness values was considerably reduced as the number of indentations was increased. This study indicated that the optimum number of impressions is ten for a non-porous material and, so, for each test location a minimum of ten impressions was used. It was considered that this procedure would provide a reasonably complete range of microhardness values for the location under investigation. The samples were subjected to microhardness investigation approximately 150 days after the slabs were cast, and the procedure is described below.

The polished specimen was placed on the graduated moveable stage, so that when the stage was moved in the X direction, under the objective, the surface of the sample could be scanned, i.e. the surface moved in parallel with the objective. Two micrometer screws, at right angles to each other, allowed a network pattern of impressions to be conducted. For each level, thirteen readings were recorded, these were distributed across the width of the sample at the same level. The position of each indentation was selected on the basis that it should not be over an aggregate particle. Initially, the low-power objective was used to select the approximate position, with the high-power objective subsequently being used to select the precise point for indentation. The accuracy of this procedure is about 1-2 µm.

An appropriate load was selected within the range of 50 grams to 200 grams. Small loads produced small indentations with which large optical measuring errors may occur leading to large errors in the microhardness value. The load was, therefore, selected to produce an indentation with a minimum diagonal of 100 μm. The period of indentation was kept constant in all tests, at 15 seconds, for it has been reported (148) that there is a gradual increase in the size of the indentation with time. The lengths of the diagonals of the impression were accurately measured, twice, using the optical micrometer eyepiece and the high-power objective.

The readings at the surface level, 0.00 mm, were in fact 4 μm below the surface. This was to ensure that diagonals of the impression were wholly within the sample, and any which were partly located outside the test sample were rejected. The impressions were not made adjacent to any visible voids, and were kept at least 5 diagonal lengths apart to prevent mutual interference. Any impression which developed signs of cracking or fracturing was rejected for measurement purposes. In a perfectly plastic material the Vickers indentation should, theoretically, be a perfect square. In the present study very few of the indentations were ideal squares, and where the length of the diagonals differed by more than 5%, the measurements were discarded. The three highest readings were rejected, on the assumption that they were probably taken on aggregate particles which had not been detected. The mean Vickers hardness value for any particular level was, therefore, the average value obtained from the remaining ten indentations.

### 7.3.3 Results and Discussion

The microhardness measurements of porous material have been found by Sereda (143) to provide meaningful information on the mechanical behaviour of the material. Indeed, these measurements are as significant for porous material as they are for non-porous materials. It is, therefore, useful to investigate whether links can be found between the microhardness and the abrasion resistance of concrete.

The microhardness profiles for each of the finishing technique samples, together with the range of values of the Vickers hardness measurements, are provided in Figures H.1 to H.9 of Appendix H. The largest coefficient of variation for the Vickers hardness results was 15.5%. A summary of these profiles has been plotted on one graph, Figure 7.13, to permit comparisons. Of particular interest is that the microhardness profiles provide assessments of the hardness throughout the surface layer, to a depth of 16 mm, which may be used to assess the effectiveness of the finishing techniques and the thickness of the affected zone.

From an examination of the hardness profiles in Figure 7.13, several important trends are apparent. The hardness values from mix B4 are higher than those of mixes B5 and B6, and so indicate that the technique was sensitive to variations in the water-cement ratio. Specimens treated with mechanical equipment generally displayed higher value of hardness than those which were hand finished. Furthermore, those specimens subjected to repeated power finishing registered the highest hardness profiles. These hardness profiles clearly demonstrate that the technique was able to detect the influence of the finishing techniques. Indeed, the hardness profiles of the hand finished samples show that they possessed very weak surface matrices. The layer 1mm below the surface of these slabs displayed higher hardness than that of the surface, which implies that there was a local increase in the water-cement ratio.

The hardness profiles for the power finished (P.F.) samples indicates the hardness of the surface matrix has been increased, compared to that of the hand finished sample. The application of power finishing appears to have resulted in a more uniform surface matrix than the hand finished sample. The magnitude of this increase is greatest at the immediate surface, with the influence of power finishing diminishing with increase in the depth below the surface. At a depth of around 8 mm, the hardness of the power floated slabs was very similar to that of the hand finished slabs. The hardness profiles of the repeated power finished (R.P.F.) samples clearly demonstrate that repeated power finishing significantly increased the hardness of the slab and, in particular, the hardness of the top few mm of the surface matrix has been greatly increased. The hardest part of the R.P.F. sample profiles is between level 0.00 mm and 1.00 mm, while, with the H.F. samples, this region appears to be the softest part of the hardness profile. The influence of repeated power finishing on the hardness profiles appears to diminish with the depth below the surface to a depth of 5.00 mm, at which point the rate of decrease is very low. However, the effect of repeated power finishing is clearly apparent even at 16.00 mm below the surface.

By comparing the hardness in Figure 7.13, and the rate of abrasion graphs, Figures 6.1 to 6.15, it is clear that the abrasion resistance is controllled by the hardness of the surface layer, some 200-500 microns in thickness. These results are summarised in Figure 7.14 where the abrasion depth, obtained with the various finishing technique (H.F., P.F., R.P.F.) are plotted against the microhardness values at the surface of each slab. This graph shows that abrasion resistance is directly related to microhardness of the sample. A surface matrix with high value of hardness leads to a very low rate of abrasion as is demonstrated by the repeated power finished (R.P.F.) samples. Alternatively, where the immediate surface had a low value of hardness, then a high rate of abrasion resulted, as was the case with the hand finished (H.F) samples. Once this immediate surface matrix had been penetrated the sample has effectively failed so far as abrasion resistance is concerned, therefore, the main objective in increasing the abrasion resistance of concrete must be to reinforce this top surface matrix which is less than 0.5 mm in thickness.

It is accepted that the technique developed for obtaining microhardness profiles may be questionable, with regard to minimising the influence of the aggregate.However, it has been reported (31,38,62,66), that no correlation exists between the abrasion resistance of concrete and the quality of aggregate, although when the concrete mix is of low quality or compressive strength, the quality of the aggregate may become more important (38). This implies that, primarily, it is the surface matrix which controls the abrasion resistance and only when this matrix is penetrated does the influence of aggregates become apparent. The implication of this is that the influence of aggregate is secondary.

It has been found (149) that the microhardness indentation of a non-porous material produces a plastic deformation which has been observed as a barrel-shaped indentation due to the accumulation of debris at the centre of the pyramidal faces. In the case of a porous material this accumulation is not observed, since the disturbed material can be accommodated by the pores (143). For a given porous material the strength is a function of porosity, (150) and so a reduction in porosity should produce an increase in the hardness value. On this basis it is suggested that the hardness profiles are consistent with the results of the MIP tests. This is further supported by the relationship shown in Figure 7.15, where the total pore volumes, obtained from the MIP tests, are plotted against the microhardness values at the surface. The graph shows a direct relationship between porosity and microhardness. This finding is consistent with the conclusion reached by other investigators (142-144), linking the microhardness and porosity of cement pastes.

The mechanisms, presented in Chapter 6 to explain the influence of different finishing techniques, basically proposed that these procedures influenced the water-cement ratios and the density of the layer nearest to the surface. The results of the abrasion tests clearly showed that the rate of abrasion was dependent on finishing technique. Both the MIP and microhardness tests have demonstrated that the individual finishing techniques produced significant changes in the quality of the surface matrix of the slab. The MIP results showed that the PSDs were modified by these finishing techniques, suggesting that the effective water-cement ratio of the surface layer had been reduced through the application of the various finishing techniques. The microhardness results also showed that the hardness depended on the finishing technique and that the benefits from these techniques also influenced the concrete immediately below the surface layer. This further confirms that the different finishing techniques resulted in production of layers with reduced porosity. It is suggested that the abrasion resistance of concrete is primarily controlled by the porosity of the surface layer, and from the present work, this layer appears to be less than 1 mm thick.

The microhardness tests carried out on the surface treated samples did not reveal any significant differences between the various treated and untreated samples. As the preliminary results were not encouraging, with only one sample being tested from each slab, the results have not been included. It is considered that this apparent inability to distinguish between treated and untreated samples may be due to the hardness tests being carried out on sections perpendicular to the surface of the slab. If the various treatments only had limited penetration into the slabs, they are unlikely to influence significantly the results of the microhardness test. It is probable that the sensitivity of the technique could be increased by conducting the microhardness tests on the actual surface which received the treatments. A profile could be obtained by progressively testing different layers at various locations below the surface. This could not be accommodated in the present study but should be incorporated in future work.

## 7.4 Scanning Electron Microscope

The Scanning Electron Microscope (SEM) has been used by many investigators (151-154), and it has proven to be a particularly useful tool for determining the structure, origin of strength and fracture behaviour of hydrated cement (153,154). It was, therefore, appropriate to consider this technique in the present investigation.

Samples were taken from the finishing technique slabs which had been used in the MIP investigation. A 2mm thick slice was cut, parallel to the surface, from the surface matrix of each slab. These slices were oven dried and, prior to the observation they were broken into small pieces approximately 2mm thick by 5mm by 10mm, so that samples with freshly exposed surfaces could be used. The examination was confined to those faces which contained a 2mm thickness of the surface matrix. The samples were mounted on aluminium stubs and coated with a thin conducting film, about 250 Angstroms thick, of carbon to carry the incident electrons away to earth. The samples were examined with a "Cambridge Stereoscan 150" scanning electron microscope and photographs were taken at various magnifications over the range of (1000X) to (5000X).

Generally, the examination of the samples from the finishing technique specimens, did not produce reliable evidence which could be used to confirm, or contradict, the results obtained by MIP method and microhardness technique, or to further the knowledge of microstructure of the specimens. The main problem was that the results were very dependent on the location at which the micrographs were taken. When the samples were scanned, different morphologies were observed on the same sample and a typical morphology was not found which could be attributed to the use of particular finishing techniques. It would have been possible to "select" an area which would show well-defined morphology but this would have comprised only a very small percentage of the sample. This is the main difficulty with micrographs produced by the SEM and has been noted and criticised by other investigators (155). Three of the forty micrographs taken are shown in Plate 7.1. These micrographs were taken from mix B4, for H.F., P.F., and R.P.F. samples respectively, and they are sufficient to demonstrate that very little real difference was observed using the SEM.

An alternative method, which could produce more reliable results, was considered. This is to impregnate the samples with a low viscosity resin containing trace-metal ions and, using X-ray mapping, it might be possible to trace the concentration of the metal which has impregnated the pores. Thus, those samples with high volume of pores would have higher concentrations of metal and those with low volume of pores would have much lower concentrations. This technique was not employed in the present study but, again, it presents a promising technique for future investigation.

## 7.5 Petrographic Examination

Petrography involves the identification, systematic description and geological classification of rocks. Similar techniques have been used to provide valuable information concerning the characteristic minerals and structures occuring within concrete (156-159). A frequently used technique is the examination of thin sections coupled with the quantitative determination of the different components of rocks (framework grains, pores, cement) by microscopic methods. Point counters of various kinds have been used for this purpose. In the present study, thin sections have been employed to conduct examinations of the specimen slabs.

### 7.5.1 Preparation of the Impregnated Sections

The 100 mm diameter cores which were obtained for MIP were also utilized for this investigation. Thin sections were prepared from the various specimen slabs to examine the effect of finishing technique, curing regime and liquid surface treatment. Thin slices, from the core samples, were impregnated with a green-dyed araldite resin prior to the preparation of the thin sections.

The resin was araldite CY 212 and HY 951 hardener together with green dye. The green dye enabled easier identification of the pores and allowed visual estimation of the percentage porosity in the thin section. Each thin section was taken parallel to the axis of the core and the 30 micron slice was mounted on to a glass slide.

### 7.5.2 Results and Discussion

Thin sections may be used to calculate pore volumes by a microscopic method. To minimize errors, about 8-10 photographs are taken over an area of approximately $4mm^2$. From these photographs the porosity is determined by means of measuring the pore space area. This was done with a Hewlett-Packard 9825A Desktop Computer and 9874A Digitizer. The area of each pore space was measured by tracing its boundary by moving a cursor around the edge of the close figure. The coordinate of each point upon which the cursor moved was recorded and converted into area by the computer. The total area of pore spaces was calculated from the integration of the separate areas of pore spaces. The area measurements are considered to represent volume according to Delesse's area-volume relationship (160).

This procedure was used for only a few samples, because the accuracy of the method did not warrant the time and the expense involved. The point count estimates of pore volume from thin sections have been found to be inaccurate, often by more than 100 per cent (161). The errors result from the abundance of micro-pores which are not easy to trace even with high magnification. In addition, the standard thin sections introduce edge effects, due to grain curvature, that overestimate cement and aggregate volume and underestimate pore volume. The qualitative observations from the prepared thin sections generally, confirmed the test results and so no real advantage resulted from an estimation of pore volume using the point count method. It was decided, therefore, to confine this work to a detailed visual inspection of the photomicrographs, which are shown in Plates 7.2 to 7.4. These are of the top 20mm of each slab and relate to the various finishing techniques (H.F., P.F., and R.P.F.) with all three mixes.

Visual inspection of these photomicrographs generally shows that the intensity of the green dyed resin is greatest in the H.F. samples, particularly nearest to the surface, as can be seen in Plates 7.2(i), 7.3(i), and 7.4(i). The intensity of the green dyed resin is less in the P.F. samples, Plates 7.2(ii), 7.3(ii) and 7.4(ii) than with the H.F. sample. This trend is even more apparent with R.P.F. samples - Plates 7.2(iii), 7.3(iii) and 7.4(iii) - where the intensity of the green dyed resin nearest to the surface is much reduced compared with that displayed in the samples of the other two finishing techniques. Moreover, the intensity of green dyed resin increases with increasing depth below the surface, indicating that the effect of power finishing diminishes with depth. The intensity of the green dye is least in mix B4, with the lowest water-cement ratio, and is greatest in mix B6 with the highest water-cement ratio.

These observations suggest that the intensity of the green dyed resin is related to the finishing technique and the water-cement ratio. The intensity of the green dye is directly proportional to porosity, and so it follows that the photomicrographs visually confirm the results of:-

(1) MIP tests

(2) Microhardness profiles

(3) Abrasion tests

(4) Existence of the proposed mechanisms for increasing the abrasion resistance through the application of power finishing equipment.

The results of this section are consistent with the findings of other investigators (158-159) who have used thin sectioning and fluorescent microscopy. They have reported (158-159) that the intensity of the fluorescence is proportional to the porosity and, thus, proportional to the water-cement ratio of the concrete. By using this techniqúe, it has been possible to estimate directly the water-cement ratio of hardened concrete to within 0.05 (158).

The thin sections prepared from the curing regime slabs, were used to produce photomicrographs of the top 40mm. The results for mix B4 (P.F.) are shown in Plate 7.5. In addition, the result from the mix B4 specimen cured by plastic sheeting is shown in Plate 7.2(ii). The examination of these thin sections, suggests that the air cured sample (A.C.) had a much higher porosity, indicated by the intensity of the green dye, than the samples cured by the other methods. There is little difference between the other types of curing regimes, although the porosity of the samples cured by compounds C.C.1 and C.C.3 may have been slightly more than that of the samples cured by P.S., W.B., and C.C.2. These general observations are consistent with the results of the MIP tests.

Thin sections were also prepared from the liquid surface-treated slabs. These were examined with a microscope at high magnification, specifically to a depth of 1mm below the surface. This examination did not reveal any significant penetration of the treatments into the surface. It is possible that the penetration of these treatments may have been too small to have been detected by the present method of taking thin sections parallel to the axis of the core. The method may be improved by taking the thin section parallel to the surface of the slab, i.e. perpendicular to the axis of the core.

Overall, the thin sections from both the curing regime and surface treatment samples demonstrated that mixes with low water-cement ratios have a lower intensity of green dye than those with higher water-cement ratios. Furthermore, a higher intensity of green dye was noted with the surface treated samples than with the curing regime samples, with the exception of the air cured sample. This was due to the surface treated samples being air cured and these results lend further support to the contention that the intensity of the green dye is a measure of the porosity of the concrete specimens.

This section did not provide accurate quantitative data, but the qualitative results obtained are consistent with the results of the quantitative tests described in the earlier sections. Furthermore, this technique does provide a visual display of the mechanisms involved in increasing the abrasion resistance of concrete. It is important to note that the foregoing conclusions are based on one thin section taken from one slab, for each variable under investigation and for each concrete mix. This suggests that the results may not be conclusive. For the results to be more conclusive, it would have been necessary to take at least three thin sections from different parts of each slab. However, the present findings demonstrate that the method is promising, and may be used for studying the microstructure of concrete.

7.6 Differential Thermal Analysis

Differential Thermal Analysis (DTA) determines the physicochemical changes in a substance as a function of temperature changes. In DTA the absorption and release of energy due to thermal changes, such as the loss of water of crystallisation, are recorded. The method has been used extensively in the analysis of hydrated cement (162-163) and hydrated aluminous cement (164). In addition to being a convenient means for characterising the main compounds of hydrated cement and related materials (165), it is also a method which may be used to assess the effects of admixtures on the hydration products of cements (166) and concrete (167). This suggested that the technique could be utilized to assess the comparative influence of the various liquid surface treatments on the concrete specimens.

In DTA the temperature difference ($\Delta T$) between the sample under investigation and a thermally inert material is plotted against temperature. In this plot, phase changes or chemical reactions produce peaks and troughs which are characteristics of the compounds present in the sample. The dimension of these features are dependent on the amount of a specific compound present in the sample. The peaks are due to exothermic reactions and the troughs are evidence of endothermic reactions. In the present investigation, the DTA was conducted using a Stanton Redcroft Differential Thermal Analyzer - Model 673-4. This system consisted of four basic components:-

1) Analyzer module including sample holder, platinum V 13% platinum - rhodium thermocouples and furnace.

2) Temperature programmer.

3) DC amplifier module.

4) Potentiometric recorder.

Dimpled platinum-rhodium crucibles were used to support the test samples. In this programme the tests were limited to samples obtained from the slabs subjected to the liquid surface treatments.

### 7.6.1 Experimental Procedure

A one mm thick sample was sliced from the surface matrix of each specimen, using a diamond cutting wheel, and allowed to dry. These slices were ground by hand using a pestle and mortar, and then sieved over a 150 µm sieve. The powdered samples were dried over silica gel in a $CO_2$-free system at ambient temperature. Calcined alumina was used as the thermally inert substance. The packing procedure was found to be a major source of error. To minimize this source of error and to maximize the reproducibility between successive experiments, a similar packing procedure was used in all tests. The temperature of the crucibles was raised from ambient to 950 degrees C at a rate of 20 degrees C per minute, and the temperature differences determined throughout this cycle.

### 7.6.2 Results and Discussion

The differential thermograms obtained for each of the surface treated samples from mix B4 are shown in Figure 7.16. The thermograms for the other concrete mixes (e.g. B5, B6) have not been included as they were very similar to those of mix B4 for each of the treatments. The differential thermogram for the control sample (e.g. treatment 0) in Figure 7.16(0), shows the typical peaks for OPC (165) which are as follows:-

(1) Calcium - Silicate - Hydrate Gel (C-S-H Gel)

(2) Calcium Sulphoaluminate Hydrate (Ettringite)

(3) Calcium Hydroxide (Portlandite).

The exothermic peak around 800 degrees C, indicates the presence of calcium carbonate which is due to carbonation, as would be expected since the samples were exposed to atmosphere for some 150 days after casting.

By comparing the differential thermograms for the surface treated samples to that of the non-treated, control sample, it can be seen that the thermograms produced by samples treated with surface hardeners, (A) and (B), are very similar to that of the control sample. The thermograms produced by samples treated with the in-surface seals, C, D and E, do not generally display the exothermic peaks which were observed with the control sample. Indeed, these thermograms also do not possess some of the endothermic troughs, which are present in the thermograms produced by the control sample and the samples treated by the surface hardener. The thermograms, produced by the samples treated with in-surface seals, cannot be analysed, because of the large number of variables present and the incomplete differential thermograms that were obtained. This, however, does not mean that the results are not useful, as can be seen below.

The similarity between the differential thermograms for the samples treated by surface hardeners (A) and (B) and that of the control sample (O), indicates that these treatments did not appreciably influence the surface matrix of the concrete slabs. In contrast the discrepancies observed between the thermogram of the control sample and those of the samples treated with in-surface seals, suggest that the application of these seals influenced the surface of the concrete slabs. This influence is likely to be due to limited penetration of the surface by the in-surface seals.

## 7.7 Summary

In this chapter the investigations have been concerned with the miscrostructure of the concrete specimens which had been produced for abrasion resistance study. Five different techniques were used:-

(1) The Mercury Intrusion Porosimetry method, which revealed that:

(a) Finishing techniques, curing regimes and surface treatments influenced the pore structure of the cement matrix within specimens.

(b) Cement matrix porosity is a major factor controlling the abrasion resistance.

(c) The concrete surface hardeners did not penetrate the surface matrix, but the in-surface seals appear to have penetrated the surface.

(2) Microhardness Analysis, which showed that:

(a) The abrasion resistance of concrete is directly related to microhardness and porosity of the surface matrix.

(b) The microhardness of the top 1mm of the surface matrix controls the abrasion resistance of the slab.

(c) The influence of power equipment diminishes with depth below the surface, but the influence of repeated power finishing was evident at 16mm below the surface.

(3) Scanning electron microscopy did not reveal typical morphology which could be attributed to the influence of different finishing techniques.

(4) Petrographic examination of thin sections generally confirmed the results of MIP method and Microhardness analysis.

(5) Differential Thermal Analysis indicated that the application of surface hardener did not influence differential thermograms, while they were influenced by the application of in-surface seals. The implication is that the in-surface seals must have penetrated the surface of the concrete.

The results obtained from microstructure studies, generally confirm the mechanisms which were proposed in Chapter 6 to explain the influence of a number of variables upon abrasion resistance of concrete in quantitative and qualitative terms.

| Mix No. | Type of Finishing | Depth of Abrasion (mm) | Total Pore Volume (ml/g) x $10^{-2}$ | |
|---|---|---|---|---|
| | | | Top | Middle |
| B4 | H.F. | 0.46 | 7.47 | 7.95 |
| | P.F. | 0.30 | 6.10 | 8.24 |
| | R.P.F | 0.10 | 5.20 | 8.22 |
| | V.D. | 0.23 | 6.13 | 9.20 |
| B5 | H.F. | 0.61 | 8.60 | 8.95 |
| | P.F. | 0.48 | 7.80 | 9.00 |
| | R.P.F. | 0.18 | 5.45 | 9.10 |
| | V.D | 0.25 | 6.35 | 9.55 |
| B6 | H.F. | 0.84 | 8.60 | 10.06 |
| | P.F. | 0.66 | 8.25 | 10.00 |
| | R.P.F | 0.17 | 5.90 | 9.90 |
| | V.D | 0.27 | 6.58 | 10.60 |

TABLE 7.1 Abrasion Depth and Total Pore Volume for Finishing Technique Samples

| Mix No. | Curing Regime | Depth of Abrasion (mm) | Total Pore Volume (ml/g) x $10^{-2}$ |
|---|---|---|---|
| B4 | A.C. | 0.47 | 6.75 |
| | W.B. | 0.31 | 6.00 |
| | P.S. | 0.30 | 6.10 |
| | CC1 | 0.25 | 6.30 |
| | CC2 | 0.22 | 6.00 |
| | CC3 | 0.26 | 6.45 |
| B6 | A.C. | 1.29 | 9.60 |
| | W.B. | 0.82 | 8.50 |
| | P.S. | 0.66 | 8.25 |
| | CC1 | 0.58 | 8.75 |
| | CC2 | 0.60 | 9.45 |
| | CC3 | 0.58 | 9.30 |

TABLE 7.2 Abrasion Depth and Total Pore Volumes for Curing Regime Samples

| Mix No. | Type of Liquid Surface Treatment | Abrasion Depth(mm) | Total Pore Volume (ml/g) x $10^{-2}$ |
|---|---|---|---|
| B4 | A | 0.40 | 6.98 |
| | B | 0.38 | 6.80 |
| | C | 0.08 | 6.20 |
| | D | 0.07 | 6.43 |
| | E | 0.12 | 6.67 |
| | O | 0.54 | 6.85 |
| B6 | A | 0.89 | 8.89 |
| | B | 1.00 | 9.04 |
| | C | 0.26 | 8.28 |
| | D | 0.14 | 7.94 |
| | E | 0.28 | 8.64 |
| | O | 1.18 | 9.50 |

TABLE 7.3 Abrasion Depth and Total Pore Volumes for Surface Treated Samples

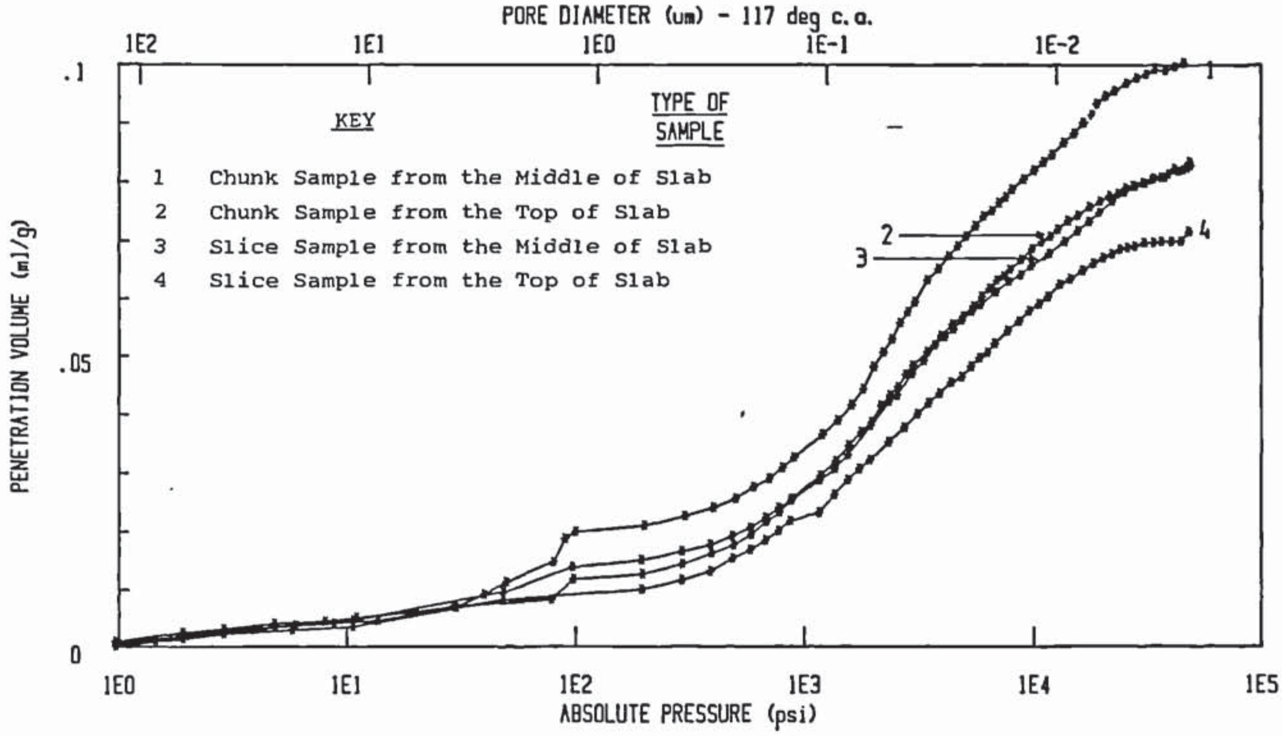



FIGURE 7.1 Pore Size Distribution Curves of Types of Sample

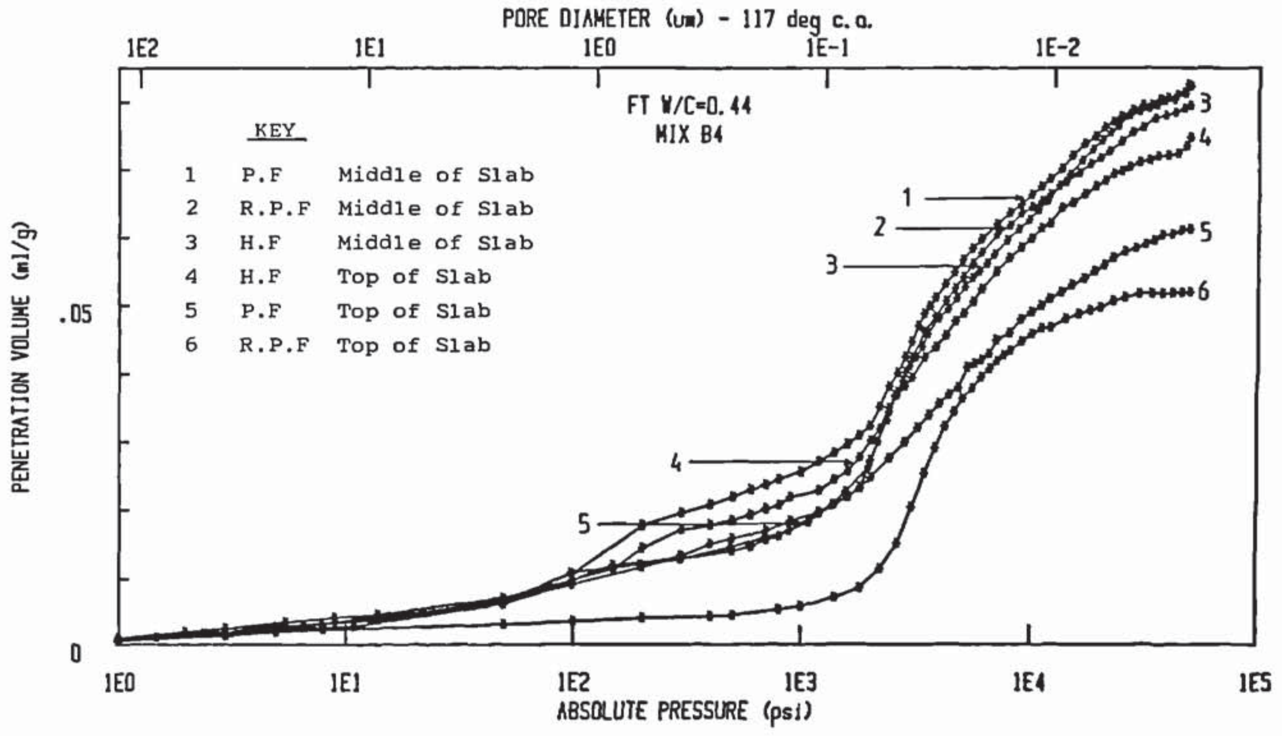



FIGURE 7.2 Pore Size Distribution Curves of Finishing Technique Samples For Mix B4

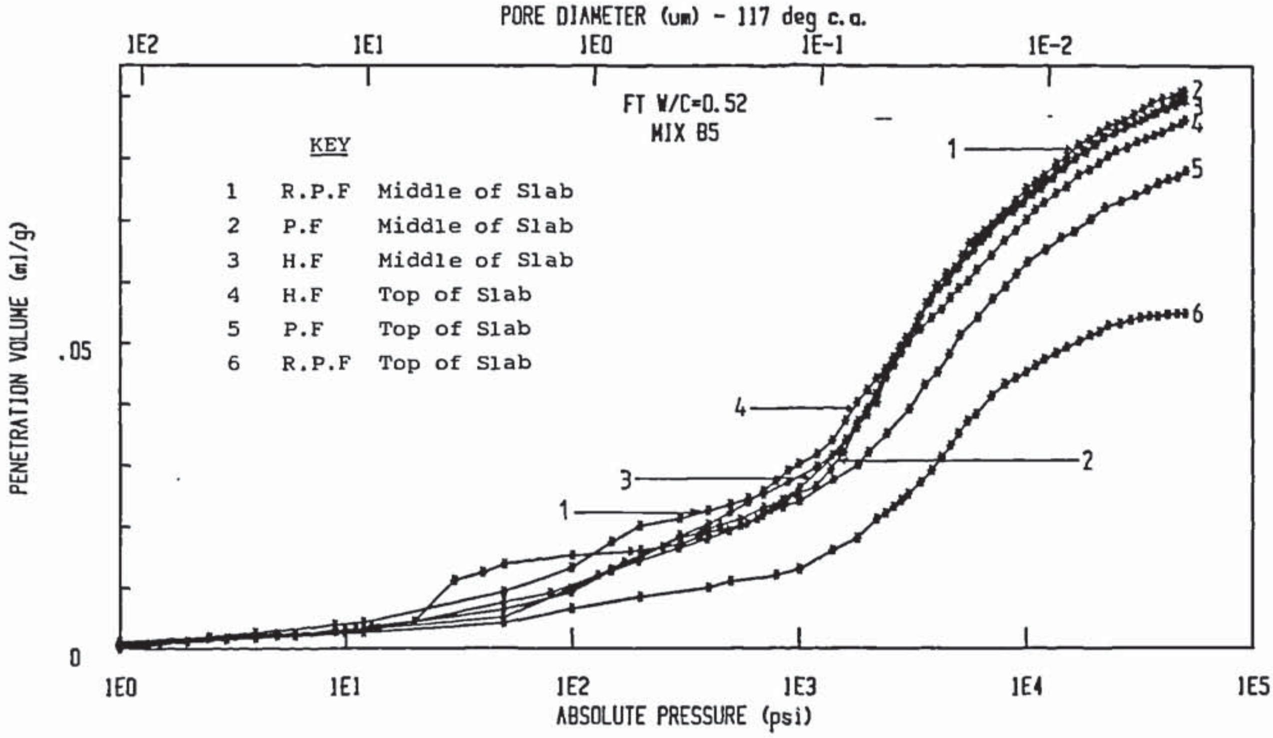



FIGURE 7.3 Pore Size Distribution Curves of Finishing Technique Samples For Mix B5

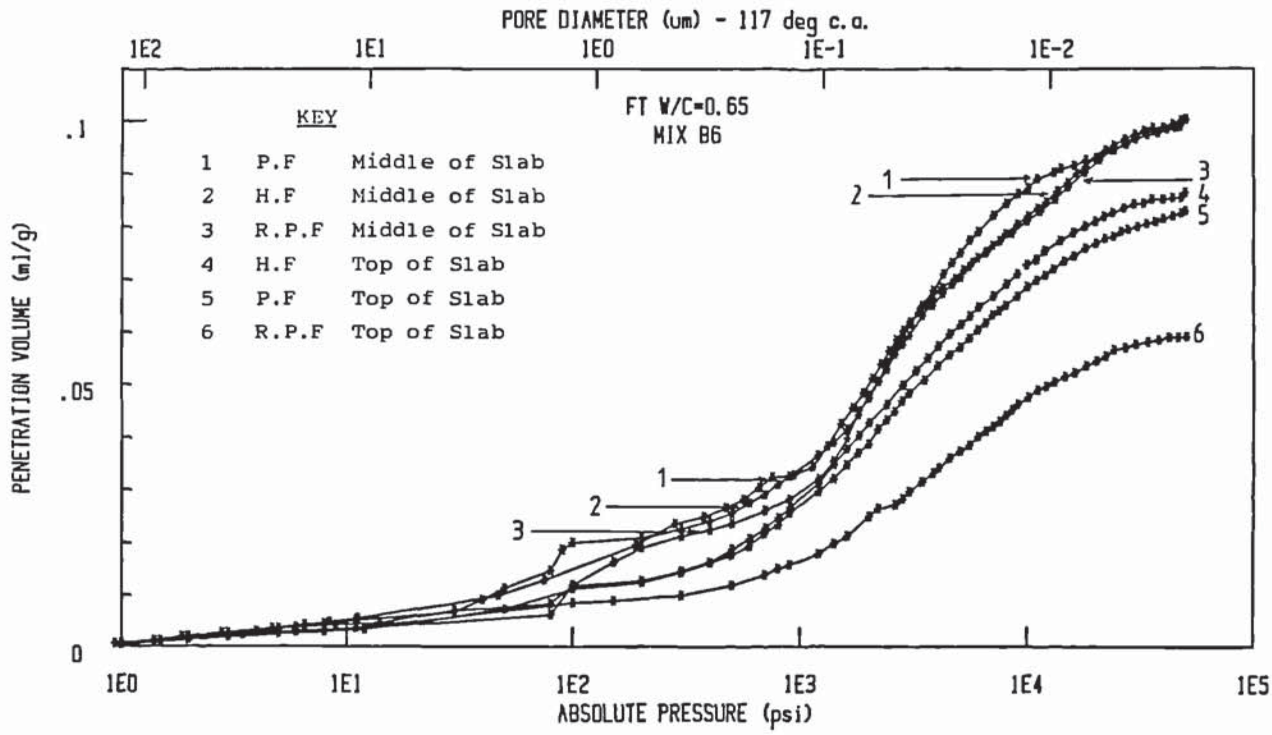



FIGURE 7.4 Pore Size Distribution Curves of Finishing Technique Samples For Mix B6

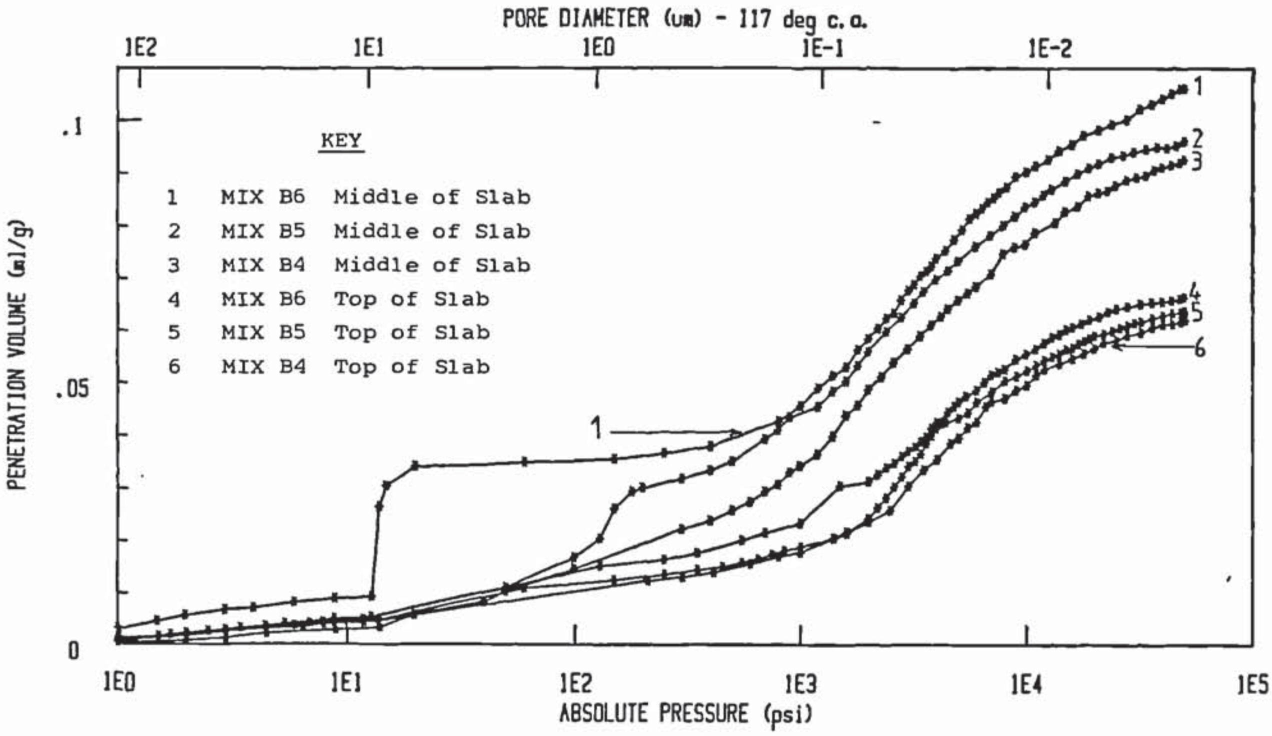



FIGURE 7.5 Pore Size Distribution Curves of Vacuum Dewatered Samples

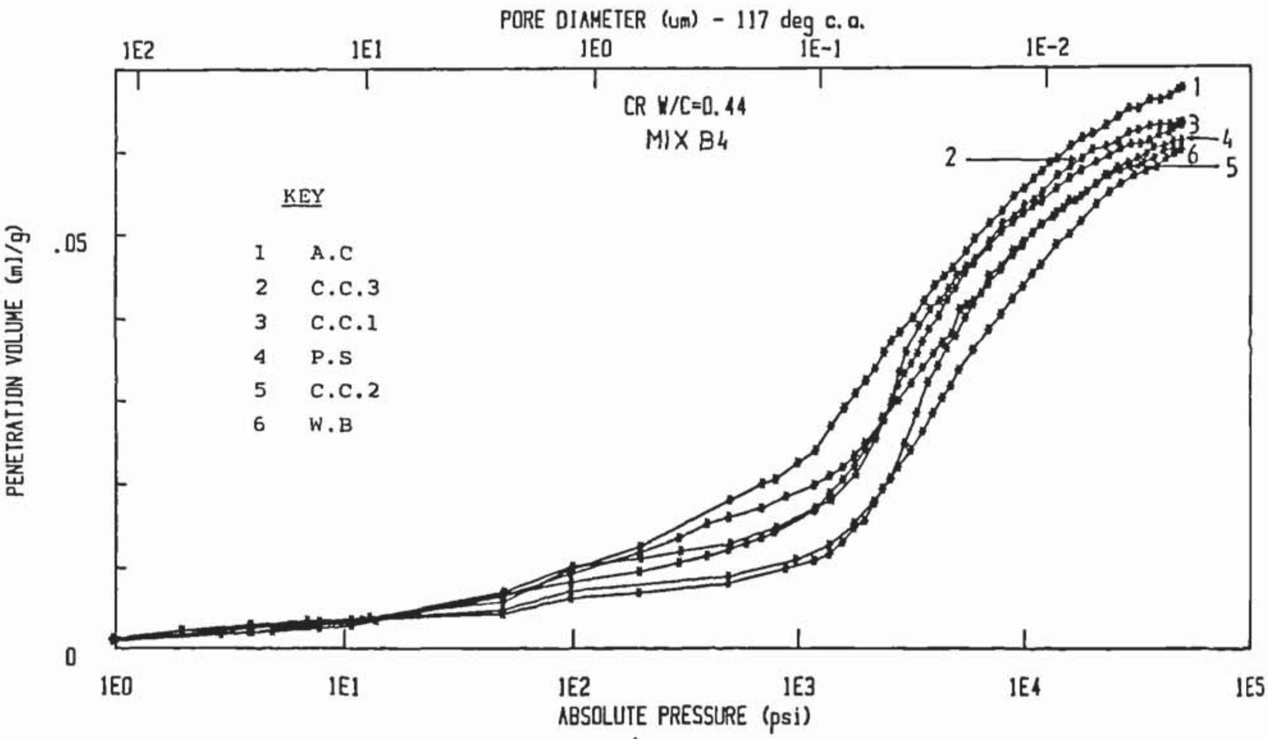



FIGURE 7.6 Pore Size Distribution Curves of Curing Regime Samples for MIX B4

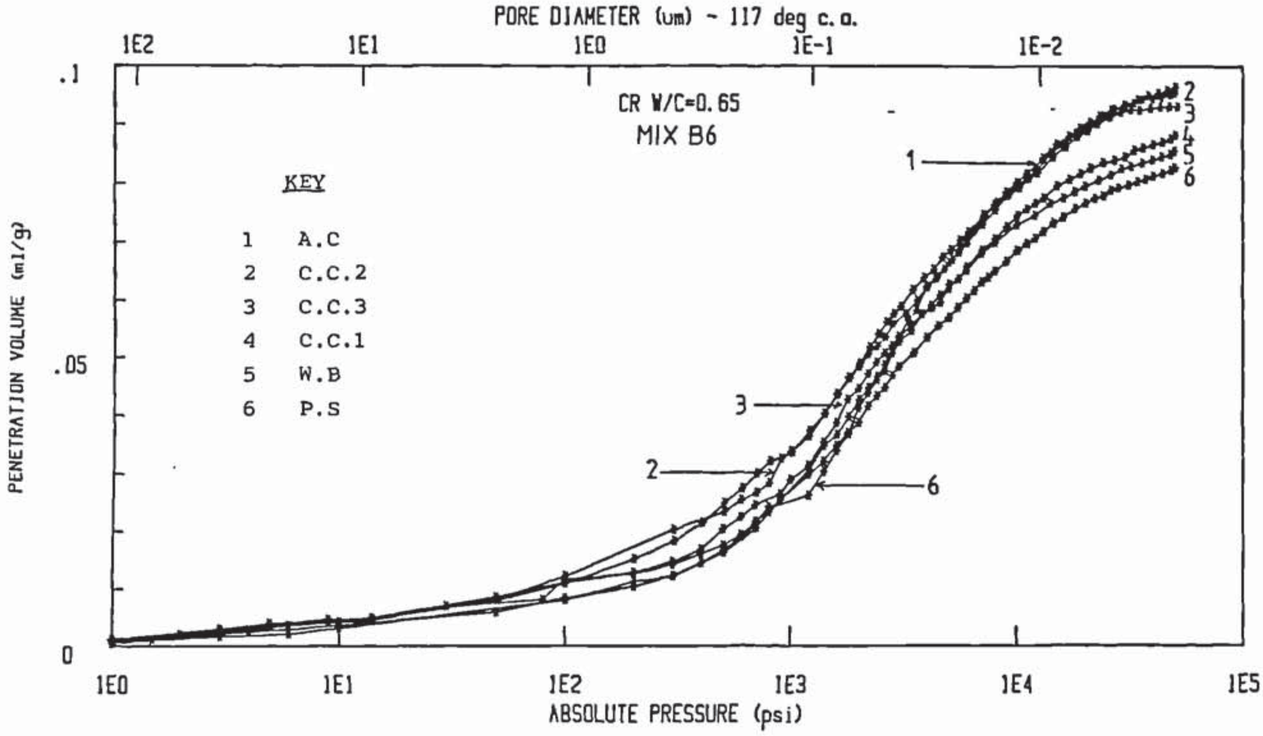



FIGURE 7.7 Pore Size Distribution Curves of Curing Regime Samples For MIX B6

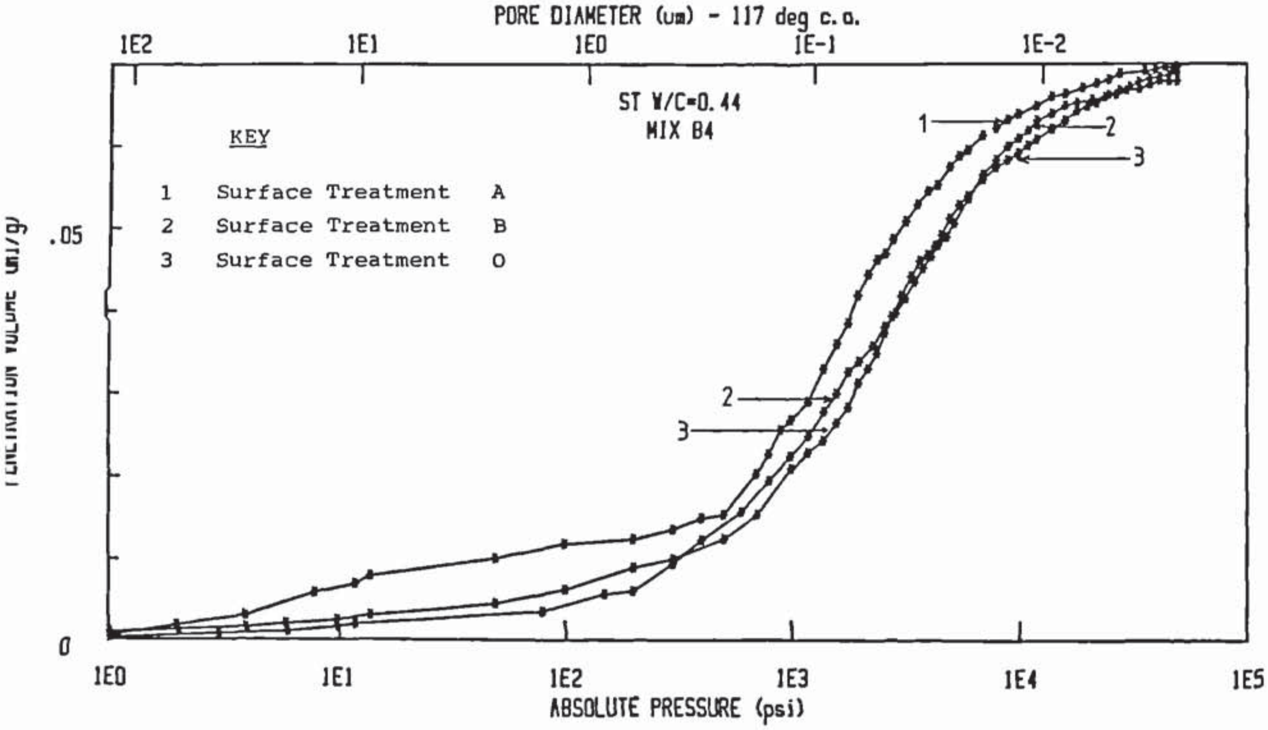



FIGURE 7.8 Pore Size Distribution Curves of Surface Treated Samples For Mix B4

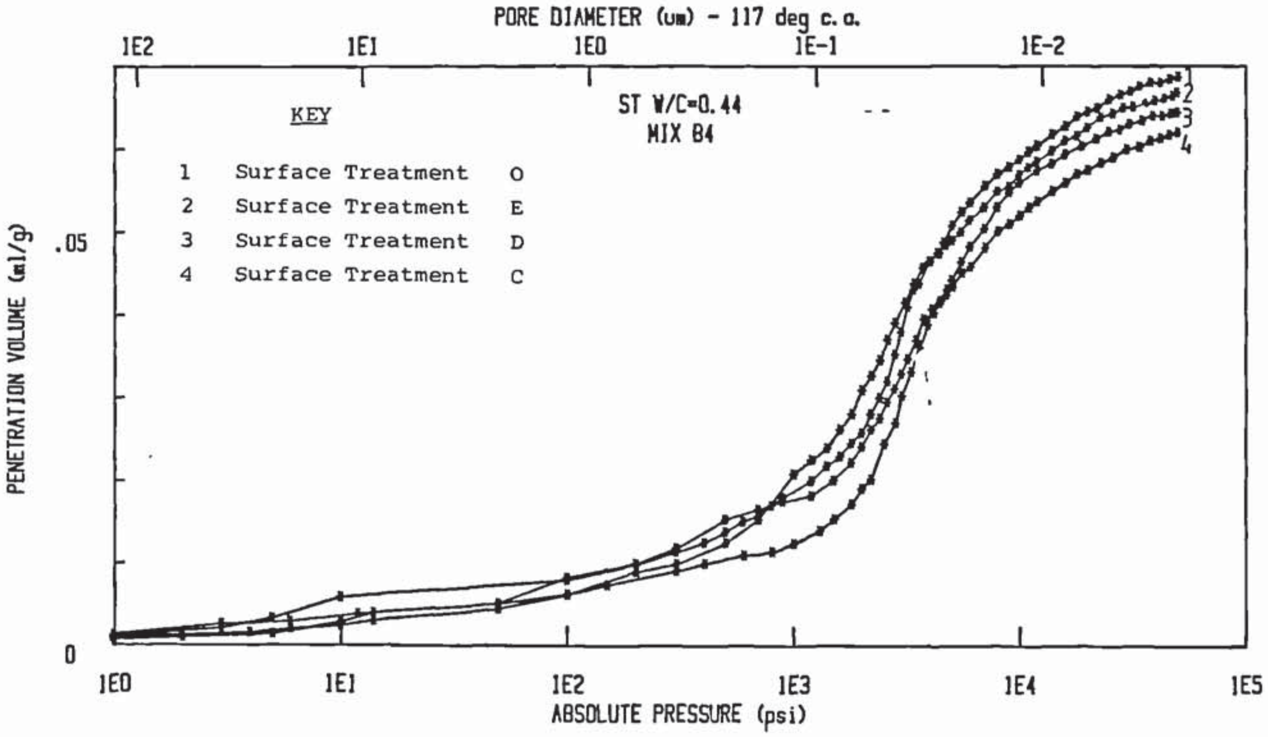



FIGURE 7.9 Pore Size Distribution Curves of Surface Treated Samples For Mix B4

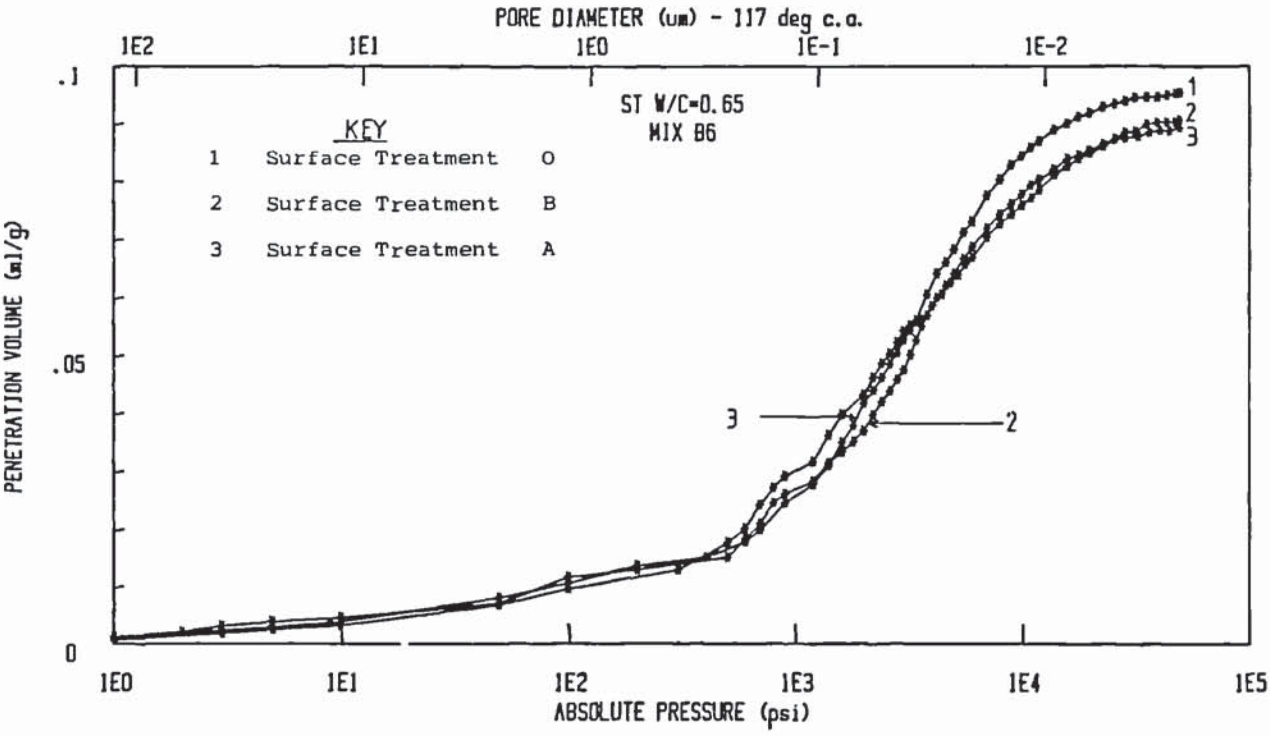



FIGURE 7.10 Pore Size Distribution Curves of Surface Treated Samples For Mix B6

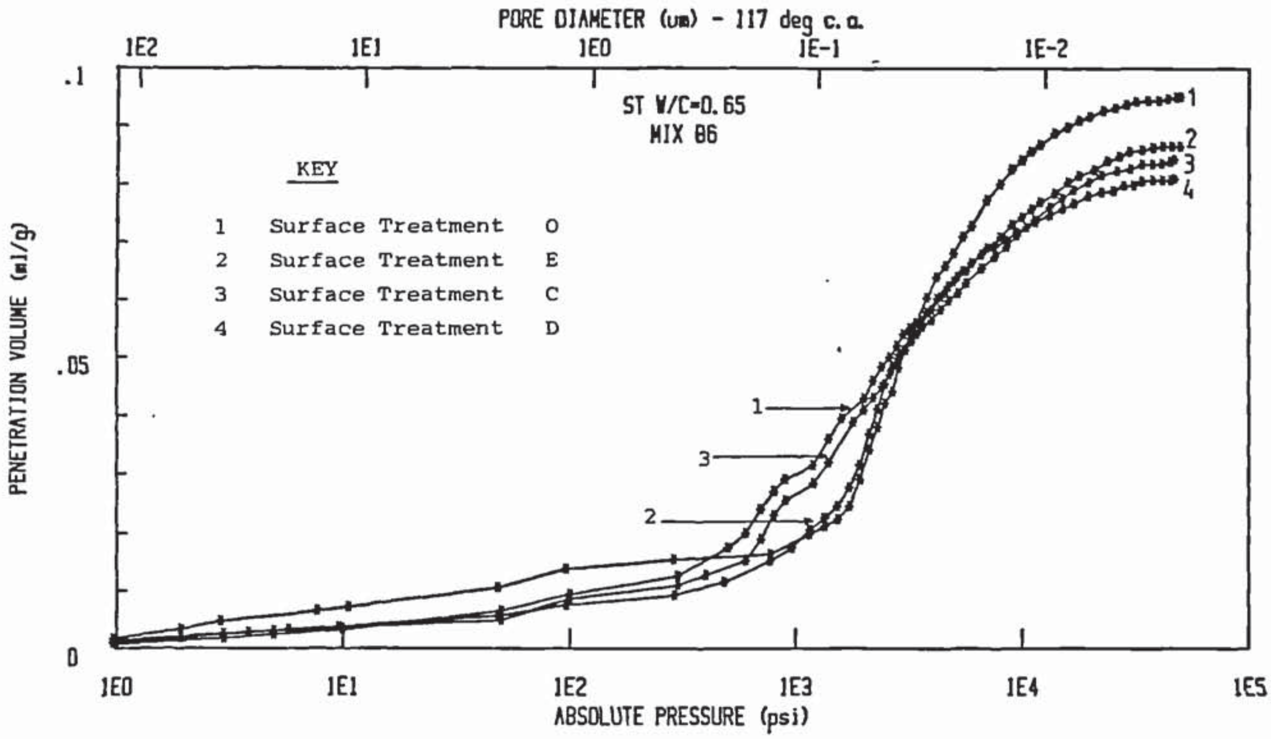



FIGURE 7.11 Pore Size Distribution Curves of Surface Treated Samples For Mix B6

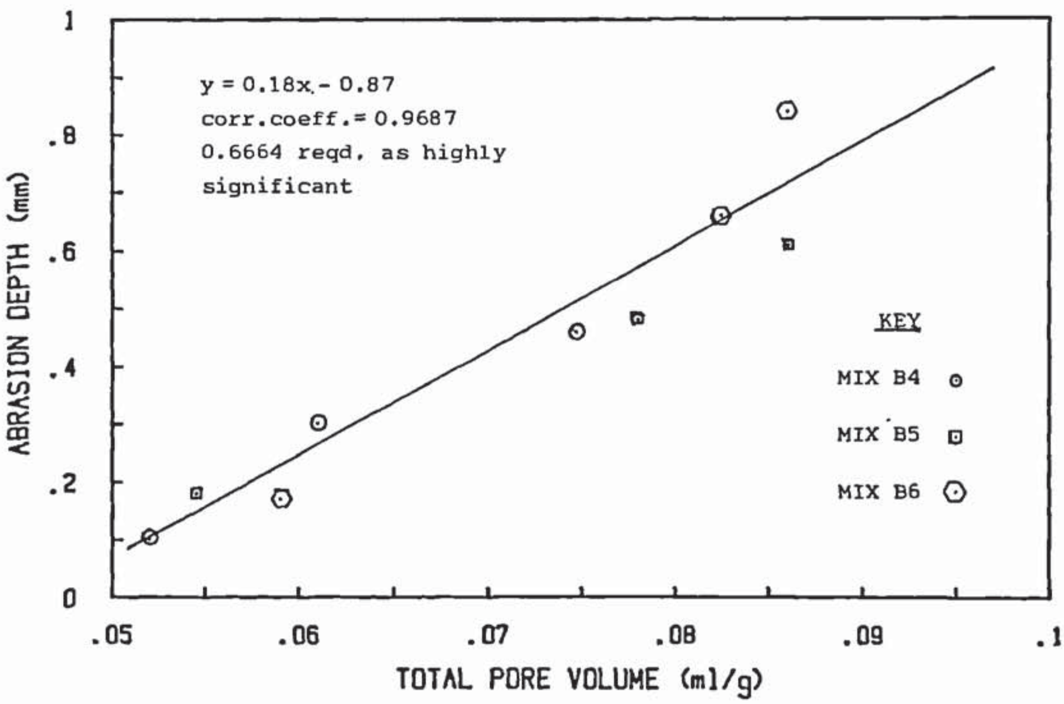



FIGURE 7.12 Abrasion Depth V's Total Pore Volume

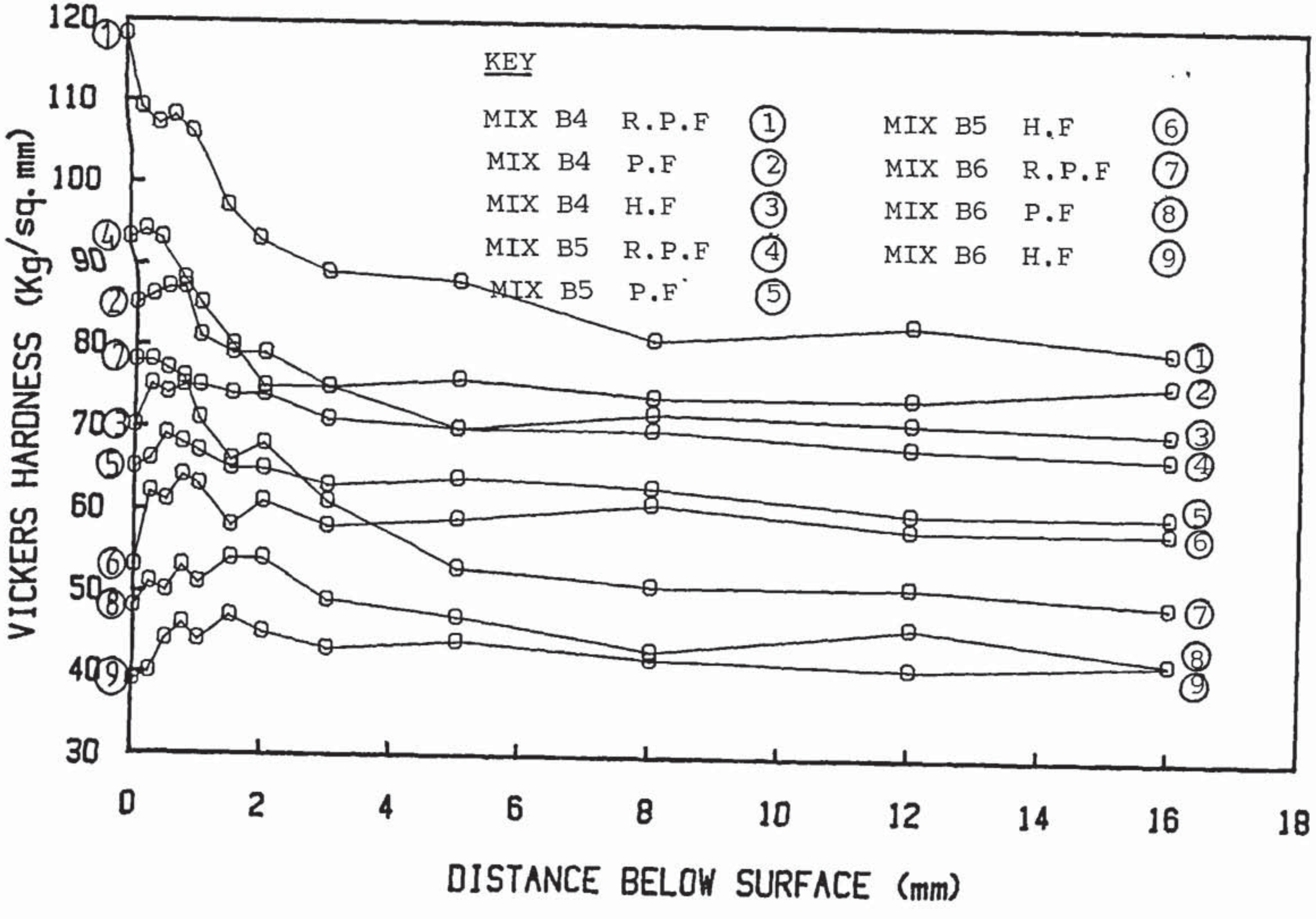



FIGURE 7.13 Summary of the Microhardness Profiles for Finishing Technique Samples

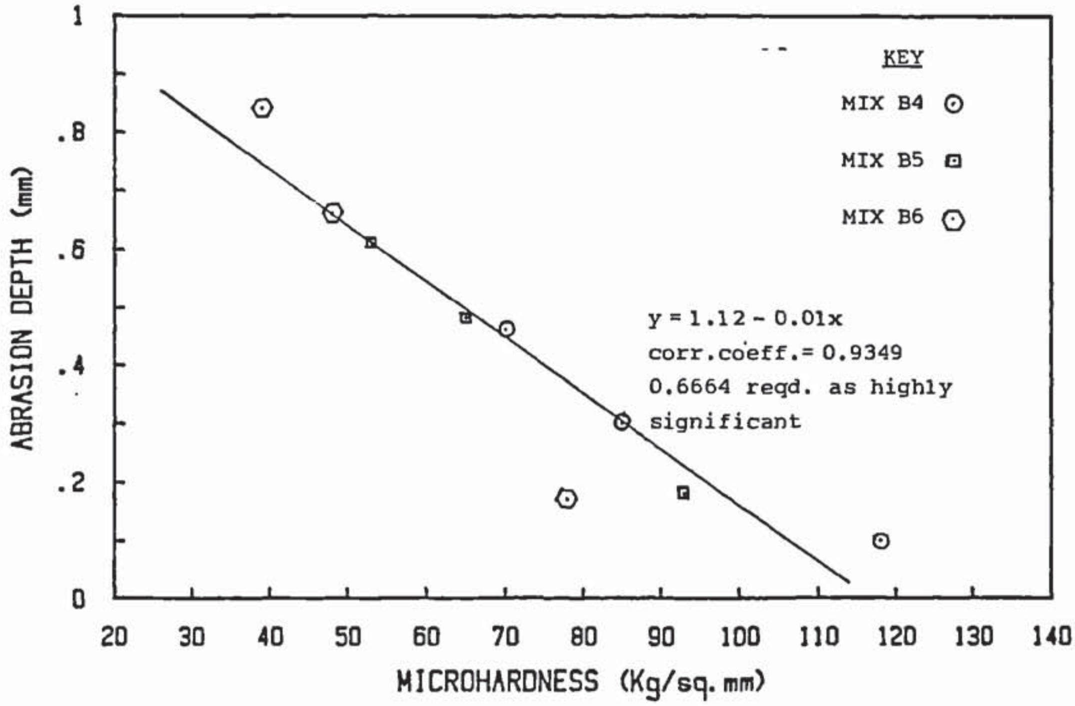



FIGURE 7.14 Abrasion Depth V's Microhardness

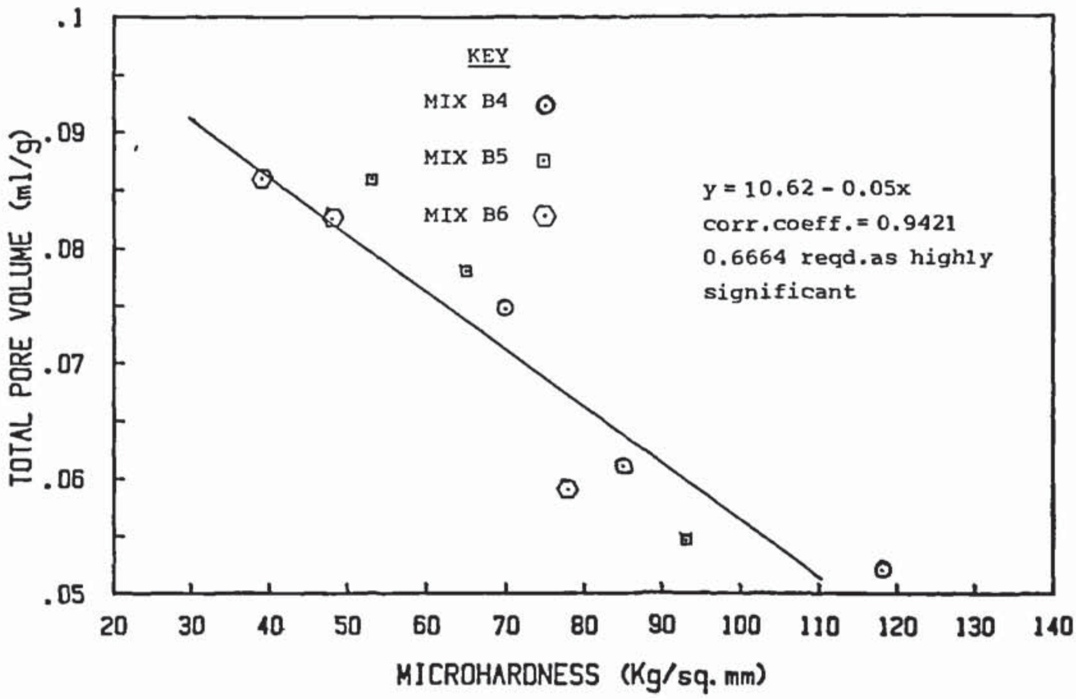



FIGURE 7.15 Total Pore Volume V's Microhardness

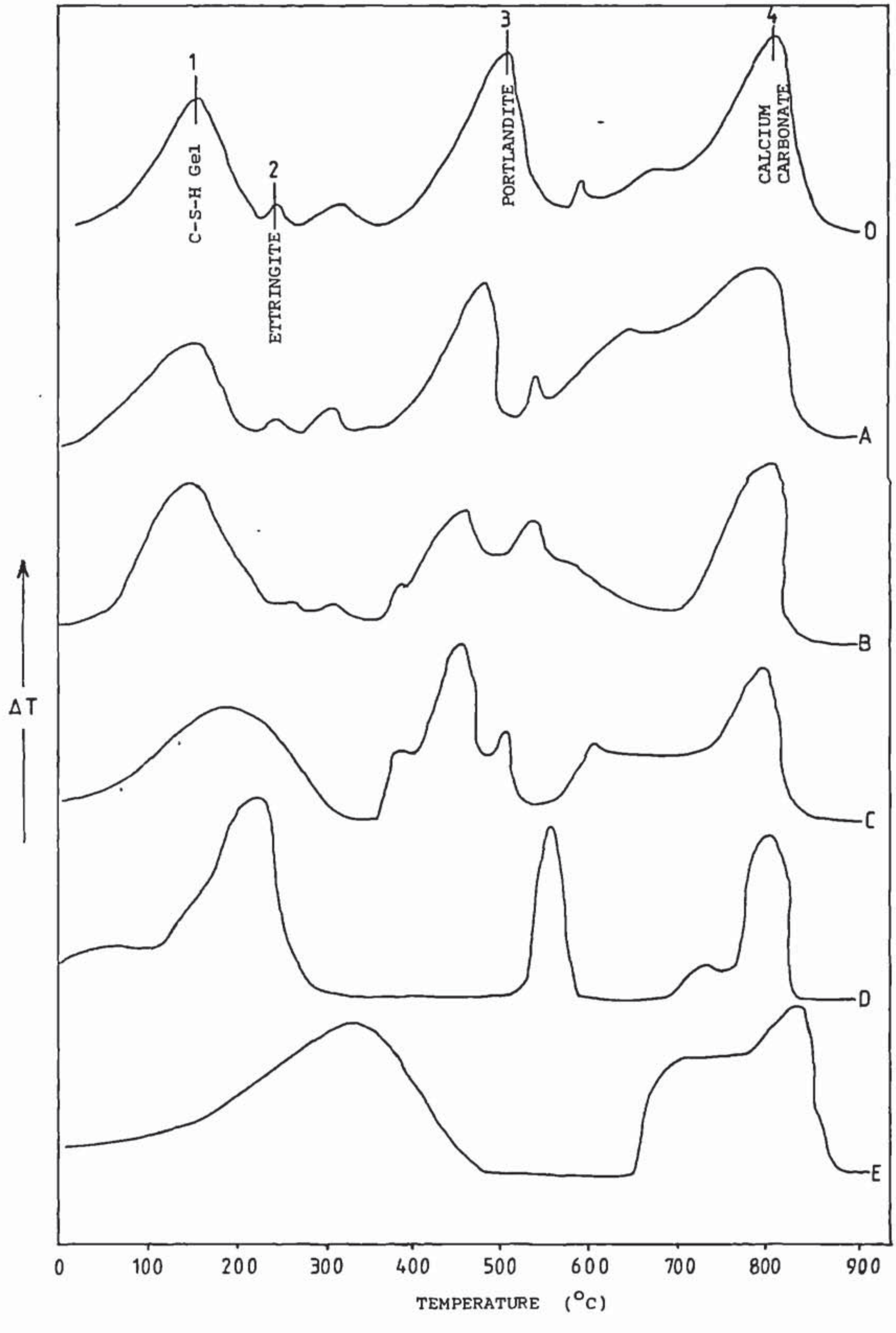
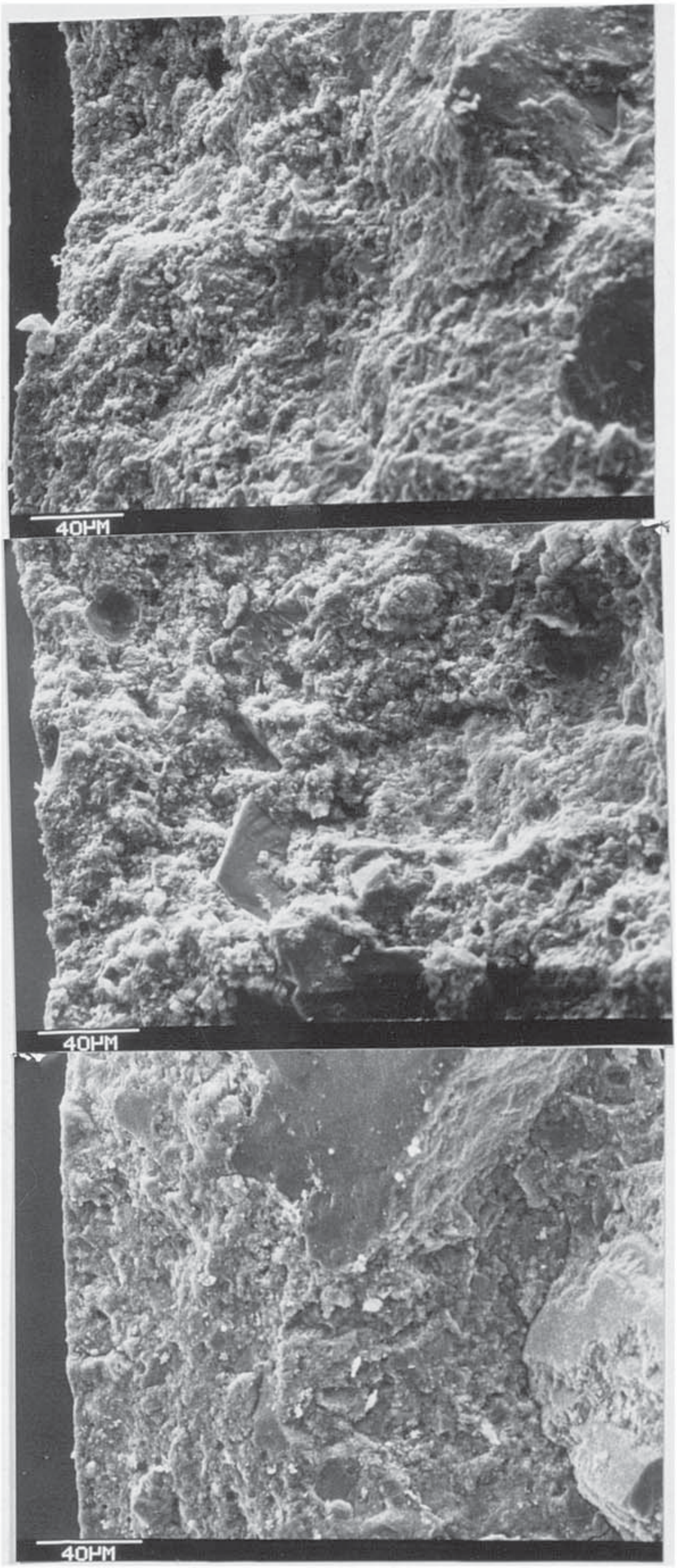



FIGURE 7.16 Differential Thermograms for Concrete Mix B4

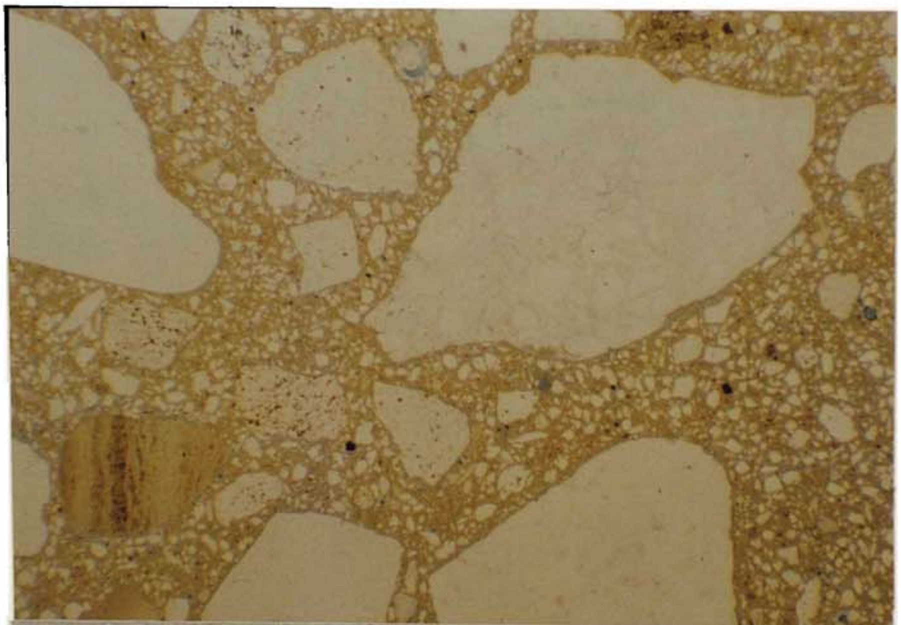



(i) H.F. Sample

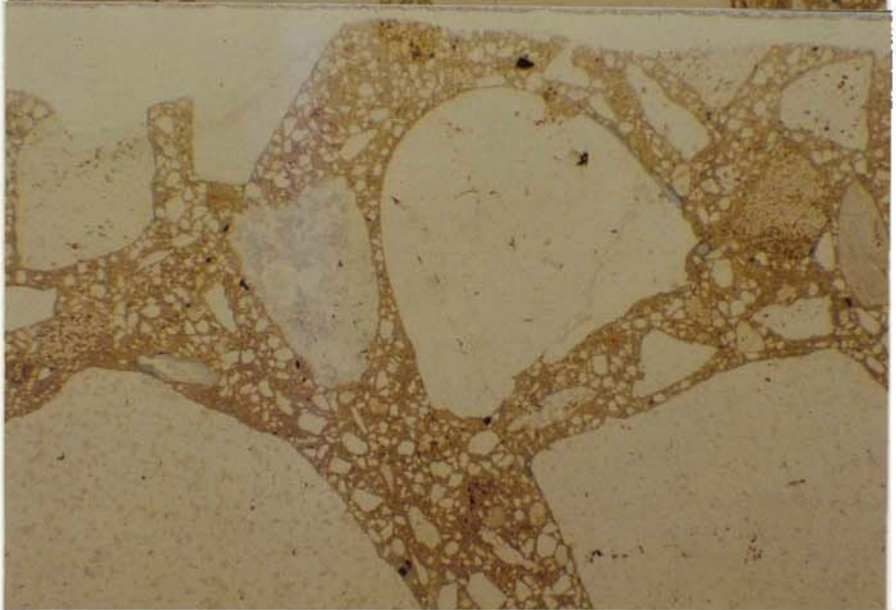
(ii) P.F. Sample

(iii) R.P.F. Sample

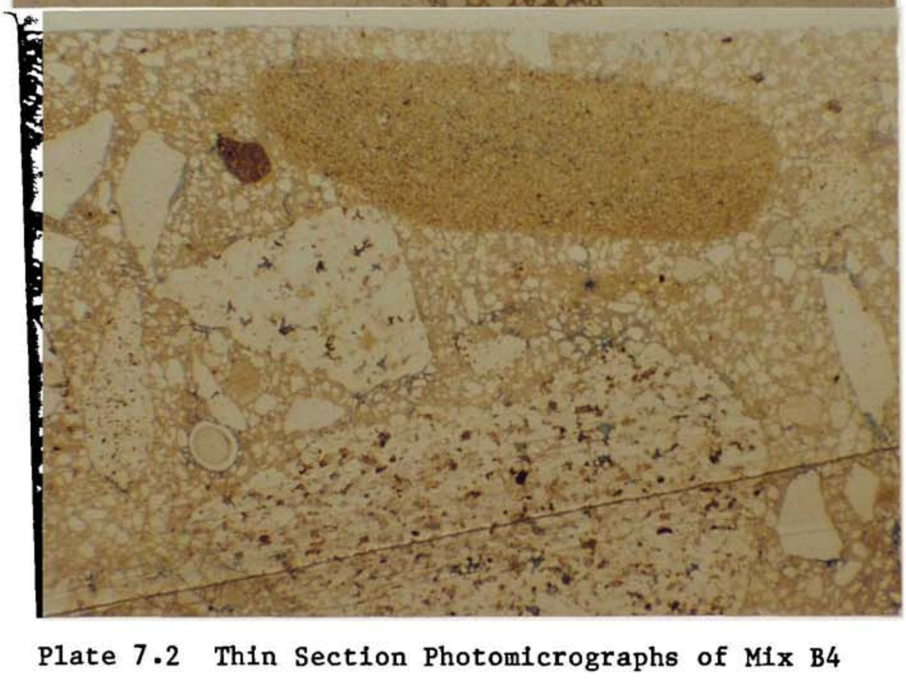
Plate 7.1 Electromicrographs of Mix B4



(i) H.F.
Sample

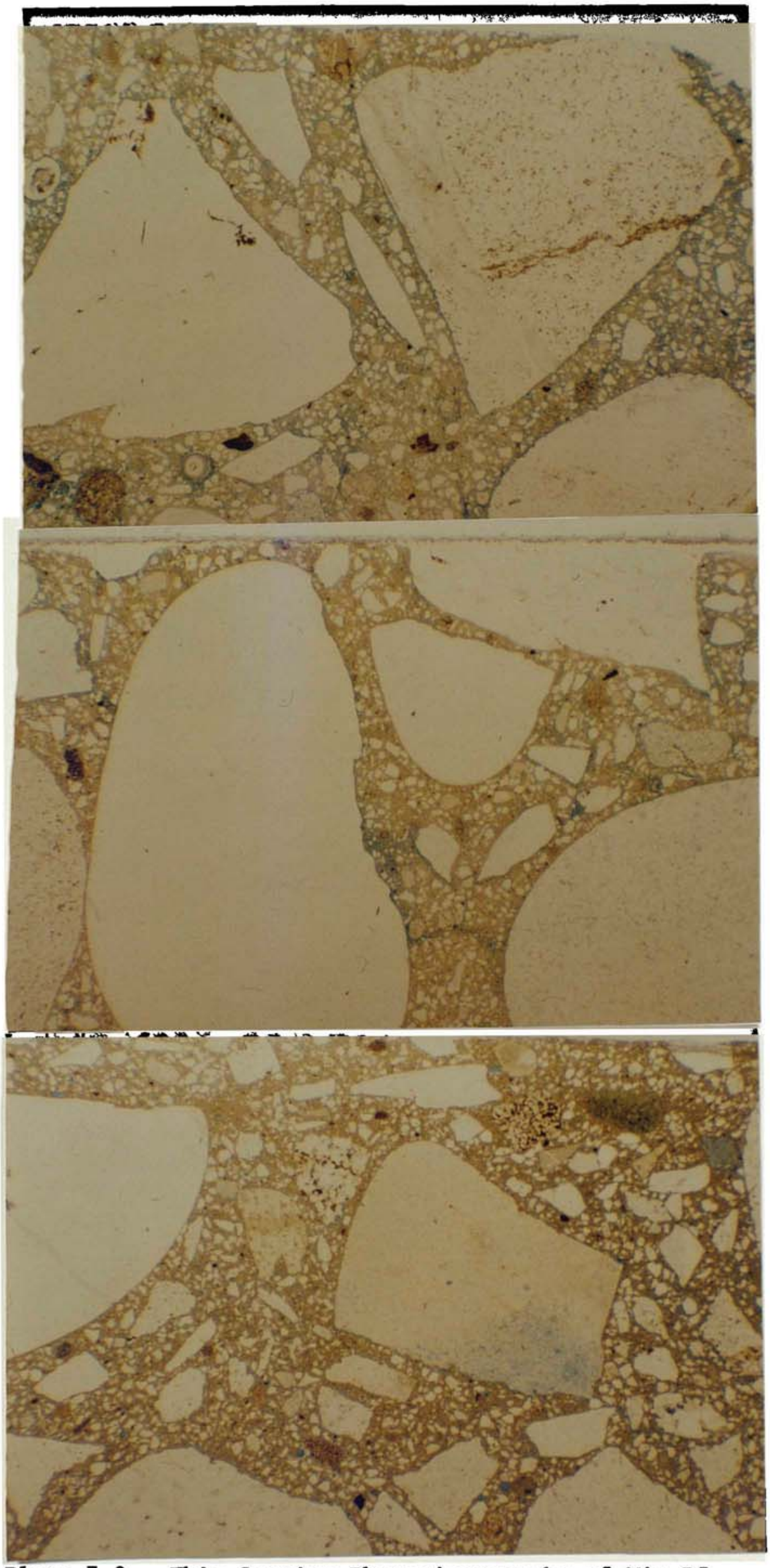


(ii) P.F.
Sample



(iii) R.P.F.
Sample

Plate 7.2 Thin Section Photomicrographs of Mix B4



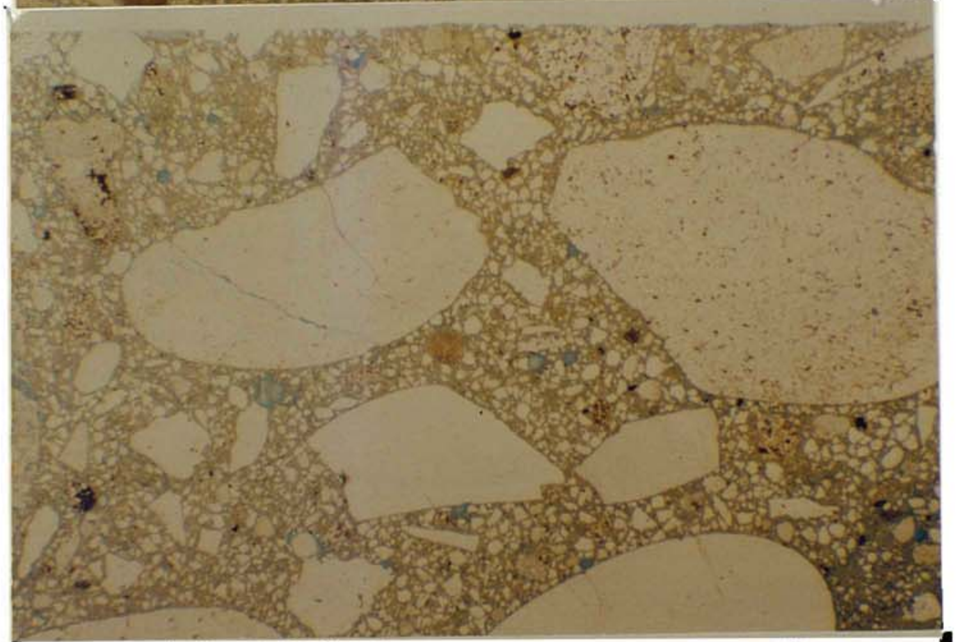
(i) H.F. Sample

(ii) P.F. Sample

(iii) R.P.F. Sample

Plate 7.3 Thin Section Photomicrographs of Mix B5

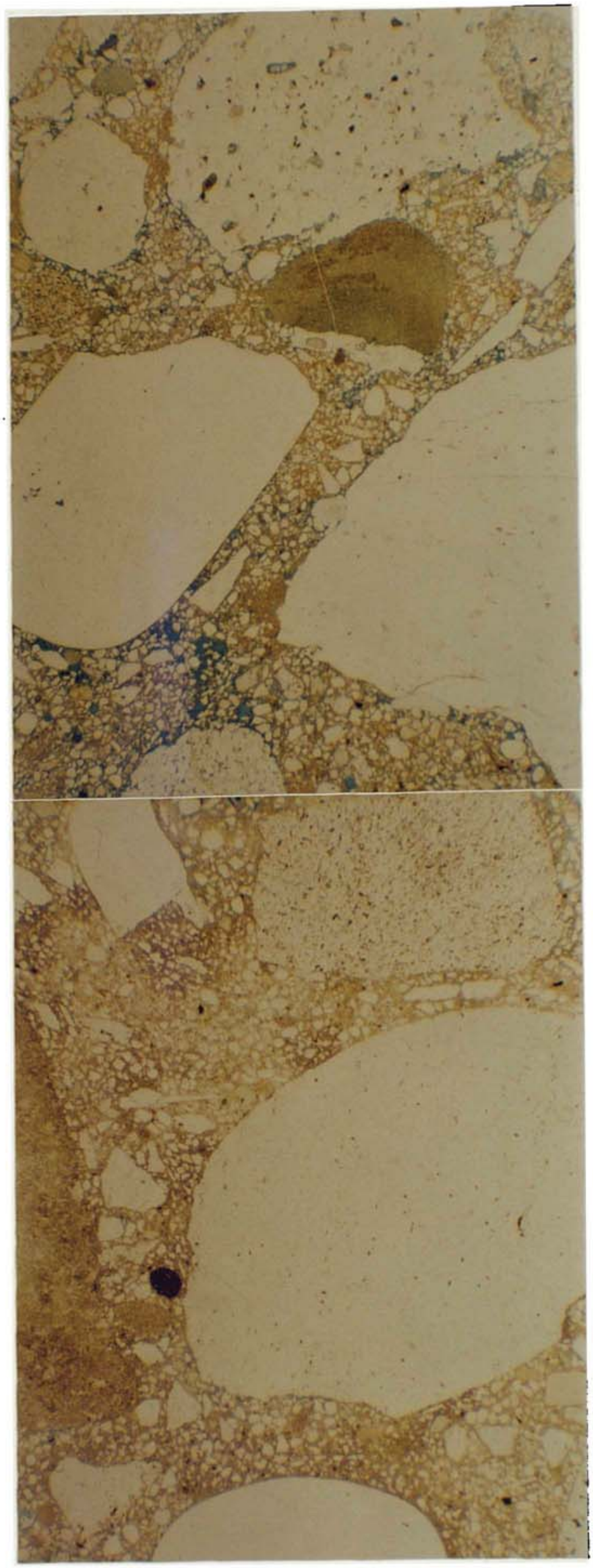
(i) H.F. Sample



(ii) P.F. Sample

(iii) R.P.F. Sample

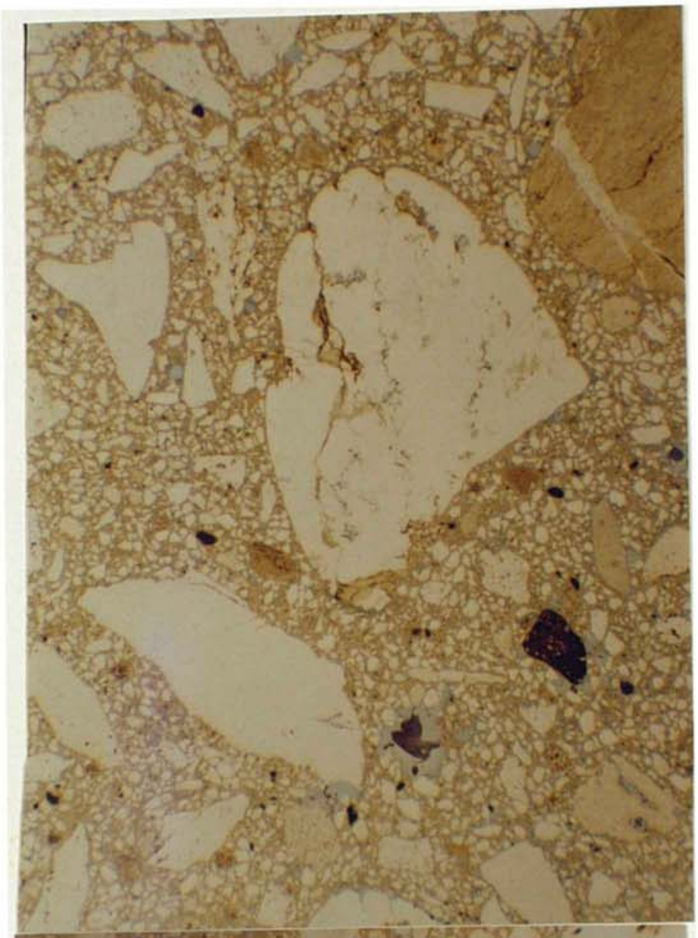
Plate 7.4 Thin Section Photomicrographs of Mix B6



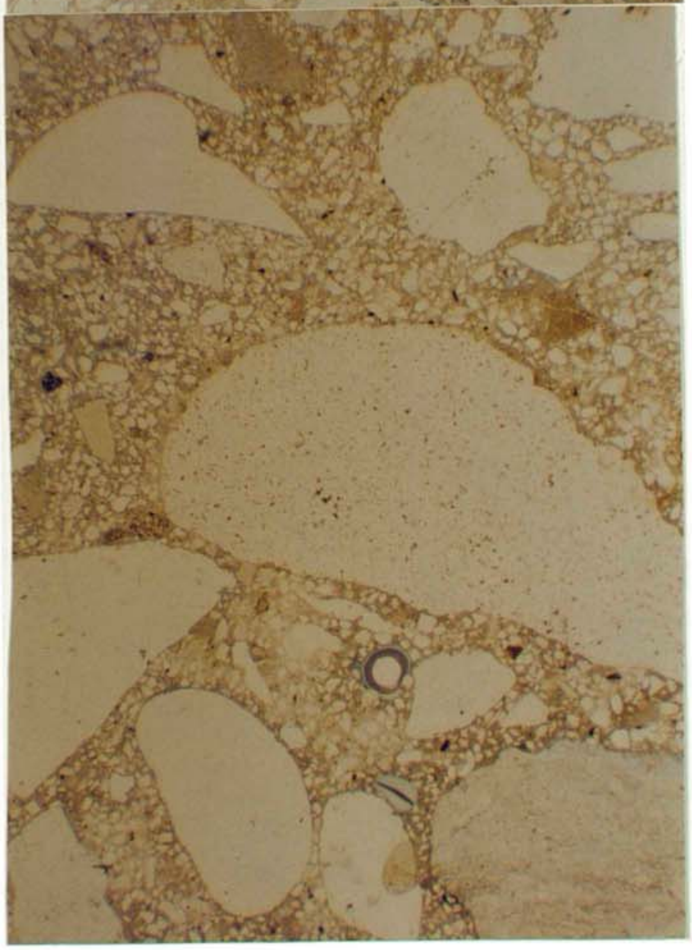
(i) A.C.

(ii) W.B.

Plate 7.5 Thin Section Photomicrographs of Curing Regimes, Mix B4

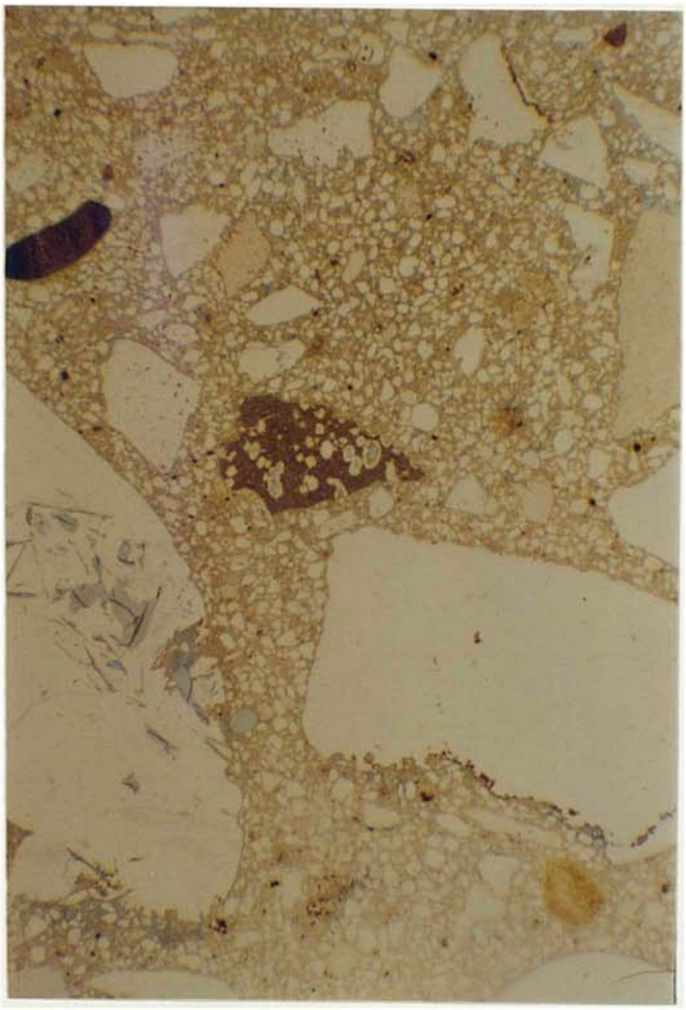


(iii) C.C.1



(iv) C.C.2

Plate 7.5 Thin Section Photomicrographs of Curing Regimes, Mix B4



(v) C.C.3

Plate 7.5 Thin Section Photomicrographs of Curing Regimes, Mix B4

# CHAPTER 8

## INDIRECT AND NON-DESTRUCTIVE METHODS FOR ASSESSING ABRASION RESISTANCE OF CONCRETE

### 8.1 Introduction

The accelerated abrasion tests produce valuable information regarding the quality of the concrete slab, so far as its abrasion resistance is concerned. However, these types of tests are destructive and permanently damage the test areas, and so it is difficult to obtain access for testing industrial slabs. Thus, from the standpoint of the factory occupier, the ideal test system should not damage the floor during the test, i.e. a non-destructive test is desirable. Such a test should be sensitive to the factors influencing the abrasion resistance and should not damage the concrete slab. With such a test system, research into the abrasion resistance of concrete slabs in industrial environment could be performed without damaging the test area, and so, more industrial premises would be available for investigation.

The aim of this part of the programme was to investigate the feasibility of assessing the abrasion resistance of concrete by indirect and non-destructive methods. The particular methods that were investigated have frequently been used for assessing the quality of concrete, and they were:-

(1) Ultrasonic pulse velocity

(2) Rebound Hardness

(3) Initial Surface Absorption

### 8.2 Ultrasonic Pulse Velocity

Measurements of the ultrasonic pulse velocity have been extensively used by many investigators (168-170) to assess the properties of concrete. The ultrasonic pulse velocity depends (168) mainly on the density of the concrete, with modulus and poissons ratio being less critical. All these factors will be influenced by a change in the water-cement ratio for a given mix. The earlier work has already clearly shown that the abrasion resistance of concrete is influenced by water-cement ratio and so it was decided to investigate the possibility of relating the pulse velocity to the abrasion resistance.

The technique and instrument have been thoroughly discussed by Bungey (171) and the test method is also covered by B.S 4408: pt 5: 1974 (172), and so a similar discussion is not repeated. Briefly, the wave velocity is calculated from the time taken by the ultrasonic pulse to travel a measured distance. The instrument used for the present investigation was a portable ultrasonic non-destructive digital indicating tester, commonly known as the PUNDIT (173).

The PUNDIT programme was restricted to tests on specimen slabs, produced for the comparative study, from mixes B1, B2 and B3, and which had been subjected to the standard abrasion test with rolling wheels.

### 8.2.1 Experimental Procedure

The procedures which were adopted for the PUNDIT test followed the general requirements of B.S 4408: pt 5: 1974 (172). The test slabs were placed on top of a 20mm layer of sand in order to isolate the test slab from the laboratory floor. Each test was conducted 29 days after casting, on a dry and clean concrete surface, this being the finished top of each slab. One transducer plate was placed on the inside of the circular groove worn during the abrasion test, and the other transducer was placed on the outside of the circle opposite the first plate, such that a minimum path length of 100mm was obtained

(172). This is the indirect method of test with both transducers being placed on the same concrete surface. A small amount of grease was used as couplant, so that a strong pulse was transmitted. For each test, eight readings were recorded around the abrasion path, and at each of these locations a minimum of three, repeated readings were taken. For each slab three sets of results were recorded. Special effort was made to avoid recording readings over the 20mm Ø reinforcing bar, which had been used to handle the slab. No effort was made to avoid the other two 10mm Ø bars, as it has been suggested (171) that the effect of reinforcing bars may be ignored when their diameter is 12mm or lower.

### 8.2.2 Results and Discussion

The results obtained for the pulse velocity together with the abrasion depth and mean cube crushing strength are summarised in Table 8.1. It can be seen that, generally, the pulse velocity of mix B1 with a low water-cement ratio, is higher than those of mixes B2 and B3 with the higher water-cement ratios. However, the difference between those pulse velocity values for the three mixes is very small and only the difference between the values of mix B1 and mix B3 is statistically significant as shown in Table C.18 of Appendix C.1. This suggests that the ultrasonic pulse velocity technique, as used in the present study, was not sensitive to variationsin mix design. This apparent insensitivity may have been caused by the combination of several factors which can be summarised as follows:-

(1) The contact surfaces. The specimen slabs for the comparative study were finished by hand floating (see Section 5.5) and so had relatively rough faces on which the tests were performed. Although grease was used as a coupling medium, the contact between the transducers and the concrete was suspect. This was apparent from the

readings which were dependent on the pressure applied to the transducer plate when the readings were taken. The concrete surface was not ground smooth because such action could have modified the surface layer which was being investigated.

(2) The method of transmission. The indirect method of transmission is considered (171) to be the least satisfactory method, as this wave has much less energy than the direct wave and so the possibility of error is much greater. In the present study it would have been possible to use the direct method of transmission, with the transducers on either side of the slab, but the technique would have required considerable handling of the large slab and is not practical for site application.

The ultrasonic pulse velocity, determined by the indirect method of transmission, has been used by Tomsett (170) for assessing the quality of concrete floor slabs. He found that the technique was sufficiently sensitive to distinguish between a "sound" concrete and a "poor" concrete. The main difference, between the present method and that adopted by Tomsett (170), was that carlite bonding plaster pads were placed over the slab as the coupling medium, whereas grease was used in the present study. The sensitivity of the technique may be increased by using a probe transducer instead of a plate. This would eliminate the influence of surface texture, because only a point contact is made.

It has already been demonstrated that it is the surface layer of the slab, which may be less than 1 mm thick, which is most affected during finishing. Due to the limited sensitivity of the technique as used in the present study and, that the pulse passes through the slab it penetrates to a depth greater than 1 mm, changes in the surface layer may well be masked by the bulk properties of the concrete slab, and further investigation was not considered to be fruitful. The specimen slabs, which had been finished by different finishing techniques, subjected to different curing regimes, and treated with different surface treatments were not, therefore, subjected to the ultrasonic pulse velocity test.

### 8.3 Rebound Hardness

Many attempts (99) have been made to predict the strength of concrete from assessments of its hardness, and a widely used instrument is the Schmidt rebound hammer (174). This device is in common use for assessing the quality of in-situ concrete. It consists essentially of a spring loaded hammer which impacts against a metal plunger located on the test surface. The rebound of the hammer records a reading on a test scale, to produce a rebound number. The method is described in the B.S 4408:Pt 4 (175). The use of this hammer for estimating concrete strength has been found to be greatly influenced by surface effects such as surface quality, surface density, carbonation and dampness (176).

The sensitivity of the Schmidt rebound hammer to surface variation makes it a suitable technique for assessing indirectly the abrasion resistance of concrete. This potential suitability has been noted by several investigators (56,177,178). The present study provided an opportunity, for further examination of the relationship between rebound index, as measured by Schmidt rebound hammer, and the abrasion resistance of concrete, as measured by the standard accelerated abrasion test. All the specimen slabs which had been tested by the standard accelerated abrasion method were, therefore, also subjected to Schmidt rebound hammer tests.

#### 8.3.1 Experimental Procedure

As with the PUNDIT test the adopted procedure followed the main requirementsof the standard method (175). The test slabs were placed on top of a 20 mm layer of sand and the tests were conducted 28 days after casting, on the dry and clean concrete surface. For each test the measurements were made around the outside of the groove worn during the accelerated abrasion test. A total of 12 readings was recorded, these being equally spaced around the outside of the groove. It was considered that this procedure avoided bias in selecting the impact points. From each set of readings, the highest and the lowest were discarded, on the assumption that the highest reading may have been taken on a large aggregate particle, while the lowest reading may have been recorded on voids. Three sets of readings were taken on each slab.

8.3.2 Results and Discussion

The results from the preliminary tests, which were conducted on the specimen slabs used in the comparative study, are provided in Table 8.1. These demonstrate that the Schmidt rebound hammer is sensitive to the mix design. The differences in the rebound index between the various concrete mixes are all statistically significant, as can be seen from Table C.19, of Appendix C.1. In view of these encouraging results, it was decided to also test the specimen slabs subjected to different finishing procedures, curing regimes and surface treatments. These results are provided in Table 8.2 and 8.3, and from these, several observations have been made.

The air cured specimens generally have lower rebound indices, than the cured specimens. The lack of curing appears to have influenced the rebound index of the high water-cement ratio mix B6, more than those of mixes B5 and B4 with lower water-cement ratios. Further, this trend is more apparent with the H.F., P.F., and R.W.C. specimens than with the R.P.F. and V.D. specimens. This is consistent with the proposition that curing is more important for mixes with high water-cement ratios than for those with lower water-cement ratios as was suggested in section 6.6.2. Specimens subjected to W.B. and P.S. curing generally have lower rebound indices than those cured with curing compounds. This confirms that the hydration process is more efficient in specimens treated with curing compounds than was achieved with the other curing methods, this being particularly marked in the surface matrix.

The H.F. slabs generally display lower rebound indices than the P.F. specimens. The rebound indices of the three concrete mixes are, however, significantly different from one another for both H.F. and P.F. specimens. This indicates that the rebound index is influenced by power finishing, and that it is sensitive to variation in mix design, as was reported earlier. The R.P.F. and V.D. specimens have significantly higher rebound indices than the equivalent H.F., P.F., and R.W.C. specimens. However, the difference between the rebound indices of the three mixes appears to diminish with the application of R.P.F. and V.D. This is consistent with the results of the abrasion tests, and is attributed to the surface density of the specimens becoming similar due to the action of these power finishing techniques.

The rebound indices of the R.W.C. specimens are generally greater than those of the P.F. specimens, but they are less than those of the equivalent V.D. specimens. These results further demonstrate that the rebound index is sensitive to reduction in the water-cement ratio. With the V.D. specimens the reduction in water-cement ratio at the surface was much greater than that of the uniform reduction in the R.W.C. specimens, and the respective rebound indices are sensitive to this difference.

The rebound index does not appear to be sensitive to the various liquid surface treatments. Indeed the rebound indices for the treated surfaces are generally the same as that for the non-treated surface. The rebound index for dry shake surface treated specimens shows that the rebound index for surfaces treated with the metallic dry shake are higher than those of the surfaces treated with the non-metallic dry shakes. However, very little difference is apparent between the rebound indices of the three mixes, indicating that the dry shake dominated the properties of the base slab. This similarity in the rebound indices is apparent with both the metallic and non-metallic dry shakes. Although the rebound indices obtained with the non-metallic dry shakes are lower than those obtained with the metallic dry shake, they are generally greater than those obtained from the R.P.F. specimens.

The results and experimental observations confirm the findings of other investigators (176) that the Schmidt rebound hammer is sensitive to surface variation, but they also indicate that it is not sensitive to presence of various surface treatments. The results in Tables 8.1 to 8.3, also indicate that the rebound index is generally related to abrasion resistance of the concrete surface. This is confirmed by Figure 8.1, where the abrasion resistance is plotted against rebound index. This graph uses the results from the H.F. specimens cured by wet burlap. These data were used so that the results of both the comparative study, (mixes B1, B2 and B3) and the laboratory programme, (mixes B4, B5 and B6) could be used, the common treatments between both programmes being hand finishing and wet burlap curing. From Figure 8.1 it is clear that the abrasion resistance is directly related to rebound index. The cube strength of these specimen slabs has also been compared with the appropriate rebound indices as shown in Figure 8.2. This demonstrates that the cube crushing strength is inversely related to rebound index. From the detailed results in Tables 8.2 and 8.3, it is clear that this relationship is not so apparent due to influence of the finishing techniques, curing regimes and dry shake surface treatments. Whilst these techniques modify the surface layer, and hence the hardness, they do not significantly influence the strength, thus illustrating the danger of using the Schmidt rebound hammer to determine the strength of concrete.

The close relationship between the abrasion resistance and the rebound index, may be explained by considering the quantities measured in the rebound hardness methods. Two factors (174) dominate these measurements and they are the loss of energy due to local crushing of the cement paste and the loss of energy due to the absorption of the stress wave set up in the material by the hammer impact. The variables which were investigated (e.g. finishing techniques, curing regimes, dry shake surface treatments) influence the surface matrix, and the losses of energy are dependent on the properties of this surface matrix.

The results of the rebound tests for the H.F., P.F. and R.P.F. specimens, given in Table 8.2, are consistent with the corresponding microhardness results, given in Figure 7.13. Both indicate that the quality of the surface matrix has been influenced by the various finishing techniques. However, the results in Table 8.3 show that, whilst the liquid surface treatments influenced the abrasion resistance, the rebound indices are similar to those of the untreated control slabs. This supports the contention that these treatments do not significantly penetrate into the surface layer but merely form a smooth surface by filling the surface pores or produce a thin film of material on the surface. The results, therefore, suggest that the Schmidt rebound hammer is not sensitive to variation in surface texture produced by the application of liquid surface treatments. This conclusion is not consistent with the findings of other investigators (174) that the Schmidt rebound hammer is sensitive to variation in surface texture. The main reason for this apparent discrepancy is suggested to be due to the level of influence on the surface texture. In the case of liquid surface treatment the micro-surface texture has been influenced, while trowelling of the concrete surface influences the macro-surface texture. It can, therefore, be stated that the Schmidt rebound hammer is not sensitive to variation in micro-surface texture as created by the application of liquid surface treatments.

Overall, the results are consistent with the conclusions of other investigators that there is a correlation between the abrasion resistance and the rebound index (174,178), and that the rebound index is influenced by curing (177,178), and by finishing techniques (56,178). A classification system for floors has been proposed by Chaplin (2), see Figure 8.3. It is in the form of a relationship between the depth of wear and rebound index for a mature concrete floor. The results of the present study (using the values provided by P.F. specimens cured by P.S.) appears to fall below the curve. This is mainly because the present results were obtained 28 days after cast, i.e. young concrete, unlike the mature concrete used to obtain the classification system provided by Chaplin (2). Part of the difference between the results is due to carbonation. Since, the mature concrete has been exposed to the atmosphere, and that Portland cement concrete becomes harder and stronger as it carbonates (179), (this is not true for blast furnace slag cement or high alumina cement), therefore, higher rebound index results are obtained.

The results of the present study suggest that rebound index is partially sensitive to the quality of the surface matrix, and that it is generally related to abrasion resistance. Further research is necessary to investigate such relationships, particularly with respect to the influence of other variables, e.g. cement, sand; coarse aggregate, carbonation etc., on both the rebound index and the abrasion resistance of concrete.

## 8.4 Initial Surface Absorption

The Initial Surface Absorption is defined as the rate of flow of water into concrete per unit area over a stated interval of time from the start of the test at a constant applied head and temperature. The Initial Surface Absorption Test (ISAT) has been used to assess the permeability (180) of concrete. However, the method has been criticized (99) on the basis that it only gives information regarding the very thin "skin" of the concrete under investigation, since the ISAT relates only to moisture movement into the immediate surface layer. These properties have already been shown to have a significant influence on the abrasion resistance, and so it was considered that the ISAT may be suitable for indirect assessments of the abrasion resistance of concrete.

To fully assess the suitability of this technique, a range of specimen slabs was selected for the ISAT so as to cover several aspects of the main investigation. The specimens were selected from those used for:-

(1) The comparative study, mixes B1, B2 and B3.

(2) The study of the finishing techniques, mixes B4, B5 and B6, restricted to the H.F., P.F., and R.P.F., techniques, all cured by the wet burlap method.

(3) The study of the liquid surface treatments, again mixes B4, B5 and B6 using treatments, O, A, B, C, D and E.

### 8.4.1 Experimental Procedure

The Initial Surface Absorption Tests were performed 30 days after casting, on the clean, dry surface of the slabs, three tests being performed on each slab. To maintain consistency, each test was located inside the circular groove cut during the accelerated abrasion test as is shown in Plate 8.1 and Figure D.5 in Appendix D. The test procedure is fully described in B.S 1881 : Pt 5 (181), and this procedure was followed in this study. It involved fixing a sealed cap onto the surface of the test specimen, the face area of this cap being known. This fixing was achieved using a specific clamping device which was developed for this investigation, the general arrangement can be seen in Plate 8.1. The top of the cap was fitted with two access pipes, one connected to a filter funnel reservoir, the other to a capillary tube of known dimensions. The inlet pipe connected to the reservoir was fitted with a stop tap.

To start testing, the reservoir was filled with water which entered the cap via the inlet tube and could exit the apparatus via the end of the capillary. Immediately the water came into contact with the specimen a clock was started to register the beginning of the test period. When the reservoir was disconnected the rate of absorption of water can be determined by timing the movement of the meniscus as it travels back along the capillary. Measurements were taken after 10 minutes, 30 minutes and 60 minutes and at each interval, three readings were recorded.

### 8.4.2 Results and Discussion

In the initial series, the ISAT was performed on the specimen slabs which had been prepared for the comparative study. The results of this preliminary study are shown in Table 8.1, and it can be seen that the Initial Surface Absorption is sensitive to mix design. This variation is statistically significant, as is illustrated in Tables C.20 to C.22 of Appendix C.1. The results of the ISAT on specimen slabs prepared for assessing the influence of finishing techniques, and liquid surface treatments, are provided in Tables 8.4 and 8.5, respectively. These results provide further confirmation that the ISAT is sensitive to variation in mix design. The results from the comparative study, together with those from the H.F. slabs produced in the study of finishing techniques, have been used to plot the abrasion depth and cube strength, against the Initial Surface Absorption value determined after 10 minutes. These plots are shown in Figures 8.4 and 8.5, and they illustrate that abrasion resistance varies inversely with the Initial Surface Absorption, whilst the cube strength varies directly with the Initial Surface Absorption. Although this plot relates only to the values determined at 10 minutes, similar relationships were observed with the 30 minute and 60 minute values.

The ISAT results on the finishing technique specimens, shown in Table 8.4, clearly demonstrate that there is a significant difference between the Initial Surface Absorption rates for the H.F., P.F., and R.P.F. specimen slabs of each concrete mix. This, therefore, indicates that the ISAT is sensitive to variation in finishing technique, and is consistent with the abrasion depths obtained with the accelerated abrasion test.

The sensitivity of the ISAT to differences in mix design and finishing technique is consistent with the conclusion that porosity is a function of water-cement ratio and that permeability is related to porosity and pore size distribution (99,182). The results of the ISAT further confirm the conclusion of the MIP method that higher PSD and pore volumes are associated with higher water-cement ratio mixes and, that finishing technique influences the PSD and pore volume of the surface matrix of the specimen (see Section 7.2.3.1). Furthermore, the present results for the finishing technique specimens, see Table 8.4, confirm the contention that the ISAT does not wholly represent the true permeability characteristic of the concrete, only of its surface matrix.

The ISAT results for the surface treated slabs are provided in Table 8.5. These results show that, for each mix, Initial Surface Absorption values for the treated specimens were significantly lower than that of an equivalent, non-treated specimen. This indicates that the ISAT is sensitive to variation in surface treatment. The Initial Surface Absorption values for the specimens treated with surface hardeners, were significantly higher than those surfaces treated with in-surface seals. Furthermore, the Initial Surface Absorption values for treated specimens from mix B6, with the high water-cement ratio, were greater than those with correspondingly lower water-cement ratio from mix B4. The implication is that the Initial Surface Absorption is influenced by both the type of treatment and the mix properties of the concrete under investigation. This is consistent with the conclusion that the permeability of concrete is a function of the surface porosity (99). These ISAT results are consistent with the results of the abrasion test obtained by the accelerated abrasion machine.

The results obtained by the Initial Surface Absorption technique suggest that the method is extremely sensitive to mix design, finishing technique and surface treatments. Furthermore, there is a very close relationship between the abrasion resistance and the Initial Surface Absorption. This is mainly attributed to both tests being influenced by the micro-surface texture and the quality of the surface matrix. The application of liquid surface treatment influences the micro-surface texture of concrete by filling pores and valleys available to produce a smoother surface. The blocking of the pores will, therefore, reduce permeability and abrasion resistance of the surface.

The maximum coefficient of variation found with the ISAT results was 5.2%, which compares well with the value of 5% reported by other investigators (183). No published results have been located which can be compared directly with the results and conclusions of the present study. However, Levitt (184) has proposed a classification for the quality of concrete, based on the ISAT, and this is provided in Table 8.6. It is interesting to compare some of the results of the present study with the limits proposed by Levitt (184). By considering the data in Table 8.4, 8.5. and 8.6 it can be seen that, with all three mixes, the R.P.F. specimens, and the slabs treated with the in-surface seals, exhibit Initial Surface Absorption values which generally fall within the "good" quality limits of the proposed classification. In comparison, Initial Surface Absorption values which fall within the "poor" quality limits, are obtained from mix B6 specimens subjected to the H.F. and P.F. processes and also those treated with surface hardeners. A comparison between the Initial Surface Absorption values, determined in the present study, and the corresponding values of abrasion depth can be used to explore the suitability of Levitt's classification for the assessment of abrasion resistance. An abrasion depth of less than 0.40 mm generally corresponds to "good" concrete, and abrasion depths greater than 0.80 mm would correspond to "poor" concrete as proposed by Levitt.

The results of this section suggest that the ISAT is more sensitive than the Schmidt rebound hammer to changes in those parameters which influence the abrasion resistance of concrete. Furthermore, the results indicate that the Initial Surface Absorption is closely related to the abrasion resistance of concrete as determined by the accelerated abrasion test. The implication of the present finding is that the ISAT may be used as the basis of a method which could be used to indirectly, and non-destructively, assess the abrasion resistance of concrete slabs. However, the present study has been limited and only a few variables have been investigated. There is a need, therefore, for further investigation to confirm the conclusions of the present study and to investigate other variables which could influence the relationship between Initial Surface Absorption and abrasion resistance. In the present study, little difficulty was encountered in fixing the cap onto the surface of the test specimen to ensure that a water-tight fit was obtained. This was made possible by the use of a clamping device which was designed for this study. However, the use of this equipment for in-situ testing may be more difficult, unless an appropriate fixing device can be designed. This would probably entail drilling holes into the concrete slab and further work is required to develop the test system for site work.

## 8.5 SUMMARY

In this part of the programme, three non-destructive test methods were investigated to determine their suitability as indirect methods for assessing the abrasion resistance of concrete slabs. The Ultrasonic Pulse Velocity technique was not found to be sufficiently sensitive to variation in the concrete mix design. The surface hardness method, using the Schmidt rebound hammer was found to be partially sensitive to factors which are known to influence the abrasion resistance of concrete. The Initial Surface Absorption method was found to be very sensitive to these factors and, was closely related to abrasion resistance of concrete as determined by the accelerated abrasion test.

| Mix No. | Slab No. | Test No. | Mean Cube Crushing Strength ($N/mm^2$) | Mean * Abrasion Depth (mm) | Mean * Pulse Velocity (Km/S) | Mean * Rebound Index | ISAT ($ml/m^2/s$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 10 Min. | 30 Min. | 60 Min. |
| B1 | | 1 | | 0.39 | 4.608 | 41 | 0.253 | 0.181 | 0.113 |
| | 1 | 2 | | 0.32 | 4.535 | 42 | 0.238 | 0.165 | 0.105 |
| | | 3 | | 0.31 | 4.709 | 40 | 0.229 | 0.174 | 0.110 |
| | | 1 | | 0.33 | 4.633 | 45 | 0.253 | 0.168 | 0.106 |
| | 2 | 2 | 69.2 | 0.34 | 4.517 | 46 | 0.245 | 0.168 | 0.109 |
| | | 3 | | 0.35 | 4.651 | 43 | 0.243 | 0.170 | 0.118 |
| | | 1 | | 0.35 | 4.382 | 42 | 0.250 | 0.187 | 0.108 |
| | 3 | 2 | | 0.29 | 4.458 | 41 | 0.247 | 0.175 | 0.113 |
| | | 3 | | 0.37 | 4.405 | 43 | 0.258 | 0.185 | 0.121 |
| B2 | | 1 | | 0.60 | 4.577 | 37 | 0.326 | 0.241 | 0.159 |
| | 1 | 2 | | 0.51 | 4.562 | 39 | 0.335 | 0.247 | 0.172 |
| | | 3 | | 0.60 | 4.680 | 37 | 0.319 | 0.238 | 0.155 |
| | | 1 | | 0.62 | 4.422 | 38 | 0.342 | 0.252 | 0.168 |
| | 2 | 2 | 60.0 | 0.59 | 4.449 | 37 | 0.349 | 0.258 | 0.170 |
| | | 3 | | 0.50 | 4.345 | 40 | 0.333 | 0.243 | 0.163 |
| | | 1 | | 0.63 | 4.361 | 34 | 0.321 | 0.237 | 0.152 |
| | 3 | 2 | | 0.60 | 4.419 | 35 | 0.307 | 0.226 | 0.149 |
| | | 3 | | 0.59 | 4.352 | 36 | 0.325 | 0.233 | 0.155 |
| B3 | | 1 | | 0.81 | 4.396 | 29 | 0.543 | 0.398 | 0.262 |
| | 1 | 2 | | 0.87 | 4.311 | 30 | 0.530 | 0.378 | 0.238 |
| | | 3 | | 0.74 | 4.292 | 33 | 0.518 | 0.381 | 0.240 |
| | | 1 | | 0.80 | 4.484 | 31 | 0.530 | 0.386 | 0.246 |
| | 2 | 2 | 39.4 | 0.72 | 4.526 | 32 | 0.515 | 0.345 | 0.220 |
| | | 3 | | 0.88 | 4.516 | 31 | 0.520 | 0.370 | 0.236 |
| | | 1 | | 0.68 | 4.388 | 33 | 0.503 | 0.364 | 0.231 |
| | 3 | 2 | | 0.97 | 4.275 | 33 | 0.540 | 0.386 | 0.242 |
| | | 3 | | 0.80 | 4.351 | 32 | 0.514 | 0.377 | 0.235 |

NOTE: * Mean of one set of readings

TABLE 8.1 Summary of Preliminary Results for Pulse Velocity, Schmidt Hammer and ISAT

| Type of Finishing Technique | Type of Curing Regime | MIX B4 Mean Cube Crushing Strength ($N/mm^2$) | MIX B4 Mean * Abrasion Depth (mm) | MIX B4 Mean * Rebound Index | MIX B5 Mean Cube Crushing Strength ($N/mm^2$) | MIX B5 Mean * Abrasion Depth (mm) | MIX B5 Mean * Rebound Index | MIX B6 Mean Cube Crushing Strength ($N/mm^2$) | MIX B6 Mean * Abrasion Depth (mm) | MIX B6 Mean * Rebound Index |
|---|---|---|---|---|---|---|---|---|---|---|
| H.F | A.C | | 0.83 | 33 | | 1.10 | 26 | | 1.68 | 19 |
| | W.B | | 0.57 | 35 | | 0.68 | 29 | | 0.89 | 25 |
| | P.S | | 0.46 | 37 | | 0.61 | 30 | | 0.84 | 24 |
| | CC1 | 63.5 | 0.49 | 38 | 45.2 | 0.62 | 32 | 27.9 | 0.65 | 28 |
| | CC2 | | 0.57 | 36 | | 0.61 | 33 | | 0.74 | 26 |
| | CC3 | | 0.58 | 36 | | 0.66 | 31 | | 1.03 | 23 |
| P.F | A.C | | 0.47 | 35 | | 0.90 | 29 | | 1.29 | 20 |
| | W.B | | 0.31 | 36 | | 0.56 | 34 | | 0.82 | 25 |
| | P.S | | 0.30 | 39 | | 0.48 | 33 | | 0.66 | 30 |
| | CC1 | 64.9 | 0.25 | 42 | 44.1 | 0.44 | 35 | 26.5 | 0.58 | 30 |
| | CC2 | | 0.22 | 41 | | 0.41 | 33 | | 0.60 | 27 |
| | CC3 | | 0.20 | 42 | | 0.45 | 34 | | 0.58 | 27 |
| R.P.F | A.C | | 0.18 | 44 | | 0.35 | 42 | | 0.38 | 38 |
| | W.B | | 0.09 | 47 | | 0.20 | 44 | | 0.27 | 40 |
| | P.S | | 0.10 | 46 | | 0.18 | 44 | | 0.17 | 42 |
| | CC1 | 61.6 | 0.05 | 48 | 47.2 | 0.14 | 46 | 28.7 | 0.16 | 43 |
| | CC2 | | 0.03 | 51 | | 0.06 | 48 | | 0.14 | 42 |
| | CC3 | | 0.02 | 49 | | 0.04 | 47 | | 0.13 | 45 |
| V.D | A.C | | 0.35 | 41 | | 0.47 | 39 | | 0.63 | 34 |
| | W.B | | 0.18 | 42 | | 0.25 | 40 | | 0.31 | 37 |
| | P.S | | 0.23 | 44 | | 0.25 | 41 | | 0.27 | 38 |
| | CC1 | 60.3 | 0.16 | 46 | 46.5 | 0.20 | 43 | 27.4 | 0.30 | 36 |
| | CC2 | | 0.14 | 45 | | 0.20 | 44 | | 0.24 | 38 |
| | CC3 | | 0.15 | 44 | | 0.23 | 40 | | 0.28 | 37 |
| R.W.C | A.C | | 0.40 | 38 | | 0.53 | 32 | | 0.98 | 26 |
| | W.B | | 0.24 | 41 | | 0.39 | 37 | | 0.60 | 30 |
| | P.S | | 0.28 | 40 | | 0.41 | 37 | | 0.51 | 27 |
| | CC1 | 71.0 | 0.22 | 40 | 55.4 | 0.27 | 39 | 38.9 | 0.57 | 31 |
| | CC2 | | 0.18 | 43 | | 0.28 | 40 | | 0.46 | 30 |
| | CC3 | | 0.20 | 42 | | 0.30 | 38 | | 0.49 | 33 |

NOTE: * Mean of Three Sets of Readings

TABLE 8.2 Summary of Rebound Index Test Results for Finishing Technique Specimens

| Mix No. | Type of Surface Treatment | Mean Cube Crushing Strength ($N/mm^2$) | Mean * Abrasion Depth (mm) | Mean * Rebound Index |
|---|---|---|---|---|
| B4 | O | 46.4 | 0.54 | 32 |
| | A | " | 0.40 | 33 |
| | B | " | 0.38 | 30 |
| | C | " | 0.08 | 33 |
| | D | " | 0.07 | 31 |
| | E | " | 0.12 | 32 |
| | D.S.1 | 62.7 | 0.01 | 52 |
| | D.S.2 | 68.3 | 0.02 | 48 |
| | D.S.3 | 62.8 | 0.03 | 48 |
| | D.S.4 | 65.5 | 0.03 | 47 |
| B5 | O | 34.6 | 0.78 | 27 |
| | A | " | 0.51 | 27 |
| | B | " | 0.48 | 28 |
| | C | " | 0.12 | 26 |
| | D | " | 0.14 | 28 |
| | E | " | 0.22 | 26 |
| | D.S.1 | 43.8 | 0.03 | 50 |
| | D.S.2 | 48.2 | 0.08 | 47 |
| | D.S.3 | 44.2 | 0.07 | 48 |
| | D.S.4 | 43.5 | 0.05 | 48 |
| B6 | O | 18.1 | 1.18 | 24 |
| | A | " | 0.89 | 24 |
| | B | " | 1.00 | 22 |
| | C | " | 0.26 | 23 |
| | D | " | 0.14 | 23 |
| | E | " | 0.28 | 22 |
| | D.S.1 | 30.1 | 0.04 | 50 |
| | D.S.2 | 27.6 | 0.13 | 44 |
| | D.S.3 | 28.9 | 0.16 | 44 |
| | D.S.4 | 30.7 | 0.15 | 48 |

NOTE: * Mean of Three Sets of Readings

TABLE 8.3 Summary of Rebound Index Test Results for Surface Treated Specimens

| Type of Finishing Technique | MIX B4 | | | | MIX B5 | | | | MIX B6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | |
| | | 10 Min | 30 Min | 60 Min | | 10 Min | 30 Min | 60 Min | | 10 Min | 30 Min | 60 Min |
| H.F | 0.57 | 0.296 | 0.224 | 0.157 | 0.68 | 0.372 | 0.273 | 0.186 | 0.89 | 0.620 | 0.496 | 0.369 |
| P.F | 0.31 | 0.222 | 0.162 | 0.099 | 0.56 | 0.299 | 0.208 | 0.134 | 0.82 | 0.516 | 0.354 | 0.229 |
| R.P.F | 0.09 | 0.057 | 0.039 | 0.017 | 0.20 | 0.180 | 0.132 | 0.083 | 0.27 | 0.212 | 0.165 | 0.103 |

NOTE: * Mean of Three Sets of Results

TABLE 8.4 Summary of ISAT for the Finishing Technique Specimens Cured by Wet Burlap Curing Method

| Type of Surface Treatment | MIX B4 | | | | MIX B5 | | | | MIX B6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | | Mean * Depth of Abrasion (mm) | ISAT*(ml/$m^2$ per Sec) | | |
| | | 10 Min | 30 Min | 60 Min | | 10 Min | 30 Min | 60 Min | | 10 Min | 30 Min | 60 Min |
| O | 0.54 | 0.282 | 0.193 | 0.138 | 0.78 | 0.543 | 0.367 | 0.228 | 1.18 | 0.899 | 0.644 | 0.395 |
| A | 0.40 | 0.216 | 0.167 | 0.116 | 0.51 | 0.282 | 0.188 | 0.108 | 0.89 | 0.677 | 0.457 | 0.292 |
| B | 0.38 | 0.227 | 0.151 | 0.120 | 0.48 | 0.290 | 0.213 | 0.136 | 1.00 | 0.747 | 0.527 | 0.327 |
| C | 0.08 | 0.057 | 0.036 | 0.028 | 0.12 | 0.100 | 0.077 | 0.052 | 0.26 | 0.226 | 0.163 | 0.102 |
| D | 0.06 | 0.033 | 0.026 | 0.015 | 0.14 | 0.158 | 0.098 | 0.056 | 0.14 | 0.173 | 0.131 | 0.089 |
| E | 0.12 | 0.062 | 0.034 | 0.021 | 0.22 | 0.20 | 0.148 | 0.092 | 0.28 | 0.213 | 0.159 | 0.103 |

NOTE: * Mean of Three Sets of Results

TABLE 8.5 Summary of ISAT for the Surface Treated Specimens

| | ISAT (ml/$m^2$/Sec) | | |
|---|---|---|---|
| | 10 Min. | 30 Min. | 1 hr. |
| GOOD | <0.25 | <0.17 | <0.10 |
| AVERAGE | 0.25 - 0.50 | 0.17 - 0.35 | 0.10 - 0.20 |
| POOR | >0.50 | >0.35 | >0.20 |

TABLE 8.6 Suggested Limits with the ISAT
(Based on Ref. 184 )

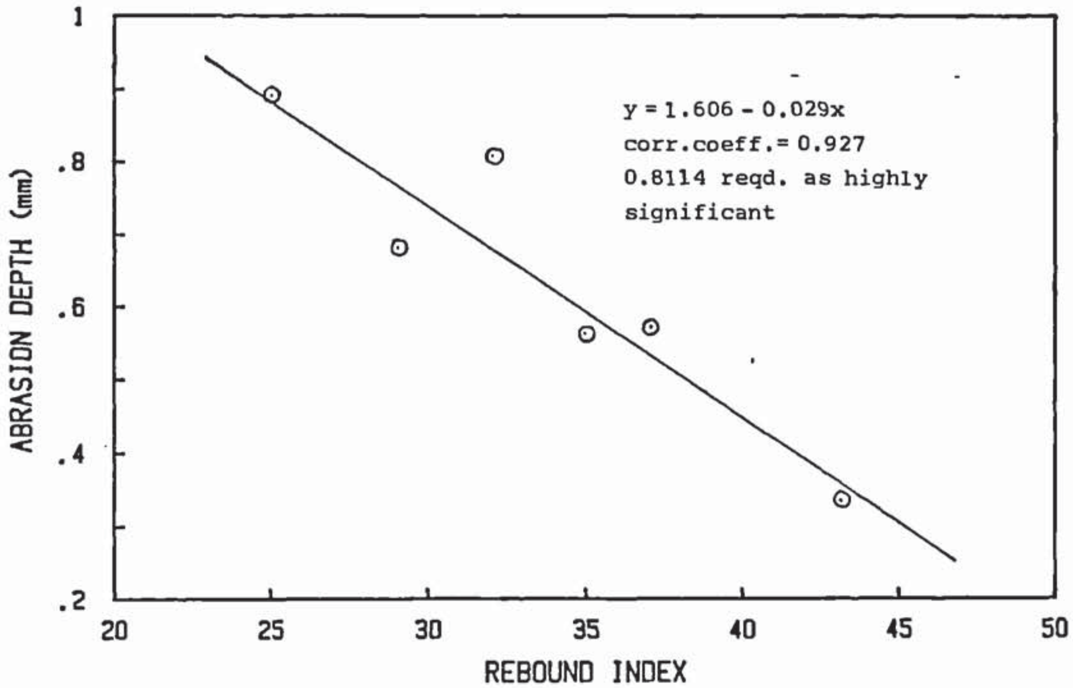



FIGURE 8.1 Abrasion Depth V's Rebound Index

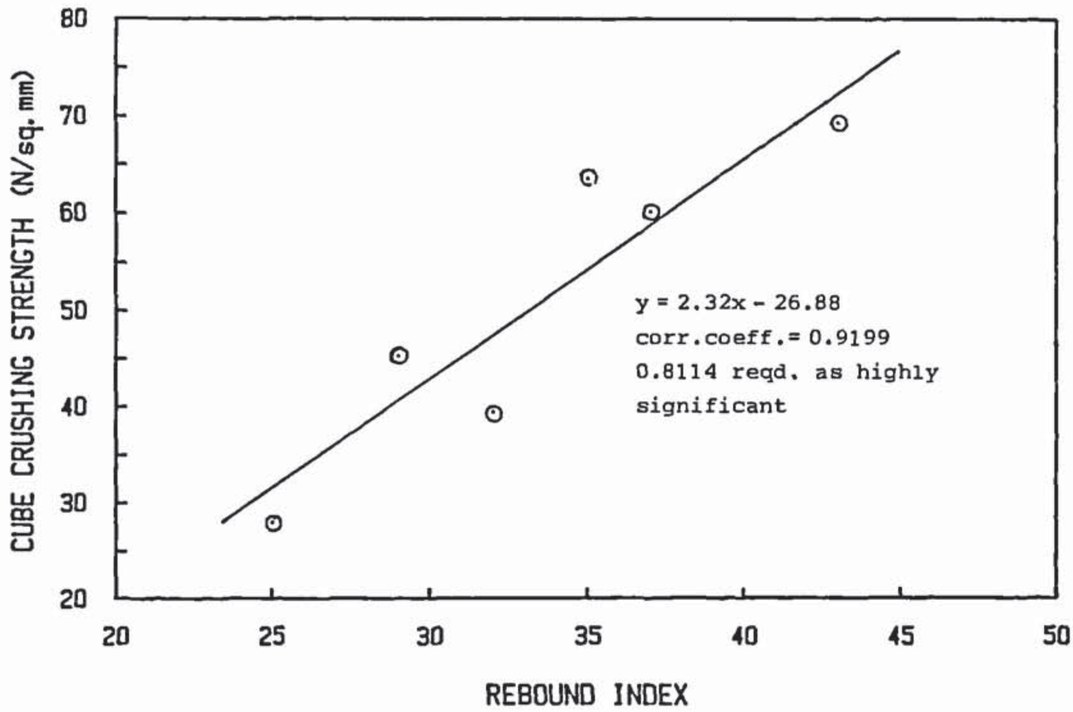



FIGURE 8.2 Cube Crushing Strength V's Rebound Index

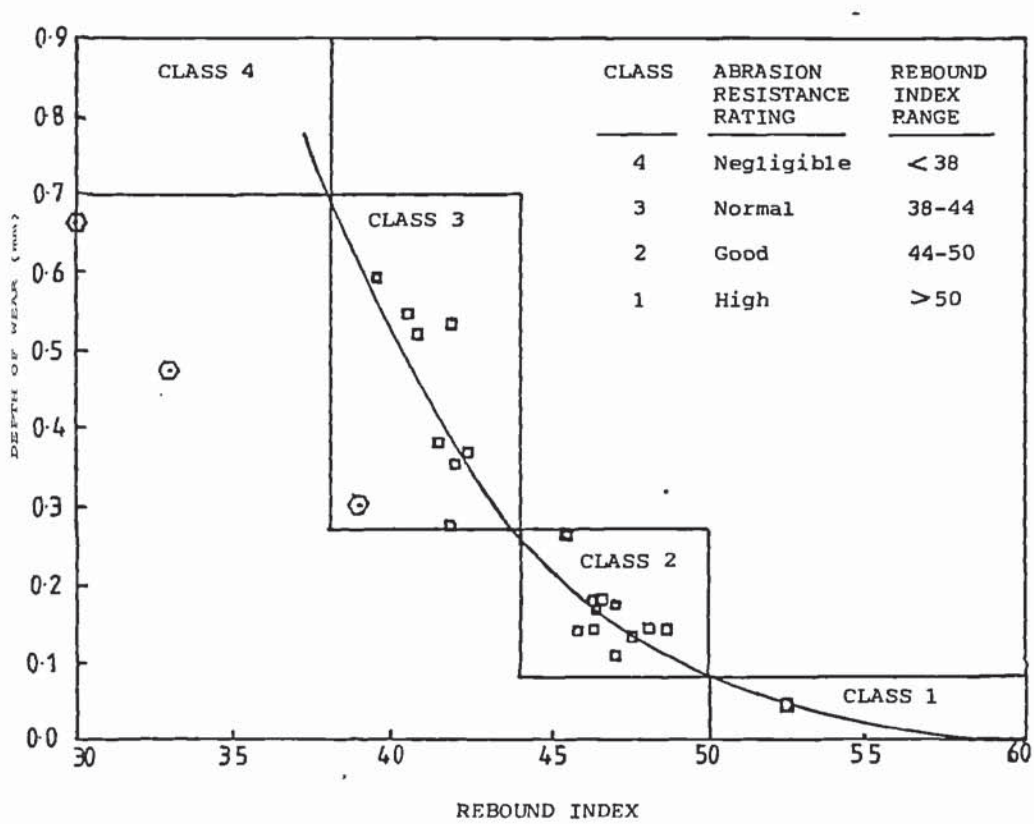



FIGURE 8.3 Relationship Between Depth of Wear and Rebound Index for Different Classes of Concrete Floors (Based on Ref.2)

KEY

CHAPLIN'S MATURE CONCRETE □

LABORATORY 28 DAYS CONCRETE ⊙

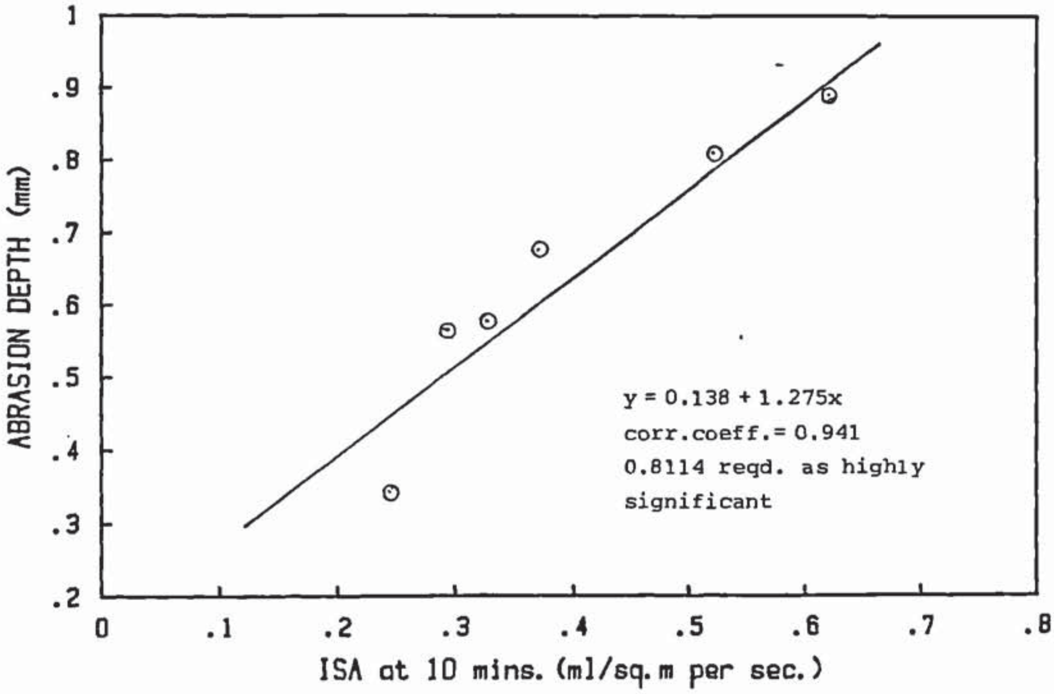



FIGURE 8.4 Abrasion Depth V's ISA at 10 Mins.

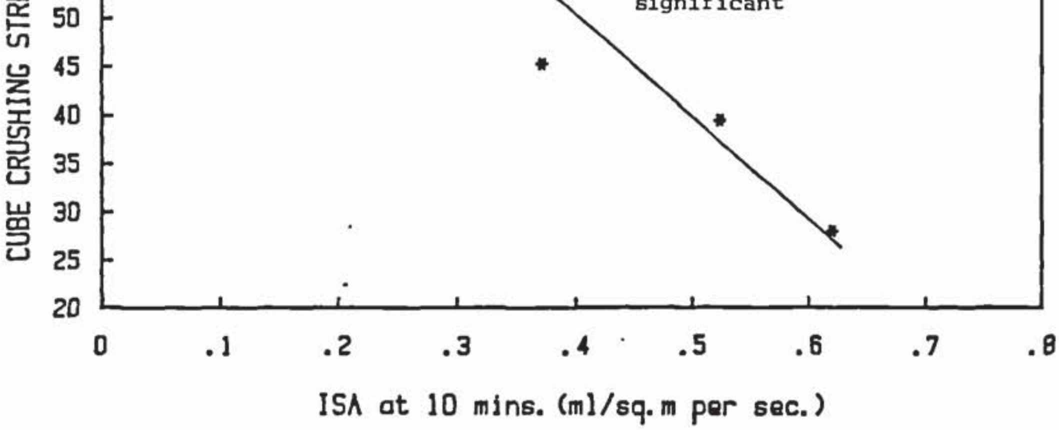



FIGURE 8.5 Cube Crushing Strength V's ISA at 10 Mins.

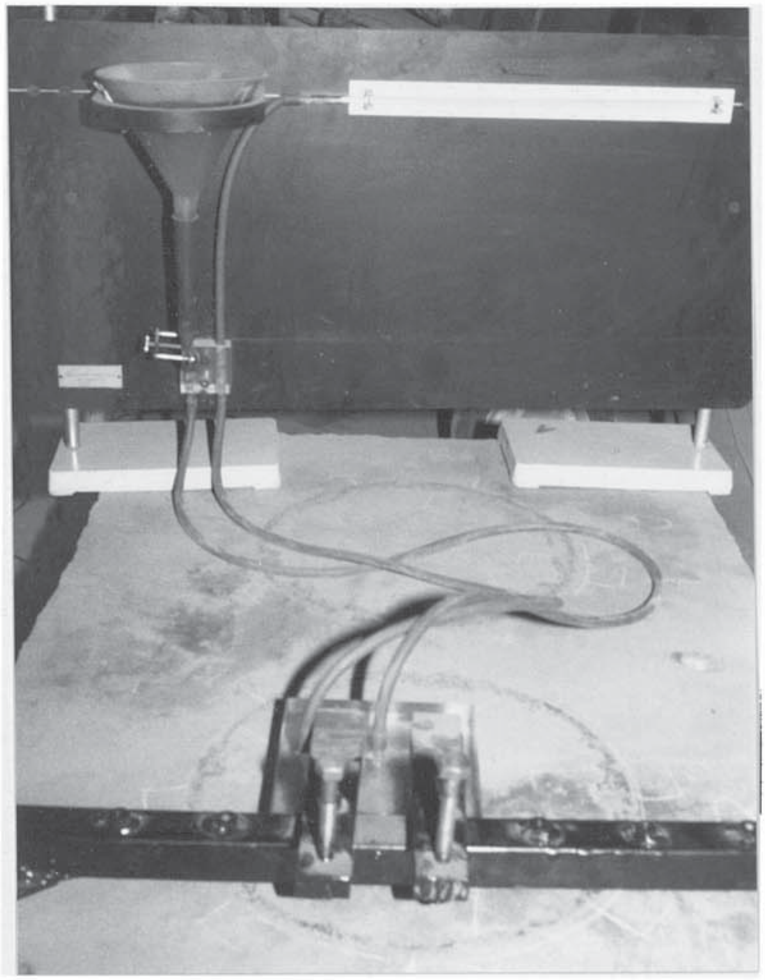


Plate 8.1 Initial Surface Absorption Apparatus in Position on a Test Slab

# CHAPTER 9

# FIELD INVESTIGATION OF ABRASION RESISTANCE

## 9.1 Introduction

The present chapter deals mainly with accelerated abrasion tests performed in-situ, on industrial, concrete floor slabs. The main purpose of this phase of the investigation was to assess:-

(1) The relationship between laboratory and site practices, as assessed by performance when subjected to the accelerated abrasion test.

(2) The current standard of newly constructed floor slabs in terms of their abrasion resistance.

(3) The relationship between the accelerated abrasion test and the service performance.

The following sections discuss the attempts which were made to achieve these objectives.

## 9.2 Laboratory and Site Comparison

Four construction sites were visited during construction of the concrete floor slabs. The construction processes adopted for 10 sections of the concrete floor slabs were carefully studied. From each of these sections two specimen slabs, 1.0 m x 0.5 m x 0.1 m were constructed to produce a total of 20 specimen slabs. The concrete with which the specimen slabs were constructed was taken from the same load of ready mix concrete as was used for the particular section of the main floor slab. This was to try to eliminate any variations due to the concrete mix.

The procedure for constructing the concrete floor slabs was similar to that described in Section 6.2.2, where the screeding was performed by two passes with a hand-tamping beam operated by two men.

Power finishing equipment was used for the finishing operations, power floating and trowelling. The slabs were subjected to one application of power floating and two applications of power trowelling, the last of these was performed the morning after casting. The rate of stiffening was largely dependent on the ambient temperature which was generally around 14 degrees C. Polythene sheeting was used to cure the floor slabs. All the concrete floor slabs were constructed by one floor contractor, Johnson Floor Company, and eight of these slabs were constructed by the same gang, these being the slabs at Eli-Lilly, Smith Industries and Sony. In addition, all these projects were under the control of IDC Limited, as the factory developer/designer.

Each pair of specimen slabs was constructed and screeded following the procedure described in Section 6.4. The finishing procedures were performed by hand, using a wooden float and a steel trowel. Attempts were made to perform the finishing operations on the specimen slabs at the same time as they were being conducted on the floor slab. This was not completely achieved, with the final trowelling being applied about 12 hours after the concrete was poured. It is suggested that the rate of stiffening of the specimen slabs was due to them having a much lower mass and depth than the floor slabs. The next day, the specimen slabs were demoulded and one was site cured, adjacent to the floor slab, and the other was transported to the University of Aston for curing. Both were cured with polythene sheeting, similar to that employed on the floor slab.

Two of the floor slabs used in this study received a cementitious dry shake called Betonac, which was supplied by Cementation Chemicals Limited. This dry shake was also applied at the same time to the appropriate pairs of specimen slabs in the same manner and in the same quantity as it was applied to the floor slab. The finishing procedure was the same as that described above.

At 28 days after casting each of the slabs was subjected to the standard accelerated abrasion test using the rolling wheels type of head. Three tests were performed on each of the slabs, i.e. the pair of specimen slabs and the floor slab, for each section of the floor slab that was investigated. In addition to the abrasion tests, each slab was subjected to a Schmidt rebound hammer test using the procedures described in Section 8.3.1.

### 9.2.1 Results and Discussion

The results of this study are provided in Table 9.1, and they show that the abrasion resistances of the various floor slabs were significantly greater than those of either of the corresponding specimen slabs. Little difference was detected between the abrasion resistance of the floor slabs treated with Betonac (As 9, As 10) and that of the similarly treated specimen slabs (Ls 9, Ts 9, Ls 10, Ts 10). Indeed, there was little difference between the abrasion resistance of the treated floor slab and that of the comparable untreated floor slabs (As 7, and As 8). It is also interesting to note that a higher specified concrete cube strength does not necessarily ensure a higher abrasion resistance. This is illustrated by the results in Table 9.1 for floor slabs 2, 3 and 5 as compared to those for floor slabs 1, 7 and 8. These effects are largely due to the application of power finishing, and the associated mechanisms have been explained in detail in Chapters 6 and 7. The present results corroborate those findings of the laboratory programme.

The test specimens, cured on site, generally exhibit more wear in the abrasion test than the laboratory cured specimens. This is attributed to the better control of curing which was achieved in the laboratory. It is interesting to note that there is very little difference between the laboratory and site cured specimens in the case of surface treated specimen slabs (Ls 9,Ts 9, and Ls 10).

The results of the rebound index tests, Table 9.1, are in general agreement with the abrasion resistance results. These results have been compared with the classification curve presented by Chaplin (2). This is shown in Figure 9.1 and it can be seen that they generally fall below the curve. These tests were performed 28 days after casting and so are the results for young concrete, whereas Chaplin's curve relates to mature concrete. This would be expected to have correspondingly higher rebound values due to the effect of carbonation on the exposed surface (See Chapter 8).

The results of this study demonstrate that the specimen slabs which were hand finished, displayed significantly lower abrasion resistances than the equivalent floor slabs finished with power finishing equipment. It is clear, therefore, that laboratory investigations must attempt to replicate site practices if the data is to be of value to the practising engineer.

## 9.3 Abrasion Resistance of Newly Constructed Industrial Concrete Floor Slabs

For this study, 5 completed industrial premises were investigated, and a total of 6 different floor slabs were tested approximately 6 months after their construction. All of these industrial premises were related to contracts being undertaken by IDC Limited. Two of these contracts were visited earlier during comparative study of laboratory and site practices, these were the Eli-Lilly and Pirelli properties.

These floor slabs were subjected to the standard accelerated abrasion test, using the rolling wheels type of head, and to the Schmidt rebound hammer test. Three sets of tests were performed on each floor slab, the test sites were separated from each other in an attempt to obtain a true representation of the abrasion resistance of each floor slab. However, it would have been desirable to perform more tests but, due to the floor slabs being newly constructed, this was not possible since the accelerated abrasion test leaves a permanent track, or a groove in the test surface.

### 9.3.1 Results and Discussion

The abrasion resistance of the floor slabs, together with the corresponding Schmidt hammer results are provided in Table 9.2. It is clear from these results that the abrasion resistance of slabs 1 and 6 which had granolithic toppings was not significantly greater than those of the plain concrete slabs, 2, 3, 4 and 5. Furthermore, the results demonstrate that a higher specified concrete strength does not necessarily increase the abrasion resistance, as can be seen by comparing the values for slabs 2, 4 and 5. With slabs 4 and 5 it was possible to obtain the mean cube strengths which were 41·5 $N/mm^2$ and 46.0 $N/mm^2$ respectively. Thus these values reinforce the earlier comment that slabs with the higher cube strength, exhibited more wear in the abrasion test.

The abrasion results from the floor slabs which were treated with granolithic toppings exhibited much more variation than those from the plain concrete floor slabs as can be seen from Table 9.2. From these results, the coefficient of variation for the surface treated floor slabs was 23% and 56%, whereas that for the plain concrete floor slabs ranged from 12% to 19%. This high variation in the results of the treated slabs is mainly due to non-uniform application of the granolithic topping mixture. With the plain concrete floor slabs the coefficients of variation are rather low, particularly when account is taken of the variations inherent in in-situ testing, arising from differences in compaction and curing, and the non-uniform supply of material. In the previous section, the coefficient of variation for the in-situ abrasion tests ranged between 6% and 8%. It is suggested that these low values were due to the variations in compaction and curing and the inconsistencies in supply being largely eliminated by conducting the abrasion tests in close proximity to each other. The variations found in these results are, therefore, due to the method of testing.

The results from the plain concrete floor slabs tested at the Eli-Lilly and Pirelli premises are of particular interest, since these slabs were tested at 28 days in the comparison study and again after 6 months for the present study. When the abrasion resistance results are compared there is no significant difference between them as can be seen by comparing the appropriate values in Tables 9.1 and 9.2. However, when the rebound hardness results are compared for these floor slabs, it can be seen that there is a significant difference between the results, with the 28 days values being lower than those obtained at 6 months. This can mainly be attributed to the effects of carbonation, but the results indicate that abrasion resistance is not influenced as much as the rebound hardness. The implication of this is that the relationship of rebound hardness and abrasion resistance is not straightforward, and should include a factor for the age of the slab. When the results of the rebound hardness for these new slabs are compared to Chaplin's (2) classification curve, shown in Figure 9.1, it appears that they are more closely related to the curve than the results obtained from the comparative study which were tested at 28 days. These site values, obtained at 6 months, either lie on the curve or are just above, giving slightly higher abrasion depths than could be expected.

The floor slab which was finished by a combination of vacuum dewatering and power finishing methods, produced the highest abrasion resistance and rebound hardness values. The lowest level of abrasion resistance was displayed by the floor slab which had been given a granolithic topping. This indicates that dry shake surface treatments do not, necessarily, increase abrasion resistance. They must be correctly formulated and carefully placed and finished.

The industrial floor slabs which have been included in the comparison study and the present investigation, may be classified as being subjected to medium industrial traffic, according to the definition given in Section 2.3. The results of these investigations suggest that for such slabs, typically the normal range for their abrasion resistance, is between 0.2 to 0.3 mm. These values have been established using the accelerated abrasion test machine, with the rolling wheels type of head, for the standard duration of 15 minutes. It should be noted that the present results were obtained from a limited number of floor slabs which had been mostly constructed by one contractor, and so the general applicability of the results will be limited. To overcome some of these limitations, it was decided to investigate the abrasion performance of a large number of mature concrete floor slabs.

## 9.4 Abrasion Resistance of Old Industrial Concrete Floor Slabs

For this study lists of clients were obtained from contracts which had been completed by IDC Limited, and Floorlife-Andek Limited, during the last 12 years. A standard letter, see Appendix E letter C, was sent to 30 of these clients asking for permission to test their factory or warehouse floor slabs. Permission was obtained from 8 of these clients. In addition, contact was made with Telford Development Corporation, who are responsible for many industrial warehouses, and permission was obtained to test a selection of their premises. A total of 22 different floor slabs were tested in this programme and these had been constructed by several different floor contractors. At most locations two or more floor slabs were examined.

The main objective of this programme was to assess the relationship between the abrasion resistance, as measured by the accelerated abrasion test, and the actual service performance. To achieve this in a quantitative manner requires periodic measurements of the actual depth of wear by reference to a series of datum points on the actual floor slab. It is also necessary to know the traffic loadings to which the floor slab has been subjected. This would have to include type of traffic, frequency, wheel loads, type of wheel etc. Furthermore, the wear on the section of floor slab will be more severe where the traffic changes direction. These suggest that the quantitative determination of the relationship between accelerated wear and actual service wear is extremely difficult and the accuracy of such an analysis will be open to question. In the present study, the adopted procedure may be described as a subjective, qualitative assessment of the actual wear which has taken place since each floor slab was constructed.

In the various premises, there was a vast range of Fork-Lift trucks, including differences both in manufacture and type. These included counter-balanced trucks, narrow aisle reach truck, narrow aisle turret truck, pallet truck and order picking trucks. These can broadly be divided into two main types, depending upon the nature of the tyres fitted to the wheels, either pneumatic or solid. Solid tyres are made from a variety of materials including steel, nylon, rubber and polyurethane. A truck with either pneumatic or rubber tyres will cause less wear to a floor slab than a truck of identical weight with solid tyres of steel, nylon or polyurethane. However, the solid types of tyres are capable of handling very high loads, while the pneumatic types of tyres can only handle light loads. The most common type of solid tyre truck which was encountered was the polyurethane.

The industrial slabs were classified in accordance with the type and the frequency of traffic operating on the floor slab, this being similar to the coding given in Table 2.1. Broadly, those floor slabs on which the trucks operated with pneumatic or solid rubber tyres were classified as light industrial use, and the accelerated abrasion test was conducted with the revolving pads type of head. When trucks with polyurethane tyres were being frequently used to handle moderately heavy loads (up to 3000 kg), the slabs were considered to be exposed to medium industrial use and the rolling wheels type of head was used in the accelerated abrasion test. Those slabs which were subjected to heavily loaded trucks, operating on steel wheels, were classified as receiving heavy industrial use and both the rolling wheels and dressing wheels system were used for the accelerated test.

Very few floor slabs were available which could be classified as receiving light or heavy industrial use, with the majority being classified as medium industrial use. Those classified as being given heavy industrial exposure, were also found to have been treated with a metallic dry shake treatment. Furthermore, some of the industrial complexes which were visited were found to have several warehouses and factories, e.g. Procter & Gamble in Manchester, whereby floor slabs which had been exposed to different types of use were available for testing. Due to difficulties in obtaining permission to test industrial floor slabs, it was not feasible to locate a sufficient number of floor slabs of a similar age for incorporation in the programme. Consequently, the in-service floor slabs examined have included slabs from 5 to 12 years old.

The procedure adopted for the assessment of the actual service wear, followed a standard format and included a measurement with accelerated abrasion test. Initially the floor slabs were visually inspected and the locations of the maximum wear were determined. These were usually at places either where the traffic changed direction or in the loading areas. Attempts were made to measure the depth of wear at these locations with a straightedge and feeler gauge. A minimum of 50 readings was recorded at these locations, and an average value was found for each floor slab which was referred to as the mean, estimated depth of wear. In addition, each slab was assessed subjectively through a combination of a visual comparison with other floor slabs in the study, together with the opinion of the user regarding the performance of the floor slab during its service life, solely in terms of wear resistance and dusting. The floor slabs were classified with a letter rating system, in which the rating was related to the combination of these findings. Three scales were used, these were "Good", "Normal" and "Poor", being represented by G, N and P respectively.

Accelerated abrasion tests were performed at the same section of concrete floor slab. These tests were performed with the appropriate type(s) of head, as discussed earlier in this section. In most cases one test was performed adjacent to each location where the actual depth of wear had been assessed. These chosen areas had not been exposed to any type of traffic, e.g. under a shelving rack, etc. A total of three abrasion tests was conducted on each floor slab, the exception being the heavy industrial floor slabs, where six tests were performed, three with the rolling wheels head and three with the dressing wheels head. At the locations where accelerated abrasion tests were performed, rebound hammer readings were also recorded.

9.4.1 Results and Discussion

The results from floor slabs exposed to light, medium and heavy industrial traffic are provided in Tables 9.3, 9.4 and 9.5, respectively. From these results it is observed that the mean estimated depth of wear is not uniquely related to the accelerated abrasion depth. It is suggested that the main reason for this scatter in the results is due to differentials in traffic intensity between the various slabs. These values have been included only as a general guide but more confidence is attached to the designated rating system, as this includes allowance for such factors as age, intensity of traffic, and the overall performance of the floor slab. Three main categories have been used to judge the performance of the floor slabs under study, these being "Good", "Normal" and "Poor". There is a relatively large number of floor slabs, subjected to medium industrial traffic, so that these categories may be related to the abrasion depth determined with the accelerated abrasion test, it is clear that depths between 0.05 to 0.18mm, 0.27 to 0.35mm and 0.41 to 0.65mm are respectively associated with the "Good", "Normal" and "Poor" categories. When these values are compared to those found in the comparison study, given in Table 9.1, and in the new floor slab study, given in Table 9.2, it can be seen that most of these floor slabs fall in either the "Good" or "Normal" categories. Using these results, together with those from the laboratory programme, it is possible to propose specific limits for the accelerated abrasion depth of concrete slabs in the medium industrial environment and this is provided in Table 9.6. Similar specific limits cannot be proposed for slabs in either the light or the heavy industrial environment, since only a few slabs have been investigated and, that none of them investigated could be classified as "poor". However, the results from the floor slabs in the heavy industrial environment demonstrates that it is necessary to use an appropriate type of test for such investigation. This, in itself, is confirmation of the proposition, which was presented in Chapters 2 and 5, regarding the necessity of simulating the condition to which the slab will be exposed during its service life. Furthermore, the results suggest that the dressing wheels type of head would have been more appropriate for investigating the influence of the various dry shakes. This would, however, have prevented a comparison across the complete range of the laboratory study, and so the rolling wheels type of head was also used with the dry shakes.

The results in Table 9.4, also indicate that the specific compressive strength does not ensure that the concrete floor will have a high abrasion resistance. For example, in the case of the Procter & Gamble H Warehouse, where the specified grade of concrete was 20 $N/mm^2$, both the accelerated abrasion resistance and the rating are higher than those of the L'Orel Warehouses, where specified strength was 30 $N/mm^2$. This finding has been noticed with many of the industrial slabs investigated in this study, and is consistent with the laboratory results, which confirmed that cube strength is not a sensitive measure of abrasion resistance.

The coefficient of variation based on the accelerated abrasion depth values, using the rolling wheels types of head ranged from 7% to 29%. For revolving pads the range was from 5% to 23%, while with the dressing wheels it was from 14% to 34%. These values are quite low when considering the variation due to compaction, curing and non-uniform supply of material. In the case of the dressing wheels, the heads were changed after every 6 tests and this was a major factor in reducing the coefficient of variation.

When the proposed specific limits for floor slabs in a medium industrial environment are compared to Levitt's classification

(184), Table 8.6, using the equivalent values for the Initial Surface Absorption, it is clear that "Good" concrete in Levitt's classification corresponds to "Normal" concrete in the proposed classification, with abrasion depths less than 0.40mm. This suggests that there is a general agreement between the two classifications, but further work is necessary to relate the Initial Surface Absorption to the abrasion depth, for floor slabs in the medium industrial environment.

The results of rebound hammer tests, which accompanied the abrasion tests with the rolling wheels head, are given in Tables 9.4, and 9.5. These values have been plotted on the classification graph provided by Chaplin (2) in Figure 9.1. It is clear that the results for the old slabs (five years or older) in the medium industrial environment do not agree closely with this curve. It is interesting to note that the results of the very young (28 days) concrete slabs fall to the extreme left of the curve, whilst those for the old concrete (five years or older) fall to the extreme right of the curve. However, the results from slabs aged about 6 months fall almost on the curve. In his paper (178), Chaplin does not make clear the age of the concrete that he investigated. This is an important factor, as has been demonstrated in the present study. It is suggested that the deviations between the results from young concrete, 6 months old concrete, and old concrete slabs are mainly due to carbonation and that this carbonation influences the rebound index more than the abrasion resistance. This implies that the difference between the present results and those of Chaplin (2) are mainly due to this age effect.

The results of the rebound hardness tests performed on slabs treated with the metallic dry shakes and exposed to a heavy industrial environment, have also been plotted in Figure 9.1. These agree more closely with the Chaplin (2) curve. It should be noted that the abrasion depth in these cases was very low due to the test head which was used, for the rolling type of head was- not sufficiently aggressive. It is also noted from the results in Table 9.5, that the highest rebound index did not produce the lowest abrasion resistance, as determined by the dressing wheels.

The rebound values for the different ratings - Good, Normal and Poor - of concrete floor slabs in a medium industrial environment are generally in the range of 50 to 55, 46 to 49, and 39 to 44 respectively. However, there are two exceptions to this, these being the results from the Procter & Gamble H ,Warehouse and from the Cryoplants (old part) as can be seen in Table 9.4. The results of in-situ tests of rebound hammer and those from the laboratory study, suggest that the relationship between rebound hardness and abrasion resistance of concrete is more complex than has been assumed in earlier classifications.

In the present study few floor slabs were investigated and so there is a danger that only contracts with a high standard of construction have been included in the programme, with those of a lower standard construction not having been made available for investigation. There is, therefore, a need to investigate more floor slabs in various industrial environments to ensure that true representation is obtained of the standard of construction present in the industry. This would allow confirmation of the relationship for classifying slabs exposed to medium industrial environments, and may permit the establishment of similar limits.

## 9.5 Summary

Laboratory and site practices have been compared for the construction of slabs, with the result that the latter produced slabs of significantly greater abrasion resistance than the former.

The abrasion resistance of slabs in industrial premises was investigated leading to the development of abrasion criteria for assessing the quality of concrete slabs in a medium industrial environment.

| Contract Name | Slab No. | Grade of Concrete ($N/mm^2$) | Surface Treatment | Ls | | Ts | | As | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | A.D | R.I | A.D | R.I | A.D | R.I |
| Eli-Lilly | 1 | 25 | NONE | 0.35 | 35 | 0.38 | 34 | 0.24 | 39 |
| Pirelli | 2 | 30 | NONE | 0.48 | 32 | 0.50 | 32 | 0.32 | 36 |
| | 3 | | | 0.50 | 31 | 0.55 | 30 | 0.34 | 35 |
| Smith Industries | 4 | 30 | NONE | 0.14 | 38 | 0.16 | 36 | 0.10 | 40 |
| | 5 | | | 0.43 | 33 | 0.52 | 29 | 0.26 | 37 |
| | 6 | | | 0.18 | 37 | 0.20 | 38 | 0.12 | 41 |
| Sony | 7 | 25 | NONE | 0.55 | 29 | 0.57 | 30 | 0.28 | 36 |
| | 8 | | | 0.52 | 30 | 0.48 | 32 | 0.26 | 38 |
| | 9 | | BETONAC TOPPING | 0.38 | 35 | 0.39 | 33 | 0.28 | 38 |
| | 10 | | | 0.34 | 34 | 0.32 | 38 | 0.25 | 40 |

TABLE 9.1 Summary of Laboratory and Site Comparison Study

KEY: Ls = Test Slab taken to the laboratory

Ts = Test slab left on site

As = Actual slab constructed on site

A.D= Abrasian Depth (mm)

R.I= Rebound Index

| Contract Name | Slab No. | Grade of Concrete ($N/mm^2$) | Finishing Technique and Surface Treatment | Abrasion Depth(mm) | | Rebound Index | |
|---|---|---|---|---|---|---|---|
| | | | | Single Test | Mean | Single Test | Mean |
| Chlorid | 1 | 25 | Granolithic Topping Power Finishing | 0.31 | | 44 | |
| | | | | 0.47 | 0.37 | 40 | 42 |
| | | | | 0.33 | | 41 | |
| Eli-Lilly | 2 | 25 | Power Finishing | 0.25 | | 46 | |
| | | | | 0.28 | 0.25 | 44 | 45 |
| | | | | 0.22 | | 46 | |
| Field Aviation | 3 | 30 | Vacuum-Dewatering Power Finishing | 0.03 | | 54 | |
| | | | | 0.04 | 0.03 | 55 | 54 |
| | | | | 0.03 | | 54 | |
| General Foods | 4 | 25 | Power Finishing | 0.23 | | 50 | |
| | | | | 0.25 | 0.27 | 47 | 47 |
| | | | | 0.33 | | 43 | |
| Pirelli | 5 | 30 | Power Finishing | 0.29 | | 44 | |
| | | | | 0.29 | 0.32 | 46 | 45 |
| | | | | 0.38 | | 45 | |
| | 6 | | Granolithic Topping Power Finishing | 0.26 | | 47 | |
| | | | | 0.56 | 0.34 | 30 | 37 |
| | | | | 0.20 | | 35 | |

TABLE 9.2 Results of New Floor Slab Investigation

| Contract Name | Grade of Concrete (N/mm$^2$) | No. of Years In-Service | Abrasion Depth (mm) | | Rating | Rebound Index |
|---|---|---|---|---|---|---|
| | | | A.D | M.E.D | | |
| Telford (Unit 18A) | 20 | 6 | 0.33 | 1.47 | N | 42 |
| Telford (Stafford Park 15 SP 8 CU) | 20 | 7 | 0.19 | 1.40 | N | 44 |
| Ditto (15 SP 9 CU) | 20 | 7 | 0.28 | 1.26 | N | 43 |
| Telford (Unit 2 SP 18 A) | 20 | 8 | 0.08 | 0.65 | G | 48 |
| Ditto (Unit 2 PP 10 A) | 20 | 10 | 0.22 | 1.32 | N | 45 |

TABLE 9.3 Summary of the Results for Floor Slabs in Light Industrial Environment

KEY: A.D = Mean Abrasion Depth (mm)

M.E.D = Mean Estimated Depth of Wear (mm)

N = "Normal"

G = "Good"

| Contract Name | Grade of Concrete ($N/mm^2$) | No. of Years In-Service | Abrasion Depth (mm) | | Rating | Rebound Index |
|---|---|---|---|---|---|---|
| | | | A.D | M.E.D | | |
| Corning Glass | 30 | 6 | 0.18 | 0.84 | G | 51 |
| L'Oreal (Warehouse 1) | 30 | 11 | 0.41 | 3.35 | P | 45 |
| L'Oreal (Warehouse 2) | 30 | 11 | 0.45 | 3.12 | P | 45 |
| Phostrogen (Main Factory) | 20 | 8 | 0.55 | 3.10 | P | 42 |
| Phostrogen (Extension) | 20 | 6 | 0.65 | 2.15 | P | 39 |
| Proctor & Gamble (H Warehouse) | 20 | 8 | 0.33 | 1.89 | N | 50 |
| Post Office Swindon (Unit 4) | 30 | 12 | 0.15 | 1.37 | G | 50 |
| Post Office (Unit 4A) | 30 | 12 | 0.12 | 1.18 | G | 55 |
| Telford (Haldane Unit 10C) | 30 | 10 | 0.35 | 2.67 | N | 47 |
| V.A.G. (Warehouse A) | 30 | 5 | 0.30 | 1.21 | N | 46 |
| V.A.G. (Warehouse B) | 30 | 5 | 0.27 | 1.05 | N | 48 |
| Cryoplants (New Factory) | 30 | 6 | 0.05 | 0.55 | G | 51 |
| Cryoplants (Old Part) | 25 | 12 | 0.47 | 2.96 | P | 46 |

TABLE 9.4 Summary of the Results for Floor Slabs in Medium Industrial Environment

KEY: A.D = Mean Abrasion Depth (mm)

M.E.D = Mean Estimated Depth of Wear (mm)

P = "Poor", N = "Normal", G = "Good"

| Contract Name | Grade of Concrete ($N/mm^2$) | No. of Years In-Service | Accelerated Abrasion Depth(mm) | | M.E.D | Rating | Rebound Index |
|---|---|---|---|---|---|---|---|
| | | | R/W | D/W | | | |
| Champion (OPF1) | 30 | 11 | 0.02 | 0.28 | 1.84 | N | 52 |
| Champion (Ex1) | 30 | 9 | 0.00 | 0.18 | 0.94 | G | 55 |
| Champion (Ex2) | 30 | 8 | 0.00 | 0.24 | 1.13 | N | 53 |
| Proctor & Gamble (IDM Loading Bay) | 30 | 12 | 0.00 | 0.11 | 1.02 | G | 53 |

TABLE 9.5 Summary of the Results for Floor Slabs in Heavy Industrial Environment

Key: R/W = Abrasion Depth using Rolling Wheels Type of Head

D/W = Abrasion Depth using Dressing Wheels Type of Head

M.E.D = Mean Estimated Depth of Wear (mm)

| Quality of Concrete Slab | Abrasion Depth (mm) |
|---|---|
| GOOD | $<$ 0.2 |
| NORMAL | 0.2 - 0.40 |
| POOR | $>$0.40 |

TABLE 9.6 Classification of Concrete Floor Slabs in Medium Industrial Environment

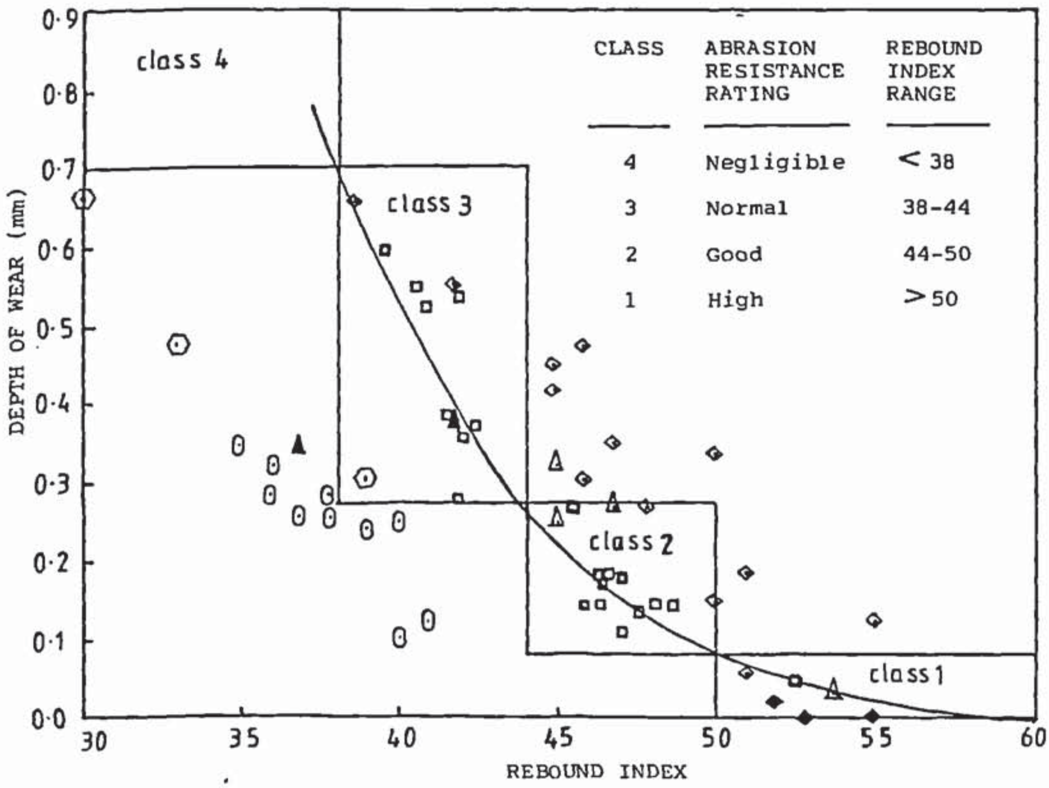



FIGURE 9.1 Relationship between Depth of Wear and Rebound Index for Different Classes of Concrete Floors (Based on Ref.2)

KEY

CHAPLIN'S MATURE CONCRETE

LABORATORY 28 DAYS CONCRETE

COMPARISON STUDY

NEW FLOOR SLABS

NEW FLOOR SLABS WITH GRANO-TOPPING

OLD FLOOR SLABS

OLD FLOOR SLABS WITH DRY SHAKE TOPPING

# CHAPTER 10

## MAIN CONCLUSIONS

### 10.1 Introduction

The experimental results obtained in this investigation have been thoroughly discussed, in the preceding Chapters of this thesis. A summary of the main conclusions arising from these sections is presented below.

### 10.2 Testing Apparatus and Procedure

(1) A portable apparatus was produced with three modes of action and, a standardised testing procedure was developed for assessing the abrasion resistance of concrete slabs in various industrial environments.

(2) The test methods and procedures that have been developed satisfy the conditions for the acceptability of an abrasion test method.

### 10.3 Macro-Study of Abrasion Resistance

(1) The abrasion resistance of concrete slabs is significantly influenced by the finishing technique.

(2) Hand finishing of concrete slabs, significantly reduced the abrasion resistance of the slab, especially with concrete mixes of lower water-cement ratio.

(3) Power finishing significantly increased the abrasion resistance of concrete slabs. This is mainly due to surface compaction and to reduction of the water-cement ratio of the surface matrix. This is caused by delayed and repeated vibratory disturbance of the power finishing equipment which reduces voids and pores nearest to the surface. This tends to bring particles in the surface matrix into more intimate contact.

(4) The abrasion resistance of concrete slabs is influenced by the number of applications of power trowelling.

(5) The application of repeated power trowelling reduces the influence of concrete mix design on the abrasion resistance. This is mainly attributed to the surface matrix of all the specimens becoming very similar to each other, after the application of repeated power trowelling, e.g. the local water-cement ratio, at the surface matrix, becomes very similar.

(6) The rate of abrasion is dependent on the structure of the surface matrix of the specimen under investigation.

(7) The workability of the concrete mix becomes less critical when power finishing equipment is used to finish the surface.

(8) The abrasion resistance of concrete subjected to hand finishing and cured by the wet burlap method,varied directly with the cube strength and inversely with the water-cement ratio. Whilst it would appear that a definite relationship exists between the cube strength and the abrasion resistance, the strength was not an absolute indicator of abrasion resistance, since it did not take into account other factors that affect the abrasion resistance of a concrete surface.

(9) The vacuum dewatering process, combined with power finishing equipment, increased the abrasion resistance of the concrete surface compared to that of a non-processed slab produced from concrete with either the same initial water-cement ratio, or the same final gross water-cement ratio as the vacuum processed specimen. This increase is due to the reduction in the water content and increase in cement content, at the surface due to the applied suction. The final gross water-cement ratio achieved by the process depended on the initial water-cement ratio of the mix. The process was more effective in increasing the abrasion resistance of high water-cement ratio mixes than those with lower water-cement ratios. The resulting water-cement

ratio at the surface of the processed slab was less than that of the bulk of the processed specimen slab. The core strength of the processed slab was greater than that of a non-processed mix, with the same initial water-cement ratio as the vacuum processed slab, but it was less than that of a non-processed slab, with the same final gross water-cement ratio as the vacuum processed slab.

(10) Efficient curing of concrete slabs significantly increased abrasion resistance. Proper curing became more critical as the water-cement ratio of the concrete mix increased. No significant difference was detected between the abrasion resistance of slabs cured by wet burlap or plastic sheeting. However, the plastic sheet method was less susceptible to error than the wet burlap method.

(11) The use of curing compounds was found to be, generally, more effective in increasing abrasion resistance, than the plastic sheeting method of curing. This is mainly due to the longer period of controlled curing provided by the curing compounds. The resin-based, 90% efficiency curing compound was the most effective means of curing and, thus produced the highest abrasion resistance. The efficiency of the curing compounds was very much dependent on the texture of the applied surface.

12) Concrete surface hardeners were more effective in improving the abrasion resistance of mixes with low water-cement ratio (higher quality) rather than those with higher water-cement ratio (lower quality) mixes. Proper curing of concrete slabs was more effective in improving the abrasion resistance than the application of concrete surface hardeners.

(13) The in-surface liquid surface treatments significantly increased the abrasion resistance of all types of concrete mixes. The abrasion resistance obtained by the use of in-surface treatments

ranked highest, when compared with other air cured specimen slabs. The application of in-surface seals, reduced the influence of the concrete mix design on the abrasion resistance of the slab.

(14) The abrasion resistance of concrete slabs was significantly increased when they were treated with the metallic aggregate, dry shake surface treatments. No significant difference was found between the abrasion resistance of specimen slabs, treated with natural aggregate or cement dry shakes and those of comparable non-treated specimen slabs. In all these specimen slabs the increase in abrasion resistance was primarily due to the application of finishing technique rather than the use of the dry shake.

(15) The highest abrasion resistance was provided by the slabs treated with the metallic aggregate type of dry shake, and the least abrasion resistance was obtained from the slab finished by the hand method.

## 10.4 Microstructural Study of Abrasion Resistance

(1) The Mercury Intrusion Porosimetry method is a very sensitive and valuable means of quantitatively investigating the influence of factors which affect the abrasion resistance of concrete.

(2) The abrasion resistance of concrete is controlled by the pore structure of the surface matrix. Finishing techniques, curing regimes and some types of liquid surface treatments influenced the pore size distribution and total pore volume of the surface matrix of the concrete slabs. Significant differences were observed in the pore size distribution and total pore volume of the surface matrix of slabs subjected to different finishing techniques. Similar changes were also produced in the specimens by some of the curing regimes and liquid surface treatments.

(3) The pore size distribution and the total pore volume of the

middle of the specimen slabs subjected to vacuum dewatering were higher than those of the equivalent unprocessed slabs, confirming that vacuum dewatering increased the porosity of treated samples.

(4) The abrasion resistance of the concrete surface varies directly with the total pore volume of its surface matrix.

(5) A standard procedure for assessing the microhardness of concrete specimen was developed. The microhardness profiles for specimen slabs subjected to the various finishing techniques were significantly different from each other. The different finishing techniques resulted in the production of layers with different hardnesses.

(6) The abrasion resistance of concrete was directly related to the microhardness of the surface matrix. The hardness of the surface matrix controlled the rate of abrasion. The ability of a concrete surface to resist abrasion forces is primarily controlled by the top 1mm of the surface matrix.

(7) The microhardness profiles clearly demonstrated the depth to which each finishing technique influenced the structure of the surface layer. The influence of the various power finishing processes clearly diminished with depth from the surface.

(8) The microhardness of the surface matrix of the specimen slabs was directly related to the corresponding total pore volume.

(9) No typical morphology was observed, when specimens were examined under the Scanning Electron Microscope.

(10) Petrographic examination of impregnated thin sections provided a qualitative means of assessing the microstructure of the specimens. This method provided visual confirmation of the conclusions derived from the data obtained with the Mercury Intrusion Porosimetry and microhardness technique.

(11) The Differential Thermal Analysis of specimens treated by various liquid surface treatments suggest that, the in-surface seals

influenced the surface matrix of the concrete, but that the surface hardeners did not have such an effect.

## 10.5 Indirect and Non-Destructive Methods

(1) The Ultrasonic Pulse Velocity was not sensitive to the variation in the concrete mix design investigated in this study.

(2) The Schmidt rebound hardness method was sensitive to some of the factors which are known to influence the abrasion resistance of concrete, e.g. finishing techniques, curing regimes. However, other factors, particularly the liquid surface treatments, did not appear to influence the rebound value of the treated surface.

(3) The Initial Surface Absorption test was very sensitive to factors which influenced the abrasion resistance of concrete surfaces. The results indicated that the Initial Surface Absorption was closely correlated to the abrasion resistance and, that it may well provide a basis for an indirect, non-destructive assessment of the in-situ abrasion resistance of concrete.

## 10.6 Field Investigation

(1) The abrasion resistance of concrete slabs finished using laboratory based methods, was significantly lower than that obtained from the equivalent floor slabs finished by site finishing methods. This indicates, therefore, that the results of research obtained solely with laboratory based methods may not be applicable to industrial concrete floor slabs.

(2) The accelerated abrasion resistance of newly constructed floor slabs in medium industrial environment was in the range of 0.03mm to 0.37mm.

(3) The relationship between the accelerated abrasion resistance, and

rebound hardness in industrial floor slabs, was more complex than has been proposed by other investigators.

(4) The accelerated abrasion resistance and the service performance of old concrete floor slabs, in different industrial environments, confirmed the necessity of simulating the actual service condition in an accelerated abrasion test.

(5) A comparison between the results obtained from the accelerated abrasion test and subjective assessments of the service wear, showed a general agreement, and indicated that the testing apparatus provides valuable information as to the wearing qualities of the concrete floor slabs in industrial environments.

(6) A criterion has been proposed for assessing the quality of concrete floor slabs in a medium industrial environment in terms of abrasion resistance.

## 10.7 Concluding Remarks

This study has developed both apparatus and test procedures for assessing the abrasion resistance of concrete. The test programme has led to the proposal of criteria for assessing the quality of concrete in terms of abrasion resistance. Furthermore, it has clearly demonstrated that abrasion resistance is influenced by various material and construction factors. Indirect and non-destructive methods have also been successfully developed for assessing the abrasion resistance. However, the most important conclusion must be that the abrasion resistance of concrete is primarily dependent on the microstructure of the concrete nearest to the surface. If the microstructure is influenced in any way then abrasion resistance will consequently be affected. In addition, the present work has demonstrated that many of the techniques available for the study of the microstructure can be adopted for research into the abrasion resistance of concrete.

# CHAPTER 11

## RECOMMENDATION FOR FURTHER WORK

### 11.1 Introduction

Based on the work undertaken, a number of recommendations are proposed regarding the need for further work. These are summarised below.

### 11.2 Testing Method

(1) Further inter-laboratory studies should be organised so that the precision of the accelerated abrasion test method may be determined according to the B.S 5497 : pt 1 : 1979.

(2) Analysis of the abraded materials and the abrasion path of the test surface should be undertaken to provide a better understanding of the mechanism(s) involved with the three modes of action of the accelerated abrasion test apparatus. This should take the form of a microscopic study.

### 11.3 Macro-Study of Abrasion Resistance

(1) The number and the time of application of power floating and trowelling should be systematically examined, so that criteria may be developed for various qualities (in terms of abrasion resistance) of concrete slabs.

(2) In order to perform the above it is necessary to develop a reliable means of determining the ideal state of stiffness of the paste. Such a method as the penetration resistance test (ASTM C-403) should be considered for development.

(3) The long term performance of the Liquid Surface Treatments need to be investigated, with abrasion tests conducted after 28, 90, 180 and 360 days.

(4) It would be interesting to compare the performance of slabs treated with dry shakes and finished by hand, and power finishing methods. Furthermore, with the accelerated abrasion test, the dressing wheel mode of action should be employed for the assessment of the performance of these dry shake slabs.

## 11.4 Microstructural Study of Abrasion Resistance

(1) Standard procedures need to be developed for using the Mercury Intrusion Porosimetry method in the investigation of those variables that influence the abrasion resistance.

(2) The Mercury Intrusion Porosimetry method can be used to investigate the distribution of porosity throughout the depth of vacuum treated, and other types of, finished slabs. This method should be used to reconfirm the results of slabs subjected to different surface treatments and curing regimes.

(3) The microhardness technique should be employed on the actual surface of the specimens subjected to liquid surface treatment, rather than employing the procedure which was used in the present study, in order to determine whether the method is sensitive to such treatments.

(4) The microhardness profiles of specimens treated with dry shakes should be compared with those obtained from comparable non-treated specimens, to determine the depth of influence of the dry shakes.

(5) X-ray mapping of samples, impregnated with a low viscosity resin containing trace metal ions, should be investigated to establish whether they can provide additional information regarding the microstructure.

(6) Low-angle X-ray scattering should be used to examine experimentally the proposition that the application of power finishing equipment increases the specific surface of cement.

(7) Thermogravimetric analysis of specimens treated by various types

of liquid surface treatments may reveal less complex and more useful information than has been obtained from the Differential Thermal Analysis, particularly with regard to the presence of the various chemicals within the surface matrix.

### 11.5 Indirect and Non-Destructive Methods

(1) Detailed study should be undertaken of the influence of carbonation on both abrasion resistance of concrete, as determined by the accelerated abrasion test, and Schmidt rebound hardness. This should also be linked with a parallel study of the effects on both the Schmidt rebound hardness and the Initial Surface Absorption.

(2) Extensive work should be undertaken to further examine the relationship between Initial Surface Absorption and accelerated abrasion test, including field investigation.

### 11.6 Field Investigation

(1) In order to confirm and complete the classification proposed in the present study, it is necessary to test more industrial floor slabs of various quality in different industrial environments.

(2) Return visits should be made to those of newly constructed industrial floor slabs which were tested in the present investigation, to compare the accelerated abrasion resistance values obtained when the floor slabs were new, both with values obtained at greater ages, and with their actual service performance.

APPRNDIX A DETAIL RESULTS

| Chemical Name | % Present |
|---|---|
| $SiO_2$ | 20.2 |
| I.R | 0.62 |
| $Al_2O_3$ | 4.8 |
| $Fe_2O_3$ | 3.4 |
| $Mn_2O_3$ | 0.07 |
| $P_2O_5$ | 0.09 |
| $TiO_2$ | 0.27 |
| CaO | 64.6 |
| MgO | 1.4 |
| $SO_3$ | 2.9 |
| Ignition Loss | 0.8 |
| $K_2O$ | 0.66 |
| $Na_2O$ | 0.11 |

TABLE A.1 Ordinary Typical Cement Chemical Analysis

| Reading No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Mean Depth of Abrasion (mm) |
|---|---|---|---|---|---|---|---|---|---|
| Initial | 11.61 | 11.47 | 11.41 | 11.61 | 11.50 | 11.43 | 11.56 | 11.52 | |
| Final (15 min) | 10.73 | 11.09 | 11.12 | 10.62 | 10.85 | 10.91 | 10.70 | 10.56 | |
| Depth | 0.88 | 0.38 | 0.29 | 0.99 | 0.65 | 0.52 | 0.82 | 0.96 | 0.69 |

TABLE A.2 Abrasion Test Results, the 8 Reading Method

| Reading No. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | | 12 | | Mean Depth of Abrasion (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial | 11.30 | 11.30 | 11.51 | 11.38 | 11.42 | 11.24 | 11.39 | 11.32 | 11.32 | 11.38 | 11.39 | 11.09 | 11.21 | 11.22 | 11.38 | 11.39 | 11.29 | 11.33 | 11.26 | 11.48 | 11.41 | 11.35 | 11.55 | 11.36 | |
| Final (15 Min.) | 10.89 | 10.95 | 10.29 | 10.32 | 10.62 | 10.52 | 10.74 | 10.80 | 10.75 | 10.80 | 10.72 | 10.78 | 10.48 | 10.75 | 10.62 | 10.65 | 10.95 | 10.93 | 10.73 | 10.70 | 10.81 | 10.74 | 10.92 | 10.53 | |
| Depth | 0.41 | 0.35 | 1.22 | 1.06 | 0.8 | 0.72 | 0.65 | 0.52 | 0.57 | 0.58 | 0.67 | 0.31 | 0.73 | 0.47 | 0.76 | 0.76 | 0.34 | 0.4 | 0.53 | 0.78 | 0.60 | 0.61 | 0.63 | 0.83 | |
| Av. Depth | 0.38 | | 1.14 | | 0.76 | | 0.58 | | 0.58 | | 0.49 | | 0.60 | | 0.76 | | 0.37 | | 0.66 | | 0.61 | | 0.73 | | 0.64 |

TABLE A.3 Abrasion Test Results, the 24 Reading Method

| Mix No. | Type of Head | Mean Crushing Strength ($N/mm^2$) |
|---|---|---|
| B1 | R/P(1) | 65.5 |
| | R/P(2) | 71.7 |
| | R/W | 69.2 |
| | D/W | 72.3 |
| B2 | R/P(1) | 58.2 |
| | R/P(2) | 62.9 |
| | R/W | 60.0 |
| | D/W | 57.9 |
| B3 | R/P(1) | 40.5 |
| | R/P(2) | 42.4 |
| | R/W | 39.4 |
| | D/W | 38.5 |

Key:

R/P(1) = Revolving pads (with the lead collar)

R/P(2) = Revolving pads (without the lead collar)

R/W = Rolling wheel

D/W = Dressing wheel

TABLE A.4 Summary of Cube Strength Results for the Comparative Test Programme

| MIX No. | Finishing Technique | Temperature $^oC$ | WAITING-TIME (Minutes) | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| B4 | H.F | 22 | 155 | 17 | - | - |
| B5 | " | 23 | 179 | 32 | - | - |
| B6 | " | 22 | 208 | 46 | - | - |
| B4 | P.F | 23 | 150 | 37 | - | - |
| B5 | " | 23 | 186 | 52 | - | - |
| B6 | " | 24 | 201 | 64 | - | - |
| B4 | R.P.F | 23 | 157 | 35 | 29 | 22 |
| B5 | " | 23 | 175 | 44 | 33 | 23 |
| B6 | " | 24 | 197 | 62 | 44 | 33 |
| B4 | V.T | 22 | - | 31 | - | - |
| B5 | " | 22 | - | 37 | - | - |
| B6 | " | 23 | - | 42 | - | - |
| B4 | R.W.C | 22 | 104 | 22 | - | - |
| B5 | " | 22 | 156 | 38 | - | - |
| B6 | " | 22 | 173 | 53 | - | - |
| B4 | Liquid S.T | 22 | 166 | 41 | - | - |
| B5 | " | 22 | 188 | 53 | - | - |
| B6 | " | 23 | 197 | 66 | - | - |
| B4 | D.S.1 | 21 | 172 | 35 | 21 | 15 |
| B5 | " | 22 | 194 | 42 | 30 | 18 |
| B6 | " | 22 | 210 | 55 | 35 | 26 |

Table A.5 Cont.....

| MIX No. | Finishing Technique | Temperature °C | WAITING TIME(Minutes) | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| B4 | D.S.2 | 23 | 160 | 38 | 20 | 15 |
| B5 | " | 23 | 185 | 42 | 26 | 20 |
| B6 | " | 22 | 210 | 60 | 40 | 25 |
| B4 | D.S.3 | 22 | 170 | 35 | 20 | 10 |
| B5 | " | 22 | 192 | 40 | 25 | 20 |
| B6 | " | 22 | 205 | 56 | 35 | 30 |
| B4 | D.S.4 | 23 | 160 | 30 | 15 | 10 |
| B5 | " | 23 | 178 | 40 | 25 | 16 |
| B6 | " | 23 | 206 | 55 | 35 | 25 |

Note:

1 Floating operation. This is the lapse of time from the end of screeding operation to the start of the floating operation

2 1st Trowelling. This is the lapse of time from the end of the floating operation to the start of the first trowelling operation.

3 2nd Trowelling. This is the lapse of time from the end of the 1st trowelling operation to the start of the 2nd trowelling operation

4 3rd Trowelling. This is the lapse of time from the end of the 2nd trowelling operation to the start of the 3rd trowelling operation

TABLE A.5 Duration of Waiting-Time for Finishing Operations

| Curing Regime | FINISHING TECHNIQUES | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H.F | | | P.F | | | R.P.F | | | V.T | | | R.W.C | | |
| | CONCRETE MIX NO. | | | | | | | | | | | | | | |
| | B4 | B5 | B6 | B4 | B5 | B6 | B4 | B5 | B6 | B4 | B5 | B6 | B4 | B5 | B6 |
| A.C | 6 | 1 | 4 | 2 | 3 | 5 | 4 | 1 | 2 | 4 | 3 | 6 | 4 | 6 | 2 |
| P.S | 5 | 5 | 3 | 6 | 6 | 1 | 5 | 4 | 1 | 1 | 4 | 5 | 6 | 3 | 4 |
| W.B. | 4 | 2 | 1 | 5 | 4 | 2 | 2 | 2 | 3 | 6 | 1 | 2 | 3 | 4 | 3 |
| CC1 | 2 | 3 | 5 | 4 | 2 | 6 | 1 | 5 | 5 | 3 | 2 | 1 | 5 | 2 | 1 |
| CC2 | 1 | 6 | 2 | 3 | 5 | 3 | 6 | 3 | 4 | 5 | 6 | 3 | 1 | 5 | 5 |
| CC3 | 3 | 4 | 6 | 1 | 1 | 4 | 3 | 6 | 6 | 2 | 5 | 4 | 2 | 1 | 6 |

Note: The numbers indicate the position of the curing regimes on the large slab

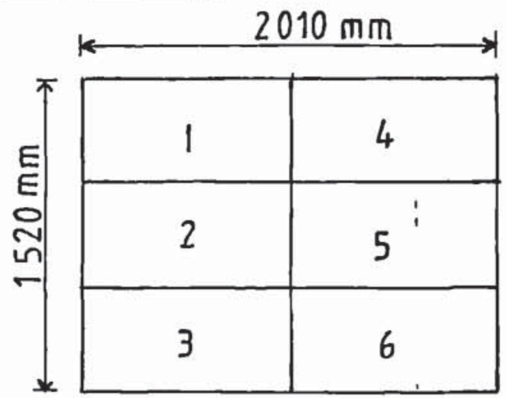



TABLE A.6 Location of Curing Regime on the Large Slab

| B.S.Sieve Size | Weight Retained (g) | % Retained | Cumulative % passing | Cumulative % retained |
|---|---|---|---|---|
| 2.4 mm | 0.0 | 0.0 | 100 | 0 |
| 1.2 mm | 74.6 | 12.6 | 87 | 13 |
| 600 µm | 151.6 | 25.5 | 62 | 38 |
| 300 µm | 56.2 | 9.5 | 52 | 48 |
| 150 µm | 72.8 | 12.3 | 40 | 60 |
| 75 µm | 41.5 | 7.0 | 33 | 67 |
| smaller than 75 um | 196.3 | 33.0 | - | - |

Total = 593 g

TABLE A.7 Sieve Analysis of Master Builders MASTERCRON Natural Aggregate Dry Shake

| MIX No. | Curing Regime | Period of Abrasion (mins.) | TYPE OF FINISHING | | | | |
|---|---|---|---|---|---|---|---|
| | | | H.F. | P.F. | R.P.F | V.D. | R.W.C |
| | | | Mean Depth of Abrasion (mm) | | | | |
| B4 | A.C | 5 | 0.48 | 0.22 | 0.08 | 0.19 | 0.22 |
| | | 10 | 0.64 | 0.35 | 0.14 | 0.31 | 0.31 |
| | | 15 | 0.83 | 0.47 | 0.18 | 0.35 | 0.40 |
| | | 30 | 1.32 | 0.82 | 0.32 | 0.51 | 0.66 |
| | W.B | 5 | 0.31 | 0.16 | 0.00 | 0.10 | 0.14 |
| | | 10 | 0.48 | 0.24 | 0.05 | 0.14 | 0.20 |
| | | 15 | 0.57 | 0.31 | 0.09 | 0.18 | 0.24 |
| | | 30 | 0.77 | 0.45 | 0.16 | 0.26 | 0.36 |
| | P.S | 5 | 0.25 | 0.17 | 0.00 | 0.12 | 0.11 |
| | | 10 | 0.37 | 0.27 | 0.06 | 0.20 | 0.19 |
| | | 15 | 0.46 | 0.30 | 0.10 | 0.23 | 0.28 |
| | | 30 | 0.75 | 0.52 | 0.20 | 0.35 | 0.38 |
| | CC1 | 5 | 0.22 | 0.12 | 0.00 | 0.10 | 0.14 |
| | | 10 | 0.35 | 0.18 | 0.00 | 0.12 | 0.18 |
| | | 15 | 0.49 | 0.25 | 0.05 | 0.16 | 0.22 |
| | | 30 | 0.85 | 0.44 | 0.08 | 0.24 | 0.32 |
| | CC2 | 5 | 0.24 | 0.10 | 0.00 | 0.10 | 0.10 |
| | | 10 | 0.41 | 0.16 | 0.00 | 0.10 | 0.15 |
| | | 15 | 0.57 | 0.22 | 0.03 | 0.14 | 0.18 |
| | | 30 | 0.81 | 0.34 | 0.05 | 0.20 | 0.24 |
| | CC3 | 5 | 0.20 | 0.10 | 0.00 | 0.00 | 0.07 |
| | | 10 | 0.38 | 0.10 | 0.00 | 0.07 | 0.14 |
| | | 15 | 0.58 | 0.26 | 0.02 | 0.15 | 0.20 |
| | | 30 | 0.89 | 0.39 | 0.04 | 0.20 | 0.32 |



Table A.8 Cont...

| MIX No. | Curing Regime | Period of Abrasion (mins) | TYPE OF FINISHING | | | | |
|---|---|---|---|---|---|---|---|
| | | | H.F. | P.F. | R.P.F | V.D. | R.W.C |
| | | | Mean Depth of Abrasion (mm) | | | | |
| B5 | A.C | 5 | 0.63 | 0.48 | 0.17 | 0.20 | 0.29 |
| | | 10 | 0.88 | 0.72 | 0.27 | 0.38 | 0.40 |
| | | 15 | 1.10 | 0.90 | 0.35 | 0.47 | 0.53 |
| | | 30 | 1.61 | 1.32 | 0.51 | 0.71 | 0.82 |
| | W.B | 5 | 0.39 | 0.31 | 0.07 | 0.08 | 0.21 |
| | | 10 | 0.58 | 0.46 | 0.13 | 0.17 | 0.30 |
| | | 15 | 0.68 | 0.56 | 0.20 | 0.25 | 0.39 |
| | | 30 | 0.93 | 0.81 | 0.36 | 0.32 | 0.64 |
| | P.S | 5 | 0.31 | 0.23 | 0.06 | 0.12 | 0.18 |
| | | 10 | 0.50 | 0.38 | 0.13 | 0.17 | 0.31 |
| | | 15 | 0.61 | 0.48 | 0.18 | 0.25 | 0.41 |
| | | 30 | 0.90 | 0.78 | 0.38 | 0.39 | 0.66 |
| | CC1 | 5 | 0.27 | 0.21 | 0.09 | 0.09 | 0.12 |
| | | 10 | 0.45 | 0.32 | 0.11 | 0.14 | 0.19 |
| | | 15 | 0.62 | 0.44 | 0.14 | 0.20 | 0.27 |
| | | 30 | 0.96 | 0.72 | 0.29 | 0.25 | 0.44 |
| | CC2 | 5 | 0.22 | 0.14 | 0.02 | 0.07 | 0.15 |
| | | 10 | 0.42 | 0.26 | 0.03 | 0.12 | 0.22 |
| | | 15 | 0.61 | 0.41 | 0.06 | 0.20 | 0.28 |
| | | 30 | 0.88 | 0.63 | 0.17 | 0.26 | 0.40 |
| | CC3 | 5 | 0.14 | 0.28 | 0.02 | 0.10 | 0.14 |
| | | 10 | 0.36 | 0.35 | 0.02 | 0.16 | 0.24 |
| | | 15 | 0.66 | 0.45 | 0.04 | 0.23 | 0.30 |
| | | 30 | 0.84 | 0.59 | 0.32 | 0.34 | 0.48 |

Table A.8 Cont...

| MIX No. | Curing Regime | Period of Abrasion (mins.) | TYPE OF FINISHING | | | | |
|---|---|---|---|---|---|---|---|
| | | | H.F. | P.F. | R.P.F | V.D. | R.W.C |
| | | | Mean Depth of Abrasion (mm) | | | | |
| B6 | A.C | 5 | 0.82 | 0.52 | 0.16 | 0.36 | 0.49 |
| | | 10 | 1.25 | 0.92 | 0.29 | 0.52 | 0.81 |
| | | 15 | 1.58 | 1.29 | 0.38 | 0.63 | 0.98 |
| | | 30 | 2.14 | 1.83 | 0.69 | 0.94 | 1.53 |
| | W.B | 5 | 0.44 | 0.32 | 0.08 | 0.15 | 0.36 |
| | | 10 | 0.68 | 0.54 | 0.18 | 0.21 | 0.52 |
| | | 15 | 0.89 | 0.82 | 0.27 | 0.31 | 0.60 |
| | | 30 | 1.18 | 0.98 | 0.41 | 0.46 | 0.85 |
| | P.S | 5 | 0.32 | 0.27 | 0.06 | 0.08 | 0.25 |
| | | 10 | 0.58 | 0.52 | 0.12 | 0.16 | 0.42 |
| | | 15 | 0.84 | 0.66 | 0.17 | 0.27 | 0.51 |
| | | 30 | 1.14 | 0.90 | 0.29 | 0.42 | 0.69 |
| | CC1 | 5 | 0.20 | 0.24 | 0.04 | 0.13 | 0.30 |
| | | 10 | 0.48 | 0.47 | 0.10 | 0.19 | 0.49 |
| | | 15 | 0.65 | 0.58 | 0.16 | 0.30 | 0.57 |
| | | 30 | 0.96 | 0.96 | 0.35 | 0.44 | 0.71 |
| | CC2 | 5 | 0.26 | 0.22 | 0.05 | 0.10 | 0.23 |
| | | 10 | 0.49 | 0.42 | 0.10 | 0.14 | 0.38 |
| | | 15 | 0.74 | 0.60 | 0.14 | 0.24 | 0.46 |
| | | 30 | 1.00 | 0.85 | 0.18 | 0.35 | 0.59 |
| | CC3 | 5 | 0.36 | 0.21 | 0.02 | 0.15 | 0.19 |
| | | 10 | 0.74 | 0.40 | 0.07 | 0.22 | 0.34 |
| | | 15 | 1.03 | 0.58 | 0.13 | 0.28 | 0.49 |
| | | 30 | 1.26 | 1.00 | 0.16 | 0.49 | 0.63 |

TABLE A. 8 Summary of Finishing Techniques Test Results

| MIX No. | Type of Surface Treatment | Period of Abrasion(min) | Mean Depth of Abrasion (mm) |
|---|---|---|---|
| B4 | A | 5 | 0.18 |
| | | 10 | 0.30 |
| | | 15 | 0.40 |
| | | 30 | 0.72 |
| | B | 5 | 0.13 |
| | | 10 | 0.25 |
| | | 15 | 0.38 |
| | | 30 | 0.66 |
| | C | 5 | 0.06 |
| | | 10 | 0.08 |
| | | 15 | 0.08 |
| | | 30 | 0.16 |
| | D | 5 | 0.03 |
| | | 10 | 0.06 |
| | | 15 | 0.06 |
| | | 30 | 0.06 |
| | E | 5 | 0.05 |
| | | 10 | 0.08 |
| | | 15 | 0.12 |
| | | 30 | 0.18 |
| | O | 5 | 0.25 |
| | | 10 | 0.41 |
| | | 15 | 0.54 |
| | | 30 | 0.78 |

TABLE A.9 cont...

| Mix No. | Type of Surface Treatment | Period of Abrasion(min) | Mean Depth of Abrasion (mm) |
|---|---|---|---|
| B5 | A | 5 | 0.23 |
| | | 10 | 0.38 |
| | | 15 | 0.51 |
| | | 30 | 1.05 |
| | B | 5 | 0.21 |
| | | 10 | 0.34 |
| | | 15 | 0.48 |
| | | 30 | 0.95 |
| | C | 5 | 0.06 |
| | | 10 | 0.11 |
| | | 15 | 0.12 |
| | | 30 | 0.14 |
| | D | 5 | 0.08 |
| | | 10 | 0.12 |
| | | 15 | 0.14 |
| | | 30 | 0.16 |
| | E | 5 | 0.11 |
| | | 10 | 0.16 |
| | | 15 | 0.22 |
| | | 30 | 0.28 |
| | O | 5 | 0.42 |
| | | 10 | 0.62 |
| | | 15 | 0.78 |
| | | 30 | 1.14 |

Table A. 9 cont....

| Mix No. | Type of Surface Treatment | Period of Abrasion(min) | Mean Depth of Abrasion (mm) |
|---|---|---|---|
| B6 | A | 5 | 0.44 |
| | | 10 | 0.69 |
| | | 15 | 0.89 |
| | | 30 | 1.59 |
| | B | 5 | 0.38 |
| | | 10 | 0.72 |
| | | 15 | 1.00 |
| | | 30 | 1.66 |
| | C | 5 | 0.16 |
| | | 10 | 0.20 |
| | | 15 | 0.26 |
| | | 30 | 0.52 |
| | D | 5 | 0.11 |
| | | 10 | 0.13 |
| | | 15 | 0.14 |
| | | 30 | 0.17 |
| | E | 5 | 0.13 |
| | | 10 | 0.23 |
| | | 15 | 0.28 |
| | | 30 | 0.82 |
| | O | 5 | 0.50 |
| | | 10 | 0.85 |
| | | 15 | 1.18 |
| | | 30 | 1.75 |

TABLE A.9 Summary of Liquid Surface Treatment Test Results

| MIX No. | Type of Dry Shake | Period of Abrasion(min) | Mean Depth of Abrasion (mm) |
|---|---|---|---|
| B4 | D.S.1 | 5 | 0.00 |
| | | 10 | 0.00 |
| | | 15 | 0.01 |
| | | 30 | 0.01 |
| | D.S.2 | 5 | 0.01 |
| | | 10 | 0.01 |
| | | 15 | 0.02 |
| | | 30 | 0.05 |
| | D.S.3 | 5 | 0.00 |
| | | 10 | 0.01 |
| | | 15 | 0.03 |
| | | 30 | 0.03 |
| | D.S.4 | 5 | 0.00 |
| | | 10 | 0.00 |
| | | 15 | 0.03 |
| | | 30 | 0.08 |
| B5 | D.S.1 | 5 | 0.00 |
| | | 10 | 0.02 |
| | | 15 | 0.03 |
| | | 30 | 0.04 |
| | D.S.2 | 5 | 0.03 |
| | | 10 | 0.05 |
| | | 15 | 0.08 |
| | | 30 | 0.12 |

Table A.10 Cont....

| Mix No. | Type of Dry Shake | Period of Abrasion(min) | Mean Depth of Abrasion (mm) |
|---|---|---|---|
| B5 | D.S.3 | 5 | 0.03 |
| | | 10 | 0.06 |
| | | 15 | 0.07 |
| | | 30 | 0.10 |
| | D.S.4 | 5 | 0.01 |
| | | 10 | 0.04 |
| | | 15 | 0.05 |
| | | 30 | 0.11 |
| B6 | D.S.1 | 5 | 0.01 |
| | | 10 | 0.03 |
| | | 15 | 0.04 |
| | | 30 | 0.06 |
| | D.S.2 | 5 | 0.03 |
| | | 10 | 0.09 |
| | | 15 | 0.13 |
| | | 30 | 0.18 |
| | D.S.3 | 5 | 0.06 |
| | | 10 | 0.11 |
| | | 15 | 0.16 |
| | | 30 | 0.22 |
| | D.S.4 | 5 | 0.07 |
| | | 10 | 0.10 |
| | | 15 | 0.15 |
| | | 30 | 0.20 |

TABLE A.10 Summary of Dry Shake Surface Treatment Test Results

| Mix No. | Finishing Technique | Mean Crushing Strength ($N/mm^2$) | |
|---|---|---|---|
| | | 1st Cast | 2nd Cast |
| B4 | H.F | 64.3 | 63.5 |
| | P.F | 68.0 | 64.9 |
| | R.P.F | 64.1 | 61.6 |
| | V.D | 66.4 | 60.3 |
| | R.W.C | 75.1 * | 71.0 * |
| | Liquid S.T | 50.7 ⊛ | 46.4 ⊛ |
| | D.S.1 | 68.6 | 62.7 |
| | D.S.2 | 70.1 | 68.3 |
| | D.S.3 | 65.3 | 62.8 |
| | D.S.4 | 67.6 | 65.5 |
| B5 | H.F | 47.6 | 45.2 |
| | P.F | 49.2 | 44.1 |
| | R.P.F | 50.2 | 47.2 |
| | V.D | 47.8 | 46.5 |
| | R.W.C | 58.1 * | 55.4 * |
| | Liquid S.T | 37.9 ⊛ | 34.6 ⊛ |
| | D.S.1 | 46.2 | 43.8 |
| | D.S.2 | 52.3 | 48.2 |
| | D.S.3 | 46.6 | 44.2 |
| | D.S.4 | 46.2 | 43.5 |
| B6 | H.F | 29.3 | 27.9 |
| | P.F | 27.9 | 26.5 |
| | R.P.F | 30.1 | 28.7 |
| | V.D | 29.1 | 27.4 |
| | R.W.C | 40.6 * | 38.9 * |
| | Liquid S.T | 20.8 ⊛ | 18.1 ⊛ |
| | D.S.1 | 31.6 | 30.1 |
| | D.S.2 | 29.7 | 27.6 |
| | D.S.3 | 30.0 | 28.9 |
| | D.S.4 | 32.0 | 30.7 |

* Reduced Water Content Cubes

⊛ Air Cured Cubes

S.T = Surface Treatment

TABLE A.11 Summary of Cube Crushing Strength Results

| Mix No. | Type of Finishing Technique | Mean-Estimated* in-situ Cube strength ($N/mm^2$) | Mean Cube⊙ Crushing strength ($N/mm^2$) |
|---|---|---|---|
| B4 | P.F | 42.5 | 66.4 |
| | V.D | 45.0 | 63.3 |
| | R.W.C | 49.0 | 73.1 |
| B5 | P.F | 32.0 | 46.6 |
| | V.D | 36.0 | 47.2 |
| | R.W.C | 43.0 | 56.8 |
| B6 | P.F | 21.0 | 27.2 |
| | V.D | 24.0 | 28.2 |
| | R.W.C | 33.0 | 39.8 |

* These values were calculated using the formula recommended by BS 1881: Part 120: 1983 for correction due to reinforcement and conversion into in-situ cube strength for cores drilled vertically

⊙ Average of the first and the second cube crushing strength test results

TABLE A.12 Summary of Core Crushing Strength Test Results

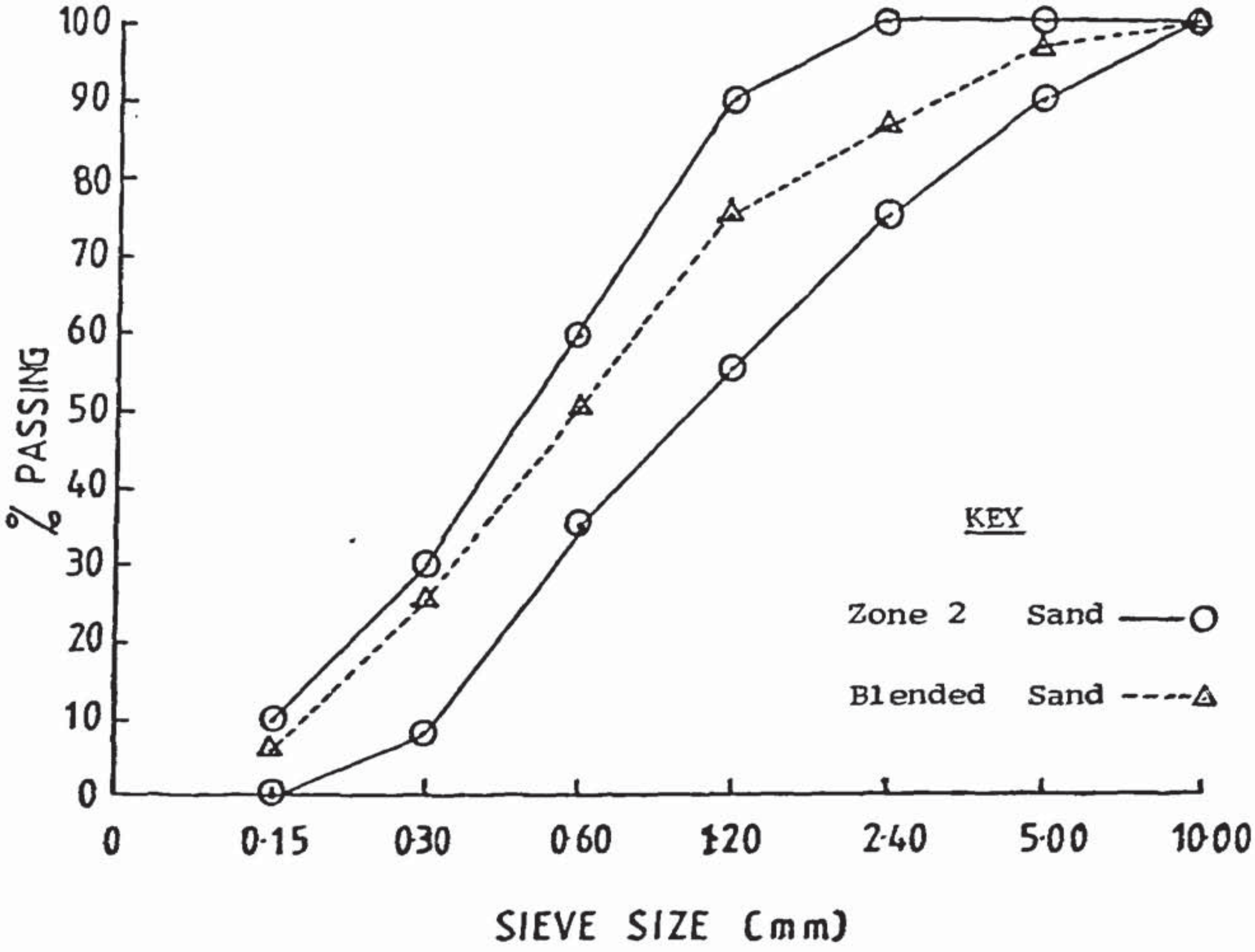



FIGURE A.1 Grading Curves for Fine Aggregates

# APPENDIX B CONCRETE MIX DESIGN

## CONCRETE MIX DESIGN DETAILS

### 1. MIX A1

Dry Weights per $m^3$

| | |
|---|---|
| Cement | 280 Kg |
| 20 - 10 mm Aggregate | 900 Kg |
| 10 - 5 mm Aggregate | 410 Kg |
| Fine Aggregate | 645 Kg |
| Free Water - Cement Ratio | 0.56 |
| Aggregate - Cement Ratio | 7 : 1 |

### 2. MIX A2

Dry Weight per $m^3$:

| | |
|---|---|
| Cement | 540 Kg |
| 20 - 10 mm Aggregate | 745 Kg |
| 10 - 5 mm Aggregate | 340 Kg |
| Fine Aggregate | 535 Kg |
| Free Water - Cement Ratio | 0.40 |
| Aggregate - Cement Ratio | 3 : 1 |

### 3. MIX B1

Dry Weight per $m^3$

| | |
|---|---|
| Cement | 430 Kg |
| 20 - 10 mm Aggregate | 935 Kg |
| 10 - 5 mm Aggregate | 310 Kg |
| Fine Aggregate | 560 Kg |

| | |
|---|---|
| Free Water - Cement Ratio | 0.37 |
| Aggregate - Cement Ratio | 4.2 : 1 |

4. MIX B2

Dry Weights per $m^3$

| | |
|---|---|
| Cement | 340 Kg |
| 20 - 10 mm Aggregate | 950 Kg |
| 10 - 5 mm Aggregate | 320 Kg |
| Fine Aggregate | 625 Kg |
| Free Water - Cement Ratio | 0.47 |
| Aggregate - Cement Ratio | 5.6 : 1 |

5. MIX B3

Dry Weight per $m^3$

| | |
|---|---|
| Cement | 300 Kg |
| 20 - 10 mm Aggregate | 880 Kg |
| 10 - 5 mm Aggregate | 295 Kg |
| Fine Aggregate | 720 Kg |
| Free Water - Cement Ratio | 0.60 |
| Aggregate - Cement Ratio | 6.3 : 1 |

6. MIX B4

Dry Weight per $m^3$

| | |
|---|---|
| Cement | 365 Kg |
| 20 - 10 mm Aggregate | 940 Kg |
| 10 - 5 mm Aggregate | 315 Kg |
| Fine Aggregate | 620 Kg |
| Free Water - Cement Ratio | 0.44 |
| Aggregate - Cement Ratio | 5.1 : 1 |

7. MIX B5

Dry Weight per $m^3$

| | |
|---|---|
| Cement | 345 Kg |
| 20 - 10 mm Aggregate | 875 Kg |
| 10 - 5 mm Aggregate | 290 Kg |
| Fine Aggregate | 685 Kg |
| Free Water - Cement Ratio | 0.52 |
| Aggregate - Cement Ratio | 5.4 : 1 |

8. MIX B6

Dry Weight per $m^3$

| | |
|---|---|
| Cement | 300 Kg |
| 20 - 10 mm Aggregate | 770 Kg |
| 10 - 5 mm Aggregate | 255 Kg |
| Fine Aggregate | 840 Kg |
| Free Water - Cement Ratio | 0.65 |
| Aggregate - Cement Ratio | 6.2 : 1 |

# APPENDIX C STATISTICAL ANALYSIS

## C.1 "Student-t" Tests

Student-t tests for small samples:

$$t = \frac{m_1 - m_2}{\sigma} \sqrt{\frac{n_1 n_2}{n_1 + n_2}}$$

Where: $n_1$ = No. of reading 1

$n_2$ = No. of Reading 2

$m_1$ = Mean of reading 1

$m_2$ = Mean of reading 2

$$\sigma^2 = \frac{n_1 \sigma_1^2 + n_2 \sigma_2^2}{n_1 + n_2 - 2}$$

Where: $\sigma_1$ = Variance of reading 1

$\sigma_2$ = Variance of reading 2

The calculated "t" parameter is compared with the appropriate value from "Student-t" tables to determine if there is significant difference between two sets of results (185).

### C.1.1 TABLES C.1 TO C.5

For Tables C.1 to C.5, $n_1 = n_2 = 8$ and the degree of freedom $n_1 + n_2 - 2 = 14$, and so at the 5 per cent level of significance the critical "t" value is 2.145. As all the calculated "t" values in Tables C.1 to C.5 are below this value, it is apparent that there is no significant difference between the results.

C.1.2 TABLE C.6

For Table C.6, $n_1 = 24$ and $n_2 = 8$, and the degree of freedom $n_1 + n_2 - 2 = 30$, and so at the 5 per cent level of significance the critical "t" value is 2.042. As all the calculated "t" values in Table C.6 are below this value, it is apparent that there is no significant difference between the two methods of assessing abrasion depth.

C.1.3 TABLE C.7

For Table C.7, $n_1 = n_2 = 9$ and the degree of freedom $n_1 + n_2 - 2 = 16$, and so at the 5 per cent level of significance the critical "t" value is 2.120. As all the calculated "t" values in Table C.7 are below this value, it is apparent that there is no significant difference in abrasion resistance of slabs of varying thickness.

C.1.4 TABLE C.8

For Table C.8, $n_1 = n_2 = 9$ and the degree of freedom $n_1 + n_2 - 2 = 16$, and so at the 5 per cent level of significance the critical "t" value is 2.120. As all the calculated "t" values in Table C.8 are above this value, it is apparent that all the different types of head were sensitive to variation in mix design.

C.1.5 TABLES C.9 TO C.15

For Tables C.9 to C.15, $n_1 = n_2 = 3$ and the degree of freedom $n_1 + n_2 - 2 = 4$, and so at the 5 per cent level of significance the critical "t" value is 2.776.

C.1.6 TABLE C.16

For Table C.16, $n_1 = 3$, $n_2 = 9$ and the degree of freedom $n_1 + n_2 - 2 = 10$, and so at the 5 per cent level of significance the critical "t" value is 2.228. This indicates that the metallic dry shake results are significantly higher than the standard, and there is no significant difference between the other dry shakes and the standard.

C.1.7 TABLE C.17

For Table C.17, $n_1 = n_2 = 9$, and the degree of freedom $n_1 + n_2 = 16$ and so at the 5 per cent level of significance the critical "t" value is 2.120. The results indicate that there is a significant difference between the results of metallic dry shake and the other dry shakes. But there is no significant difference between the other dry shakes used.

C.1.8 TABLES C.18 TO C.22

For Tables C.18 to C.22, $n_1 = n_2 = 9$, and the degree of freedom $n_1 + n_2 - 2 = 16$, and so at the 5 per cent level of significance the critical "t" value is 2.120.

## C.2 Statistical Analysis According to B.S 5497:PART 1 1979

A uniform-level experiment with number of replicates per cell. The following computational formula may be applied for determination of the repeatability (r) and the reproducibility (R):

$$P = \text{No. of laboratories}$$

$$S_1 = \sum n_i \overline{Y}_i$$

$$S_2 = \sum n_i \overline{Y}_i^{2}$$

$$S_3 = \sum n_i$$

$$S_4 = \sum n_i^{2}$$

$$S_5 = \sum s_i^{2} (n-1)$$

$$s_r^{2} = \frac{S_5}{(S_3 - P)}$$

$$s_L^{2} = \left[ \frac{S_2 S_3 - S_1^{2}}{S_3 (P-1)} - Sr^{2} \right] \left[ \frac{S_3 (P-1)}{S_3^{2} - S_4} \right]$$

$$m = \frac{S_1}{S_3}$$

$$r = 2.83 \sqrt{s_r^{2}}$$

$$R = 2.83 \sqrt{s_L^{2} + s_r^{2}}$$

## C.2.1 TABLES C.23 TO C.25

Table C.23 has been arrived at using the values in Table 5.1.

In Table C.24 the calculated valueof C (Cochran's test statistic) should not exceed critical value of C. C is calculated using

$$C = \frac{S^2_{Max}}{\sum_{i=1}^{P} S^2_i}$$

Table C.25 shows the calculated values for the repeatability (r) and the reproducibility (R).

## C.3 Two-Way Analysis of Variance

The results of abrasion tests for various finishing techniques, curing regimes and concrete strength (termed as main effect) have been regrouped into Table C.26 so that the influence of these factors can be assessed by subjecting them to a two-way analysis of variance (110). In this analysis level of factor A refers to curing regimes, level of factor B refers to finishing techniques and level of factor C refers to concrete mixes used.

The results of this analysis are presented in Table C.27 with the appropriate F-values given for the various sources of variation. The results indicates that all main effects and two-factor interactions are statistically significant at the 5% level. Although the two-factor interaction are statistically significant they are very small compared with the main effects.

| Mix No. | Slab No. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| A1 | 1 | 0.78 | 0.56 | 0.268 | 0.324 | 0.318 | 1.384 |
| | 2 | 0.71 | 0.82 | 0.076 | 0.323 | 0.251 | 0.876 |
| | 3 | 0.50 | 0.58 | 0.219 | 0.251 | 0.252 | 0.645 |
| A2 | 1 | 0.46 | 0.42 | 0.227 | 0.060 | 0.177 | 0.452 |
| | 2 | 0.53 | 0.44 | 0.074 | 0.143 | 0.122 | 1.480 |
| | 3 | 0.46 | 0.58 | 0.130 | 0.180 | 0.168 | 1.430 |

TABLE C.1 Summary of Student's t-test on Aston Machine and C & CA Machine - Testing at Aston

| Mix No. | Slab No. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| A1 | 1 | 0.78 | 0.74 | 0.268 | 0.228 | 0.266 | 0.301 |
| | 2 | 0.71 | 0.71 | 0.076 | 0.113 | 0.103 | 0 |
| | 3 | 0.50 | 0.67 | 0.219 | 0.270 | 0.263 | 1.29 |
| A2 | 1 | 0.46 | 0.44 | 0.227 | 0.121 | 0.194 | 0.206 |
| | 2 | 0.53 | 0.44 | 0.074 | 0.107 | 0.098 | 1.837 |
| | 3 | 0.46 | 0.50 | 0.130 | 0.107 | 0.127 | 0.63 |

TABLE C.2 Summary of Student's t test on Aston Machine with Aston Collar and Aston Machine with the C & CA Collar - Testing at Aston

| Slab No. | Position | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| 1 | A & D | 2.25 | 2.18 | 0.952 | 0.901 | 0.991 | 0.141 |
| | B & C | 1.40 | 1.50 | 0.662 | 0.539 | 0.645 | 0.310 |
| 2 | A & D | 0.26 | 0.14 | 0.149 | 0.053 | 0.119 | 2.02 |
| | B & C | 0.28 | 0.20 | 0.265 | 0.108 | 0.216 | 0.741 |
| 3 | A & D | 0.24 | 0.23 | 0.219 | 0.161 | 0.205 | 0.097 |
| | B & C | 0.22 | 0.21 | 0.119 | 0.112 | 0.124 | 0.161 |

TABLE C.3 Summary of Student's-t tests on Aston Machine and the C & CA Machine - Testing at the C & CA

| Slab No. | Position | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| 1 | D | 2.18 | 2.04 | 0.901 | 1.468 | 1.302 | 0.210 |
| | C | 1.50 | 1.35 | 0.539 | 0.227 | 0.442 | 0.688 |
| 2 | D | 0.14 | 0.16 | 0.053 | 0.102 | 0.087 | 0.322 |
| | C | 0.20 | 0.21 | 0.108 | 0.124 | 0.124 | 0.161 |
| 3 | A | 0.24 | 0.26 | 0.180 | 0.197 | 0.202 | 0.218 |
| | B | 0.22 | 0.28 | 0.119 | 0.177 | 0.161 | 0.745 |
| | C | 0.21 | 0.24 | 0.112 | 0.180 | 0.160 | 0.475 |
| | D | 0.23 | 0.25 | 0.161 | 0.169 | 0.176 | 0.193 |

TABLE C.4 Summary of Student's-t test on the Results of Dial Gauge and Bridge Micrometer Read ngs

| SLAB NO. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|
| | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| 1 | 0.69 | 0.70 | 0.268 | 0.237 | 0.270 | 0.074 |
| | 0.70 | 0.70 | 0.127 | 0.115 | 0.129 | 0 |
| | 0.70 | 0.68 | 0.222 | 0.241 | 0.247 | 0.162 |
| 2 | 0.73 | 0.75 | 0.418 | 0.447 | 0.462 | 0.087 |
| | 0.61 | 0.63 | 0.282 | 0.301 | 0.312 | 0.128 |
| | 0.78 | 0.75 | 0.409 | 0.415 | 0.440 | 0.136 |
| 3 | 0.68 | 0.66 | 0.226 | 0.277 | 0.270 | 0.148 |
| | 0.76 | 0.76 | 0.328 | 0.314 | 0.343 | 0 |
| | 0.76 | 0.74 | 0.233 | 0.240 | 0.253 | 0.158 |
| 4 | 1.73 | 1.70 | 0.558 | 0.508 | 0.570 | 0.105 |
| | 1.44 | 1.51 | 0.305 | 0.321 | 0.335 | 0.418 |
| | 1.22 | 1.30 | 0.353 | 0.344 | 0.372 | 0.430 |
| 5 | 1.37 | 1.33 | 0.331 | 0.351 | 0.364 | 0.220 |
| | 1.48 | 1.52 | 0.518 | 0.527 | 0.558 | 0.143 |
| | 1.93 | 1.79 | 0.943 | 0.887 | 0.978 | 0.286 |
| 6 | 1.67 | 1.61 | 0.645 | 0.621 | 0.676 | 0.178 |
| | 1.60 | 1.70 | 0.308 | 0.330 | 0.341 | 0.704 |
| | 2.16 | 2.25 | 1.192 | 1.076 | 1.213 | 0.148 |

TABLE C.5 Summary of Student's t-test on the Results of Comparing Two Sets of 8 Readings

| Slab No. | Mean | | Variance | | σ | t |
|---|---|---|---|---|---|---|
| | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| 1 | 0.64 | 0.69 | 0.218 | 0.268 | 0.239 | 0.492 |
| | 0.67 | 0.70 | 0.161 | 0.127 | 0.158 | 0.605 |
| | 0.76 | 0.70 | 0.180 | 0.222 | 0.198 | 0.817 |
| 2 | 0.68 | 0.73 | 0.376 | 0.418 | 0.400 | 0.337 |
| | 0.64 | 0.61 | 0.238 | 0.282 | 0.258 | 0.256 |
| | 0.63 | 0.78 | 0.312 | 0.409 | 0.350 | 1.015 |
| 3 | 0.75 | 0.68 | 0.239 | 0.226 | 0.244 | 0.733 |
| | 0.67 | 0.76 | 0.304 | 0.328 | 0.320 | 0.674 |
| | 0.64 | 0.76 | 0.227 | 0.233 | 0.236 | 1.350 |
| 4 | 1.70 | 1.73 | 0.525 | 0.558 | 0.551 | 0.134 |
| | 1.37 | 1.44 | 0.272 | 0.305 | 0.290 | 0.634 |
| | 1.24 | 1.22 | 0.397 | 0.353 | 0.399 | 0.160 |
| 5 | 1.59 | 1.37 | 0.623 | 0.331 | 0.583 | 0.929 |
| | 1.54 | 1.48 | 0.503 | 0.518 | 0.524 | 0.295 |
| | 1.83 | 1.93 | 0.657 | 0.943 | 0.764 | 0.334 |
| 6 | 1.92 | 1.67 | 0.747 | 0.645 | 0.747 | 0.836 |
| | 1.72 | 1.60 | 0.332 | 0.308 | 0.337 | 0.872 |
| | 2.09 | 2.16 | 1.091 | 1.192 | 1.154 | 0.136 |

TABLE C.6 Summary of Students-t test on the Results of Comparing the Two Methods of Assessing Abrasion Depth (i.e. 24 and 8 Readings Method)

| Slab Thickness (mm) | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| 50 | 100 | 0.80 | 0.79 | 0.058 | 0.045 | 0.055 | 0.386 |
| 100 | 150 | 0.79 | 0.82 | 0.045 | 0.049 | 0.050 | 1.272 |
| 50 | 150 | 0.80 | 0.82 | 0.058 | 0.049 | 0.057 | 0.744 |

TABLE C.7 Summary of Student's-t test on the Results of Different Slab Thickness

| Type of Head | Mix No. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| Rolling wheels | $B_1-B_2$ | 0.34 | 0.58 | 0.029 | 0.043 | 0.039 | 13.086 |
| | $B_1-B_3$ | 0.34 | 0.81 | 0.029 | 0.084 | 0.067 | 14.878 |
| | $B_2-B_3$ | 0.58 | 0.81 | 0.043 | 0.084 | 0.071 | 6.871 |
| Revolving pads with the lead collar | $B_1-B_2$ | 0.32 | 0.58 | 0.022 | 0.037 | 0.032 | 17.233 |
| | $B_1-B_3$ | 0.32 | 0.77 | 0.022 | 0.041 | 0.035 | 27.27 |
| | $B_2-B_3$ | 0.58 | 0.77 | 0.037 | 0.041 | 0.041 | 9.829 |
| Rolling pads without the lead collar | $B_1-B_2$ | 0.27 | 0.50 | 0.020 | 0.029 | 0.026 | 18.763 |
| | $B_1-B_3$ | 0.27 | 0.69 | 0.020 | 0.038 | 0.032 | 27.838 |
| | $B_2-B_3$ | 0.50 | 0.69 | 0.029 | 0.038 | 0.036 | 11.194 |
| Dressing wheels | $B_1-B_2$ | 0.68 | 1.28 | 0.071 | 0.266 | 0.206 | 6.178 |
| | $B_1-B_3$ | 0.68 | 2.56 | 0.071 | 0.683 | 0.515 | 7.743 |
| | $B_2-B_3$ | 1.28 | 2.56 | 0.266 | 0.683 | 0.550 | 4.936 |

TABLE C.8 Summary of Student's-t test on the Results of the Comparative Study for the Three Types of Head - 15 minutes duration

| SAMPLE | | Curing Regime | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| H.F | P.F | A.C | 0.83 | 0.47 | 0.075 | 0.051 | 0.078 | 5.654 |
| " | " | W.B | 0.57 | 0.31 | 0.047 | 0.032 | 0.049 | 6.500 |
| " | " | P.S | 0.46 | 0.30 | 0.040 | 0.021 | 0.039 | 5.026 |
| " | " | CC1 | 0.49 | 0.25 | 0.030 | 0.018 | 0.030 | 9.800 |
| " | " | CC2 | 0.57 | 0.22 | 0.031 | 0.027 | 0.036 | 11.910 |
| " | " | CC3 | 0.58 | 0.26 | 0.042 | 0.019 | 0.040 | 9.798 |
| R.P.F | P.F | A.C | 0.18 | 0.47 | 0.014 | 0.051 | 0.046 | 7.691 |
| " | " | W.B. | 0.09 | 0.31 | 0.010 | 0.032 | 0.029 | 9.291 |
| " | " | P.S | 0.10 | 0.30 | 0.013 | 0.021 | 0.021 | 11.667 |
| " | " | CC1 | 0.05 | 0.25 | 0.006 | 0.018 | 0.016 | 15.312 |
| " | " | CC2 | 0.03 | 0.22 | 0.005 | 0.027 | 0.023 | 8.260 |
| " | " | CC3 | 0.02 | 0.26 | 0.004 | 0.019 | 0.017 | 17.290 |
| V.D | P.F | A.C | 0.35 | 0.47 | 0.024 | 0.051 | 0.049 | 2.988 |
| " | " | W.B. | 0.18 | 0.31 | 0.022 | 0.032 | 0.034 | 4.684 |
| " | " | P.S | 0.23 | 0.30 | 0.015 | 0.021 | 0.022 | 3.898 |
| " | " | CC1 | 0.16 | 0.25 | 0.018 | 0.018 | 0.022 | 5.011 |
| " | " | CC2 | 0.14 | 0.22 | 0.015 | 0.027 | 0.027 | 3.176 |
| " | " | CC3 | 0.15 | 0.26 | 0.014 | 0.019 | 0.020 | 6.737 |
| V.D | R.W.C | A.C | 0.35 | 0.40 | 0.024 | 0.034 | 0.036 | 1.700 |
| " | " | W.B. | 0.18 | 0.24 | 0.022 | 0.020 | 0.026 | 2.827 |
| " | " | P.S | 0.23 | 0.28 | 0.015 | 0.021 | 0.022 | 2.784 |
| " | " | CC1 | 0.16 | 0.22 | 0.018 | 0.022 | 0.025 | 2.940 |
| " | " | CC2 | 0.14 | 0.18 | 0.015 | 0.016 | 0.019 | 2.579 |
| " | " | CC3 | 0.15 | 0.20 | 0.014 | 0.018 | 0.020 | 3.062 |

TABLE C.9 Summary of Student's-t test on the Results of Various Finishing Techniques for Concrete Mix B4

| SAMPLE | | Curing Regime | Mean | | Variance | | σ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $σ_1$ | $σ_2$ | | |
| H.F | P.F | A.C | 1.10 | 0.90 | 0.093 | 0.070 | 0.101 | 2.426 |
| " | " | W.B | 0.68 | 0.56 | 0.037 | 0.035 | 0.044 | 3.341 |
| " | " | P.S | 0.61 | 0.48 | 0.048 | 0.038 | 0.053 | 3.005 |
| " | " | CC1 | 0.62 | 0.44 | 0.036 | 0.028 | 0.039 | 5.654 |
| " | " | CC2 | 0.61 | 0.41 | 0.030 | 0.032 | 0.038 | 6.447 |
| " | " | CC3 | 0.66 | 0.45 | 0.063 | 0.048 | 0.069 | 3.728 |
| R.P.F | P.F | A.C | 0.35 | 0.90 | 0.027 | 0.070 | 0.065 | 10.365 |
| " | " | W.B | 0.20 | 0.56 | 0.016 | 0.035 | 0.033 | 13.364 |
| " | " | P.S | 0.18 | 0.48 | 0.013 | 0.038 | 0.035 | 10.500 |
| " | " | CC1 | 0.14 | 0.44 | 0.018 | 0.028 | 0.029 | 12.672 |
| " | " | CC2 | 0.06 | 0.41 | 0.008 | 0.032 | 0.029 | 14.784 |
| " | " | CC3 | 0.04 | 0.45 | 0.009 | 0.048 | 0.042 | 11.958 |
| V.D | P.F | A.C | 0.47 | 0.90 | 0.023 | 0.070 | 0.064 | 8.230 |
| " | " | W.B. | 0.25 | 0.56 | 0.019 | 0.035 | 0.034 | 11.169 |
| " | " | P.S | 0.25 | 0.48 | 0.016 | 0.038 | 0.036 | 7.826 |
| " | " | CC1 | 0.20 | 0.44 | 0.022 | 0.028 | 0.031 | 9.484 |
| " | " | CC2 | 0.20 | 0.41 | 0.017 | 0.032 | 0.032 | 8.039 |
| " | " | CC3 | 0.23 | 0.45 | 0.025 | 0.048 | 0.047 | 5.734 |
| V.D | R.W.C | A.C | 0.47 | 0.53 | 0.023 | 0.045 | 0.044 | 1.670 |
| " | " | W.B | 0.25 | 0.39 | 0.019 | 0.034 | 0.034 | 5.044 |
| " | " | P.S | 0.25 | 0.41 | 0.016 | 0.025 | 0.026 | 7.538 |
| " | " | CC1 | 0.20 | 0.27 | 0.022 | 0.023 | 0.028 | 3.062 |
| " | " | CC2 | 0.20 | 0.28 | 0.019 | 0.019 | 0.023 | 4.261 |
| " | " | CC3 | 0.23 | 0.30 | 0.025 | 0.033 | 0.036 | 2.382 |

**Table C.10** Summary of Student's-t test on the Results of Various Finishing Techniques for Concrete Mix B5

| SAMPLE | | Curing Regime | Mean | | Variance | | σ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| H.F | P.F | A.C | 1.68 | 1.29 | 0.134 | 0.115 | 0.153 | 3.122 |
| " | " | W.B | 0.89 | 0.82 | 0.052 | 0.071 | 0.076 | 1.128 |
| " | " | P.S | 0.84 | 0.66 | 0.067 | 0.044 | 0.069 | 3.196 |
| " | " | CC1 | 0.65 | 0.58 | 0.044 | 0.048 | 0.056 | 1.531 |
| " | " | CC2 | 0.74 | 0.60 | 0.056 | 0.044 | 0.062 | 2.766 |
| " | " | CC3 | 1.03 | 0.58 | 0.086 | 0.046 | 0.084 | 6.562 |
| R.P.F | P.F | A.C | 0.38 | 1.29 | 0.031 | 0.115 | 0.103 | 10.822 |
| " | " | W.B | 0.27 | 0.82 | 0.019 | 0.071 | 0.064 | 10.527 |
| " | " | P.S | 0.17 | 0.66 | 0.012 | 0.044 | 0.039 | 15.391 |
| " | " | CC1 | 0.16 | 0.58 | 0.017 | 0.048 | 0.044 | 11.693 |
| " | " | CC2 | 0.14 | 0.60 | 0.017 | 0.044 | 0.041 | 13.744 |
| " | " | CC3 | 0.13 | 0.58 | 0.012 | 0.046 | 0.041 | 13.445 |
| V.D | P.F | A.C | 0.63 | 1.29 | 0.048 | 0.115 | 0.108 | 7.486 |
| " | " | W.B | 0.31 | 0.82 | 0.032 | 0.071 | 0.067 | 9.325 |
| " | " | P.S | 0.27 | 0.66 | 0.016 | 0.044 | 0.040 | 11.944 |
| " | " | CC1 | 0.30 | 0.58 | 0.029 | 0.048 | 0.048 | 7.146 |
| " | " | CC2 | 0.24 | 0.60 | 0.013 | 0.044 | 0.040 | 11.025 |
| " | " | CC3 | 0.28 | 0.58 | 0.026 | 0.046 | 0.046 | 7.989 |
| V.D | R.W.C | A.C | 0.63 | 0.98 | 0.048 | 0.085 | 0.084 | 5.104 |
| " | " | W.B | 0.31 | 0.60 | 0.032 | 0.059 | 0.058 | 6.125 |
| " | " | P.S | 0.27 | 0.51 | 0.016 | 0.038 | 0.036 | 8.167 |
| " | " | CC1 | 0.30 | 0.57 | 0.029 | 0.050 | 0.050 | 6.615 |
| " | " | CC2 | 0.24 | 0.46 | 0.013 | 0.038 | 0.035 | 7.700 |
| " | " | CC3 | 0.28 | 0.49 | 0.026 | 0.040 | 0.041 | 6.274 |

TABLE C.11 Summary of Student's-t test on the Results of Various Finishing Techniques for Concrete Mix B6

| SAMPLE | | Finishing Technique | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| A.C | P.S | H.F | 0.83 | 0.46 | 0.075 | 0.040 | 0.074 | 6.125 |
| W.B | " | " | 0.57 | " | 0.047 | " | 0.053 | 2.542 |
| CC1 | " | " | 0.49 | " | 0.030 | " | 0.043 | 0.855 |
| CC2 | " | " | 0.57 | " | 0.031 | " | 0.044 | 3.063 |
| CC3 | " | " | 0.58 | " | 0.042 | " | 0.050 | 2.939 |
| A.C | P.S | P.F | 0.47 | 0.30 | 0.051 | 0.021 | 0.048 | 4.338 |
| W.B | " | " | 0.31 | " | 0.032 | " | 0.033 | 0.371 |
| CC1 | " | " | 0.25 | " | 0.018 | " | 0.024 | 2.552 |
| CC2 | " | " | 0.22 | " | 0.027 | " | 0.030 | 3.267 |
| CC3 | " | " | 0.26 | " | 0.019 | " | 0.024 | 2.042 |
| A.C | P.S | R.P.F | 0.18 | 0.10 | 0.014 | 0.013 | 0.016 | 6.100 |
| W.B | " | " | 0.09 | " | 0.010 | " | 0.014 | 0.875 |
| CC1 | " | " | 0.05 | " | 0.006 | " | 0.012 | 5.104 |
| CC2 | " | " | 0.03 | " | 0.005 | " | 0.012 | 7.144 |
| CC3 | " | " | 0.02 | " | 0.004 | " | 0.012 | 8.167 |
| A.C | P.S | V.D | 0.35 | 0.23 | 0.024 | 0.015 | 0.024 | 6.125 |
| W.B | " | " | 0.18 | " | 0.022 | " | 0.023 | 2.663 |
| CC1 | " | " | 0.16 | " | 0.018 | " | 0.020 | 4.288 |
| CC2 | " | " | 0.14 | " | 0.015 | " | 0.018 | 6.125 |
| CC3 | " | " | 0.15 | " | 0.014 | " | 0.018 | 5.440 |
| A.C | P.S | R.W.C | 0.40 | 0.28 | 0.034 | 0.021 | 0.035 | 4.200 |
| W.B | " | " | 0.24 | " | 0.020 | " | 0.025 | 1.960 |
| CC1 | " | " | 0.22 | " | 0.022 | " | 0.026 | 2.807 |
| CC2 | " | " | 0.18 | " | 0.016 | " | 0.023 | 5.326 |
| CC3 | " | " | 0.20 | " | 0.018 | " | 0.024 | 4.083 |

TABLE C.12 Summary of Student's-t test on the Results of Various Curing Regimes for Concrete Mix B4

| SAMPLE | | Finishing Technique | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| A.C | P.S | H.F | 1.10 | 0.61 | 0.093 | 0.048 | 0.091 | 6.596 |
| W.B | " | " | 0.68 | " | 0.037 | " | 0.052 | 1.649 |
| CC1 | " | " | 0.62 | " | 0.036 | " | 0.052 | 0.236 |
| CC2 | " | " | 0.61 | " | 0.030 | " | 0.049 | 0.00 |
| CC3 | " | " | 0.66 | " | 0.063 | " | 0.069 | 0.888 |
| A.C | P.S | P.F | 0.90 | 0.48 | 0.070 | 0.038 | 0.069 | 7.456 |
| W.B. | " | " | 0.56 | " | 0.035 | " | 0.045 | 2.178 |
| CC1 | " | " | 0.44 | " | 0.028 | " | 0.041 | 1.195 |
| CC2 | " | " | 0.41 | " | 0.032 | " | 0.043 | 1.994 |
| CC3 | " | " | 0.45 | " | 0.048 | " | 0.053 | 0.693 |
| A.C | P.S | R.P.F | 0.35 | 0.18 | 0.027 | 0.013 | 0.026 | 8.010 |
| W.B | " | " | 0.20 | " | 0.016 | " | 0.018 | 1.361 |
| CC1 | " | " | 0.14 | " | 0.018 | " | 0.019 | 2.579 |
| CC2 | " | " | 0.06 | " | 0.008 | " | 0.013 | 11.308 |
| CC3 | " | " | 0.04 | " | 0.009 | " | 0.014 | 12.247 |
| A.C | P.S | V.D | 0.47 | 0.25 | 0.023 | 0.016 | 0.024 | 11.229 |
| W.B | " | " | 0.25 | " | 0.019 | " | 0.022 | 0.000 |
| CC1 | " | " | 0.20 | " | 0.022 | " | 0.024 | 2.552 |
| CC2 | " | " | 0.20 | " | 0.019 | " | 0.021 | 2.917 |
| CC3 | " | " | 0.23 | " | 0.025 | " | 0.026 | 0.942 |
| A.C | P.S | R.W.C | 0.53 | 0.41 | 0.045 | 0.025 | 0.045 | 3.266 |
| W.B | " | " | 0.39 | " | 0.034 | " | 0.036 | 0.681 |
| CC1 | " | " | 0.27 | " | 0.023 | " | 0.029 | 5.913 |
| CC2 | " | " | 0.28 | " | 0.019 | " | 0.027 | 5.898 |
| CC3 | " | " | 0.30 | " | 0.033 | " | 0.036 | 3.743 |

TABLE C.13 Summary of Student's-t test on the Results of Various Curing Regimes for Concrete Mix B5

| SAMPLE | | Finishing Technique | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| A.C | P.S | H.F | 1.68 | 0.84 | 0.134 | 0.067 | 0.130 | 7.915 |
| W.B | " | " | 0.89 | " | 0.052 | " | 0.073 | 0.839 |
| CC1 | " | " | 0.65 | " | 0.044 | " | 0.069 | 3.373 |
| CC2 | " | " | 0.74 | " | 0.056 | " | 0.076 | 1.612 |
| CC3 | " | " | 1.03 | " | 0.086 | " | 0.094 | 2.476 |
| A.C | P.S | P.F | 1.29 | 0.66 | 0.115 | 0.044 | 0.107 | 7.213 |
| W.B | " | " | 0.82 | " | 0.071 | " | 0.072 | 2.722 |
| CC1 | " | " | 0.58 | " | 0.048 | " | 0.056 | 1.750 |
| CC2 | " | " | 0.60 | " | 0.044 | " | 0.054 | 1.361 |
| CC3 | " | " | 0.58 | " | 0.046 | " | 0.055 | 1.782 |
| A.C | P.S | R.P.F | 0.38 | 0.17 | 0.031 | 0.012 | 0.029 | 8.871 |
| W.B | " | " | 0.27 | " | 0.019 | " | 0.019 | 6.447 |
| CC1 | " | " | 0.16 | " | 0.017 | " | 0.018 | 0.680 |
| CC2 | " | " | 0.14 | " | 0.017 | " | 0.018 | 2.042 |
| CC3 | " | " | 0.13 | " | 0.012 | " | 0.015 | 3.267 |
| A.C | P.S | V.D | 0.63 | 0.27 | 0.048 | 0.016 | 0.044 | 10.023 |
| W.B | " | " | 0.31 | " | 0.032 | " | 0.031 | 1.581 |
| CC1 | " | " | 0.30 | " | 0.029 | " | 0.029 | 1.267 |
| CC2 | " | " | 0.24 | " | 0.013 | " | 0.018 | 2.042 |
| CC3 | " | " | 0.28 | " | 0.020 | " | 0.026 | 0.471 |
| A.C | P.S | R.W.C | 0.98 | 0.51 | 0.085 | 0.038 | 0.081 | 7.108 |
| W.B | " | " | 0.60 | " | 0.059 | " | 0.061 | 2.209 |
| CC1 | " | " | 0.57 | " | 0.050 | " | 0.054 | 1.361 |
| CC2 | " | " | 0.46 | " | 0.038 | " | 0.046 | 1.332 |
| CC3 | " | " | 0.49 | " | 0.040 | " | 0.048 | 0.510 |

TABLE C.14 Summary of Student's t test on the Results of Various Curing Regimes for Concrete Mix B6

| SAMPLE | | MIX No. | Mean | | Variance | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | $\sigma$ | t |
| A | 0 | B4 | 0.40 | 0.54 | 0.031 | 0.048 | 0.049 | 3.500 |
| B | 0 | | 0.38 | " | 0.030 | " | 0.049 | 4.000 |
| C | 0 | | 0.08 | " | 0.013 | " | 0.043 | 13.101 |
| D | 0 | | 0.07 | " | 0.016 | " | 0.044 | 13.082 |
| E | 0 | | 0.12 | " | 0.013 | " | 0.043 | 11.965 |
| A | 0 | B5 | 0.51 | 0.78 | 0.038 | 0.086 | 0.081 | 4.083 |
| B | 0 | | 0.48 | " | 0.041 | " | 0.083 | 4.428 |
| C | 0 | | 0.12 | " | 0.014 | " | 0.075 | 10.780 |
| D | 0 | | 0.14 | " | 0.015 | " | 0.076 | 10.316 |
| E | 0 | | 0.22 | " | 0.019 | " | 0.076 | 9.026 |
| A | 0 | B6 | 0.89 | 1.18 | 0.080 | 0.091 | 0.105 | 3.383 |
| B | 0 | | 1.00 | " | 0.073 | " | 0.101 | 2.183 |
| C | 0 | | 0.26 | " | 0.024 | " | 0.082 | 13.744 |
| D | 0 | | 0.14 | " | 0.013 | " | 0.080 | 15.925 |
| E | 0 | | 0.28 | " | 0.022 | " | 0.081 | 13.611 |

TABLE C.15 Summary of Student's-t test on the Results of Liquid Surface Treatment

| Sample | | Mix No. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| R.P.F | D.S.1 | B4 | 0.03 | 0.01 | 0.005 | 0.006 | 0.006 | 5.000 |
| R.P.F | D.S.1 | B5 | 0.06 | 0.03 | 0.008 | 0.010 | 0.010 | 4.500 |
| R.P.F | D.S.1 | B6 | 0.14 | 0.04 | 0.017 | 0.014 | 0.016 | 9.375 |
| R.P.F | D.S.2 | B4 | 0.03 | 0.02 | 0.005 | 0.010 | 0.010 | 1.500 |
| R.P.F | D.S.2 | B5 | 0.06 | 0.08 | 0.008 | 0.021 | 0.020 | 1.500 |
| R.P.F | D.S.2 | B6 | 0.14 | 0.13 | 0.017 | 0.035 | 0.034 | 0.441 |
| R.P.F | D.S.3 | B4 | 0.03 | 0.03 | 0.005 | 0.008 | 0.008 | 0.000 |
| R.P.F | D.S.3 | B5 | 0.06 | 0.07 | 0.008 | 0.015 | 0.015 | 1.000 |
| R.P.F | D.S.3 | B6 | 0.14 | 0.16 | 0.017 | 0.021 | 0.022 | 1.364 |
| R.P.F | D.S.4 | B4 | 0.03 | 0.03 | 0.005 | 0.007 | 0.007 | 0.000 |
| R.P.F | D.S.4 | B5 | 0.06 | 0.05 | 0.008 | 0.016 | 0.016 | 0.937 |
| R.P.F | D.S.4 | B6 | 0.14 | 0.15 | 0.017 | 0.015 | 0.017 | 0.882 |

TABLE C.16 Summary of Student's-t test on the Results of Dry Shake Surface Treatments Compared with the Standard (R.P.F)

| Sample | | Mix No. | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| D.S.1 | D.S.2 | B4 | 0.01 | 0.02 | 0.006 | 0.010 | 0.009 | 2.357 |
| D.S.1 | D.S.2 | B5 | 0.03 | 0.08 | 0.010 | 0.021 | 0.017 | 6.238 |
| D.S.1 | D.S.2 | B6 | 0.04 | 0.13 | 0.014 | 0.035 | 0.028 | 6.818 |
| D.S.3 | D.S.2 | B4 | 0.03 | 0.02 | 0.008 | 0.010 | 0.010 | 2.121 |
| D.S.3 | D.S.2 | B5 | 0.07 | 0.08 | 0.015 | 0.021 | 0.019 | 1.116 |
| D.S.3 | D.S.2 | B6 | 0.16 | 0.13 | 0.021 | 0.035 | 0.031 | 2.052 |
| D.S.3 | D.S.4 | B4 | 0.03 | 0.03 | 0.008 | 0.007 | 0.008 | 0.000 |
| D.S.3 | D.S.4 | B5 | 0.07 | 0.06 | 0.015 | 0.016 | 0.016 | 1.325 |
| D.S.3 | D.S.4 | B6 | 0.16 | 0.15 | 0.021 | 0.015 | 0.019 | 1.116 |

TABLE C.17 Summary of Student's-t test on the Results of Dry Shake Surface Treatments

| Sample | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| MIX NO | MIX NO | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| B1 | B2 | 4.544 | 4.463 | 0.114 | 0.117 | 0.123 | 1.397 |
| B1 | B3 | 4.544 | 4.393 | 0.114 | 0.096 | 0.112 | 2.860 |
| B2 | B3 | 4.463 | 4.393 | 0.117 | 0.096 | 0.113 | 1.314 |

TABLE C.18 Summary of Student's-t test on the Results of Ultrasonic Pulse Velocity Tests for Concrete B1, B2, B3

| Sample | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| MIX NO | MIX NO | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| B1 | B2 | 42.6 | 37.0 | 1.944 | 1.871 | 2.023 | 5.871 |
| B1 | B3 | 42.6 | 31.6 | 1.944 | 1.424 | 1.807 | 12.911 |
| B2 | B3 | 37.0 | 31.6 | 1.871 | 1.424 | 1.763 | 6.496 |

TABLE C.19 Summary of Student's-t test on the Results of Rebound Hardness Tests for Concrete B1, B2, B3

| Sample | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| MIX NO | MIX NO | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| B1 | B2 | 0.246 | 0.328 | 0.009 | 0.013 | 0.0116 | 14.993 |
| B1 | B3 | 0.246 | 0.524 | 0.009 | 0.013 | 0.0118 | 49.970 |
| B2 | B3 | 0.328 | 0.524 | 0.013 | 0.013 | 0.0137 | 30.344 |

TABLE C.20 Summary of Student's-t test on the Results of ISA at 10 minutes Test for Concrete Mixes B1, B2 and B3

| Sample | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| MIX NO | MIX NO | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| B1 | B2 | 0.174 | 0.242 | 0.0086 | 0.0097 | 0.0097 | 14.862 |
| B1 | B3 | 0.174 | 0.376 | 0.0086 | 0.0150 | 0.0130 | 32.940 |
| B2 | B3 | 0.242 | 0.376 | 0.0097 | 0.0150 | 0.0134 | 21.200 |

TABLE C.21 Summary of Student's - t test on the Results of ISA at 30 minutes Test for Concrete Mix B1, B2, B3

| Sample | | Mean | | Variance | | $\sigma$ | t |
|---|---|---|---|---|---|---|---|
| MIX NO | MIX NO | $m_1$ | $m_2$ | $\sigma_1$ | $\sigma_2$ | | |
| B1 | B2 | 0.111 | 0.160 | 0.0054 | 0.0083 | 0.0072 | 14.428 |
| B1 | B3 | 0.111 | 0.239 | 0.0054 | 0.0114 | 0.0095 | 28.564 |
| B2 | B3 | 0.160 | 0.239 | 0.0083 | 0.0114 | 0.0106 | 15.800 |

TABLE C.22 Summary of Student's - t test on the Results of ISA at 60 minutes Test for Concrete Mix B1, B2, B3

| Machine | MIX A1 | | | MIX A2 | | | MIX C & CA 1 | | | MIX C & CA 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Si | Yi | n | Si | Yi | n | Si | Yi | n | Si | Yi | n |
| Aston | 0.146 | 0.663 | 3 | 0.040 | 0.483 | 3 | 0.481 | 1.840 | 2 | 0.039 | 0.195 | 4 |
| C & CA | 0.145 | 0.653 | 3 | 0.087 | 0.480 | 3 | 0.601 | 1.825 | 2 | 0.022 | 0.250 | 4 |

TABLE C.23 Measure of Spread

| MIX | C | Critical Values of C |
|---|---|---|
| A1 | 0.503 | 0.975 |
| A2 | 0.825 | 0.975 |
| C & CA 1 | 0.610 | - |
| C & CA 2 | 0.759 | 0.939 |

TABLE C.24 Values of Cochran's Test Statistic

| J | MIX A1 | MIX A2 | MIX C & CA 1 | MIX C & CA 2 |
|---|---|---|---|---|
| $P_j$ | 2 | 2 | 2 | 2 |
| $m_j$ | 0.658 | 0.482 | 1.832 | 0.222 |
| $r_j$ | 0.412 | 0.190 | 1.540 | 0.089 |
| $R_j$ | 0.337 | 0.155 | 1.089 | 0.134 |

TABLE C.25 Computed Values of $m_j$, $r_j$ and $R_j$

| Level of Factor A | Level of Factor C | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | B4 Level of Factor B | | | | | B5 Level of Factor B | | | | | B6 Level of Factor B | | | | |
| | H.F | P.F | R.P.F | V.D | R.W.C | H.F | P.F | R.P.F | V.D | R.W.C | H.F | P.F | R.P.F | V.D | R.W.C |
| A.C | 0.83 | 0.47 | 0.18 | 0.35 | 0.40 | 1.10 | 0.90 | 0.35 | 0.47 | 0.53 | 1.68 | 1.29 | 0.38 | 0.63 | 0.98 |
| W.B | 0.57 | 0.31 | 0.09 | 0.18 | 0.24 | 0.68 | 0.56 | 0.20 | 0.25 | 0.39 | 0.89 | 0.82 | 0.27 | 0.31 | 0.60 |
| P.S | 0.46 | 0.30 | 0.10 | 0.23 | 0.28 | 0.61 | 0.48 | 0.18 | 0.25 | 0.41 | 0.84 | 0.66 | 0.17 | 0.27 | 0.51 |
| CC1 | 0.49 | 0.25 | 0.05 | 0.16 | 0.22 | 0.62 | 0.44 | 0.14 | 0.20 | 0.27 | 0.65 | 0.58 | 0.16 | 0.30 | 0.57 |
| CC2 | 0.57 | 0.22 | 0.03 | 0.14 | 0.18 | 0.61 | 0.41 | 0.06 | 0.20 | 0.28 | 0.74 | 0.60 | 0.14 | 0.24 | 0.46 |
| CC3 | 0.58 | 0.26 | 0.02 | 0.15 | 0.20 | 0.66 | 0.45 | 0.04 | 0.23 | 0.30 | 1.03 | 0.58 | 0.13 | 0.28 | 0.49 |

TABLE C.26 Experimental Data for Two-Way Analysis of Variance of a 6 x 5 x 3 Factorial Experiment

| Source of Variation | Sum of Square | Degree of Freedom | Mean Square | F-ratio | |
|---|---|---|---|---|---|
| | | | | Date | 5% Level |
| Between level of factor A..... | 1.5020 | 5 | 0.3004 | 60.08 | 2.45 |
| B..... | 3.991 | 4 | 0.9978 | 199.6 | 2.61 |
| C..... | 1.281 | 2 | 0.6405 | 128.1 | 3.23 |
| Interaction AB.............. | 0.277 | 20 | 0.0138 | 2.76 | 1.84 |
| AC.............. | 0.217 | 10 | 0.0203 | 4.34 | 2.08 |
| BC.............. | 0.296 | 8 | 0.037 | 7.40 | 2.18 |
| Remainder = Interaction ABC... | 0.200 | 40 | 0.0050 | | |
| TOTAL | 7.764 | 89 | | | |

Note: Factor A = Curing Regime
B = Finishing Technique
C = Mix Design

TABLE C.27 Analysis of Variance of Table C.26

# APPENDIX D DIAGRAMS

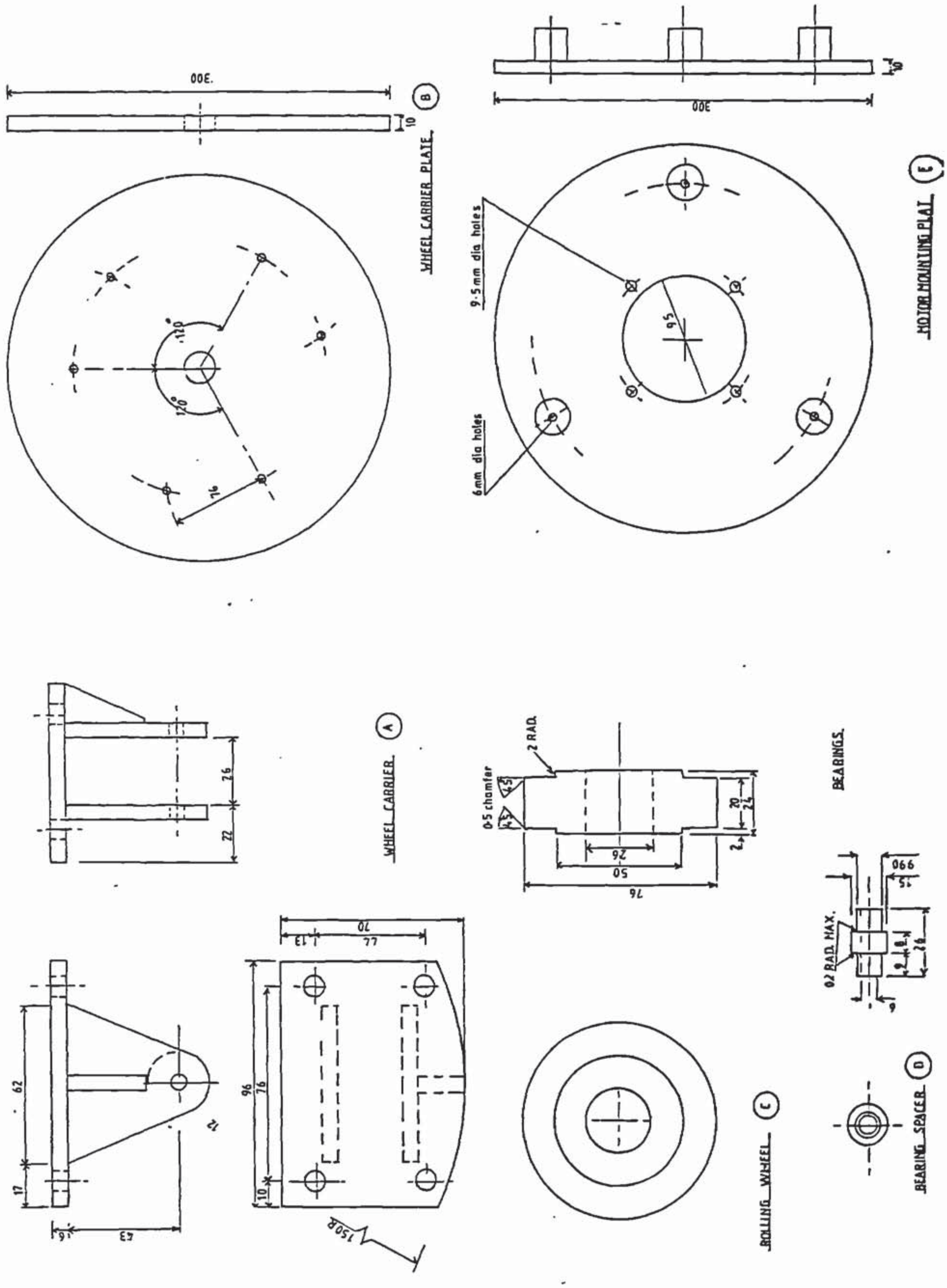



FIGURE D.1  Accelerated Abrasion Tests Apparatus and Three Types of Abrasive Heads

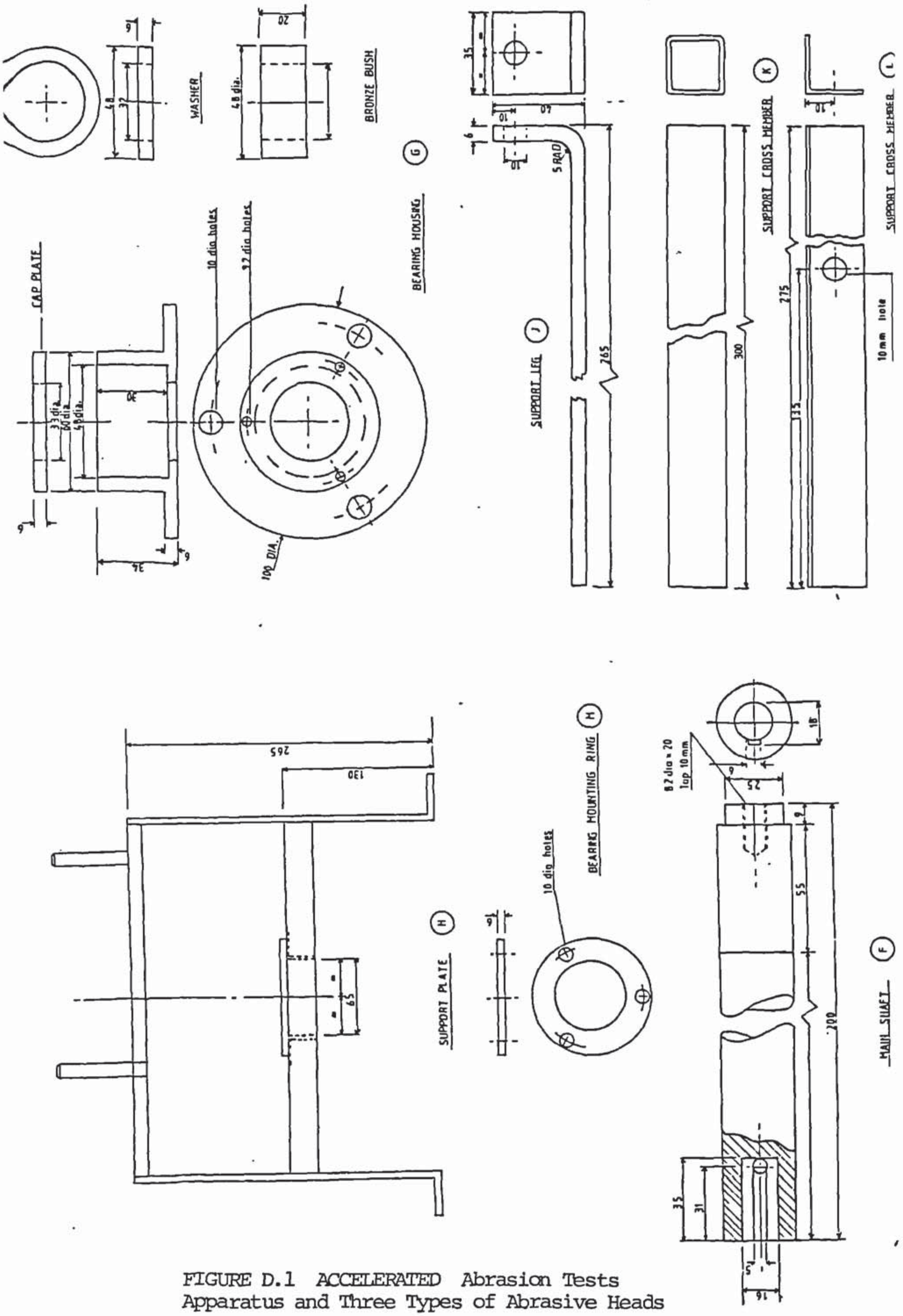



FIGURE D.1 ACCELERATED Abrasion Tests
Apparatus and Three Types of Abrasive Heads

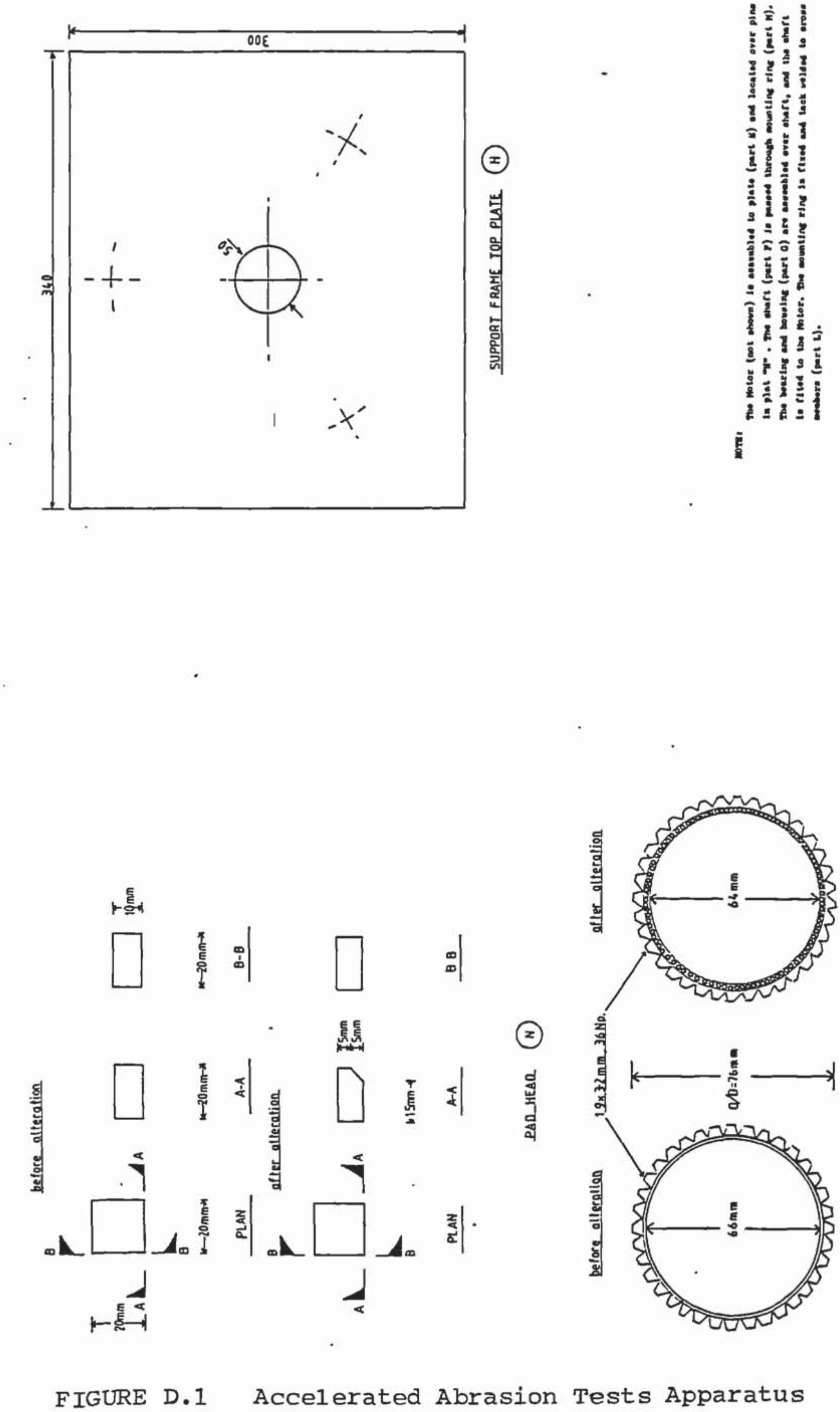
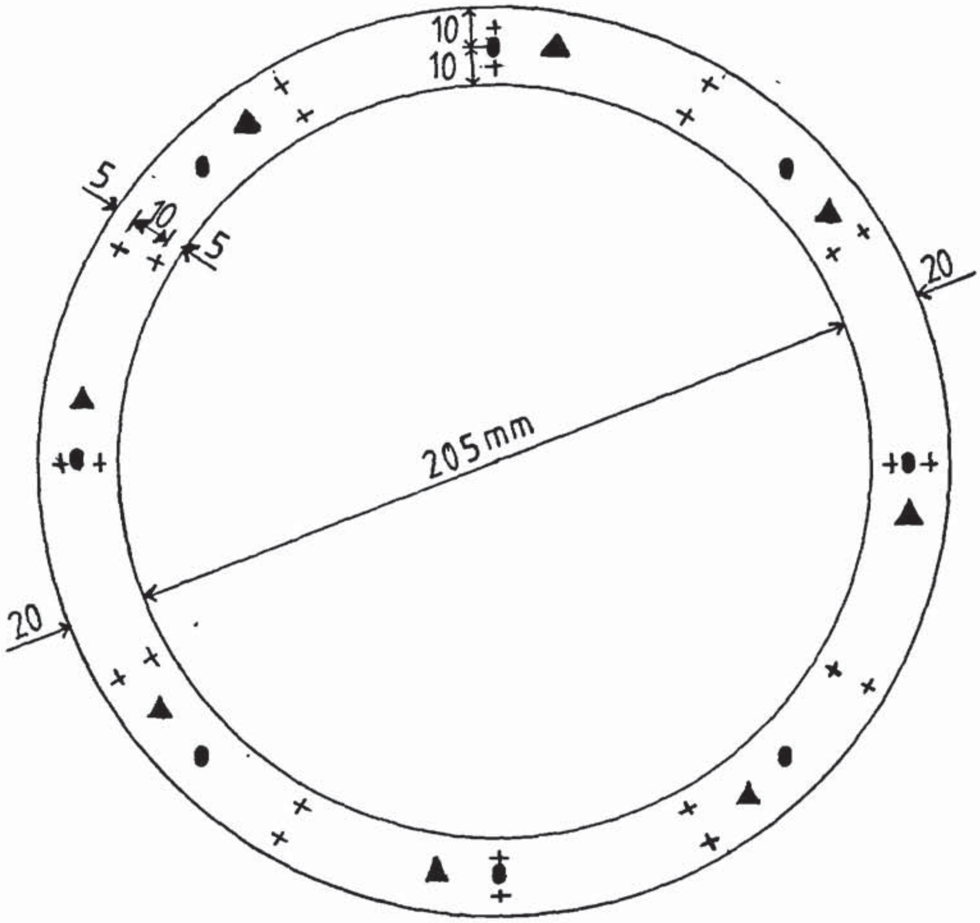



FIGURE D.1 Accelerated Abrasion Tests Apparatus and Three Types of Abrasive Heads

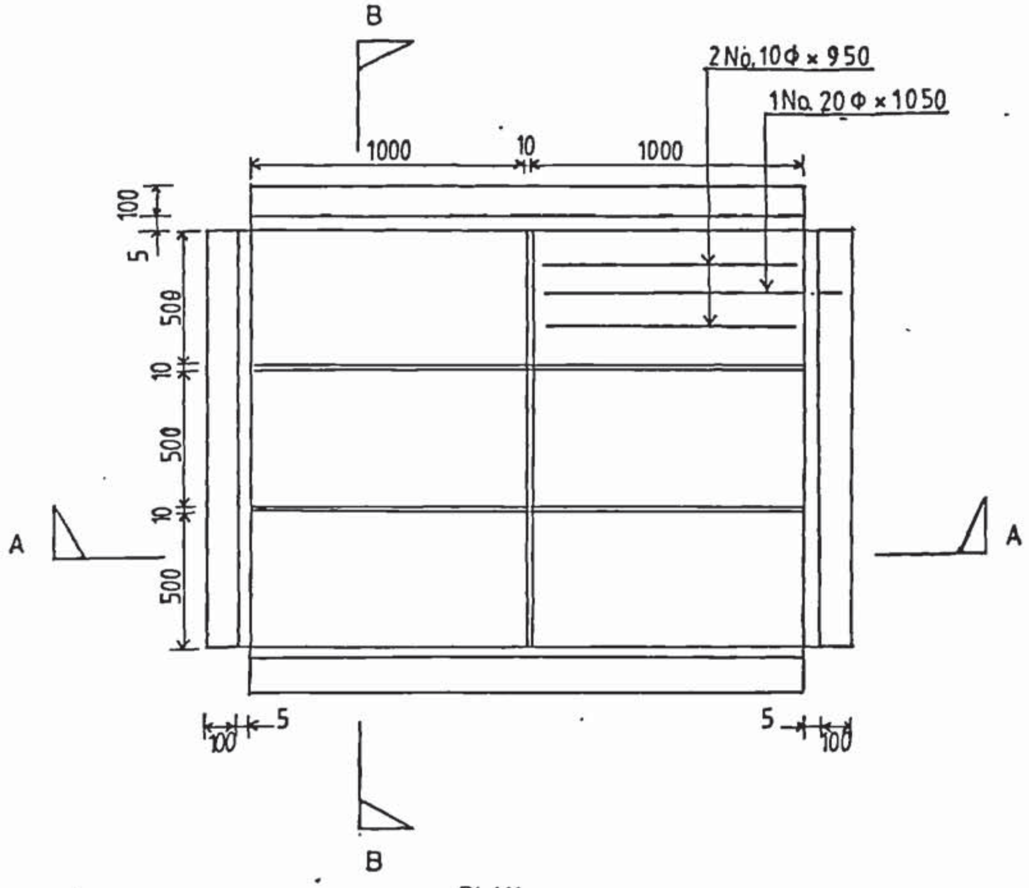



NOTE: ● = Location of the First Set of 8 Readings

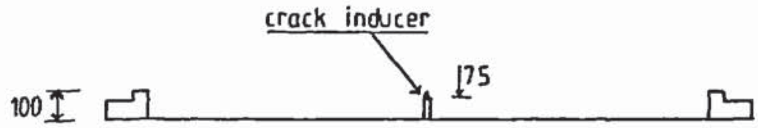
▲ = Location of the Second Set of 8 Readings

± = Location of the 24 Readings

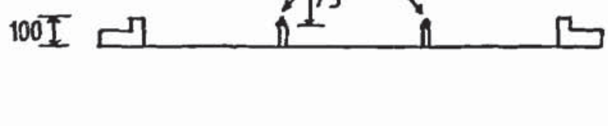
FIGURE D.2 Path of Abrasion




PLAN




SECTION A-A




SECTION B-B

FIGURE D.3 MOULD DESIGN

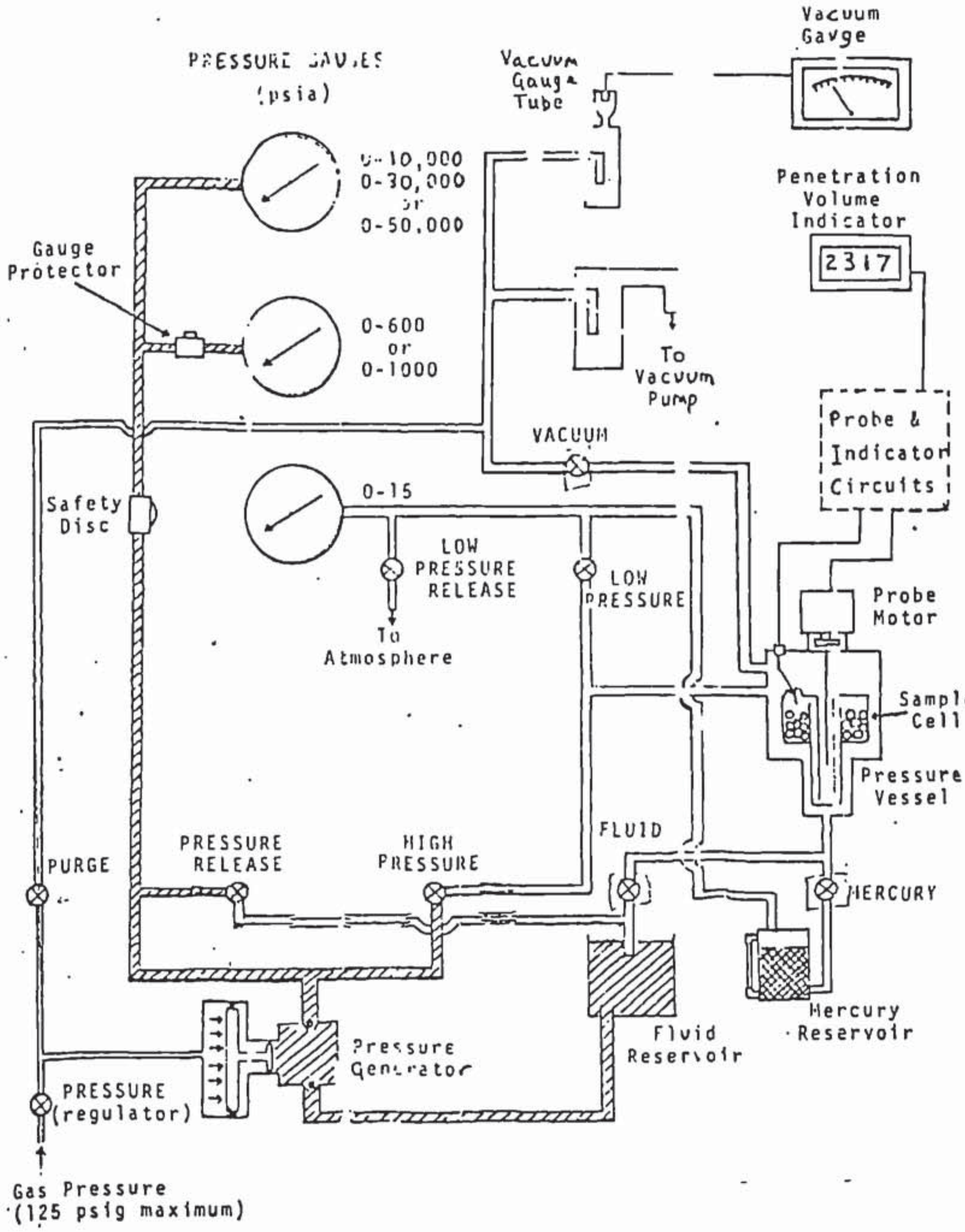
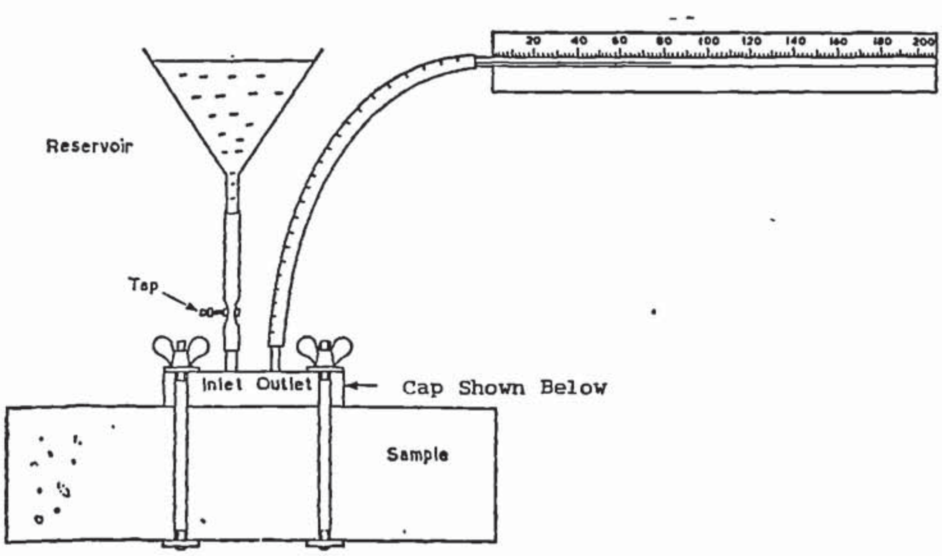
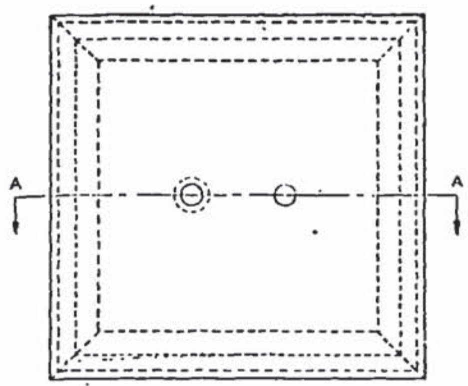
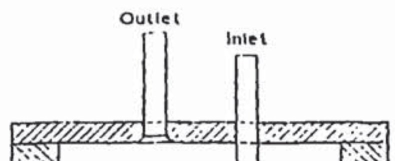



FIGURE D.4 SCHEMATIC DIAGRAM OF MERCURY INTRUSION POROSIMETER SYSTEM (BASED ON Ref.134)




Complete Assembly, Excluding Stands, Clamps, etc.




Typical cap suitable for clamping onto horizontal surface

FIGURE D.5 SCHEMATIC DIAGRAM OF INITIAL SURFACE ABSORPTION APPARATUS (Based on Ref.181)

# APPENDIX E STANDARD LETTERS

# APPENDIX F MANUFACTURER INSTRUCTIONS

# APPENDIX G CALCULATION OF PORE SIZE DISTRIBUTION

## G.1 The Washburn Formula of the Intrusion of a Non-Wetting Liquid into a Pore

Washburn (133) suggested that the surface tension opposes the entrance of non-wetting liquid into a small pore. This opposing force $F_o$ is given by:

$$F_o = -\pi d \gamma \cos \theta$$

Where d is the diameter of the pore, $\gamma$ is the surface tension of the liquid and $\theta$ is the contact angle the liquid makes with the material.

This opposition can be overcome by the application of external force $F_a$ given by:

$$F_a = \pi \frac{d^2}{4} P$$

Where P is the applied external pressure. At equilibrium

$$\pi \frac{d^2}{4} P = -\pi d \gamma \cos \theta$$

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

## G.2 Example Calculation of Pore Size Distribution

Porosimeter data and calculation for concrete mix B4, P.F.

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

$\gamma$ for mercury = 485 dynes/cm ($485 \times 10^{-6}$ N/mm)

$\theta$ is the contact angle between the oven dried sample and mercury = $117^o$

Table G.1 shows the calculation of the pore size distribution.

Sample Identification   Mix B4 [illegible]

Sample Weight ($W_s$)   = 5.6505 g

Cell Factor   = 0.000751 $cm^3$/count

| A<br>Applied Pressure (psi) | B<br>Penetration Counter Indication | C<br>Corrected Counter Indication (B - "Blank" Result) | D<br>Pore Diameter ($117^o$ Contact Angle) (124.9/A) Microns | E<br>Volume of Pores of Indicated Diameter and Larger C (Factor/$W_s$) $cm^3/g$ |
|---|---|---|---|---|
| 1 | 6 | 6 | 124.9000 | 0.0008 |
| 3 | 12 | 12 | 41.6333 | 0.0016 |
| 5 | 15 | 15 | 24.9800 | 0.0020 |
| 8 | 18 | 18 | 15.6125 | 0.0024 |
| 11 | 21 | 21 | 11.3545 | 0.0028 |
| 50 | 48 | 48 | 2.4980 | 0.0064 |
| 100 | 69 | 69 | 1.2490 | 0.0092 |
| 200 | 88 | 88 | 0.6245 | 0.0117 |
| 300 | 101 | 101 | 0.4163 | 0.0134 |
| 400 | 114 | 114 | 0.3122 | 0.0152 |
| 500 | 120 | 120 | 0.2498 | 0.0159 |
| 700 | 128 | 128 | 0.1784 | 0.0170 |
| 900 | 139 | 139 | 0.1388 | 0.0185 |
| 1200 | 149 | 149 | 0.1041 | 0.0198 |
| 1400 | 157 | 157 | 0.0892 | 0.0209 |
| 1600 | 165 | 165 | 0.0781 | 0.0219 |
| 1800 | 176 | 176 | 0.0694 | 0.0234 |
| 2000 | 187 | 187 | 0.0624 | 0.0248 |
| 2400 | 208 | 208 | 0.0520 | 0.0276 |
| 2800 | 225 | 225 | 0.0446 | 0.0299 |
| 3200 | 241 | 241 | 0.0390 | 0.0320 |
| 3600 | 255 | 255 | 0.0347 | 0.0339 |
| 4000 | 268 | 268 | 0.0312 | 0.0356 |
| 4400 | 278 | 278 | 0.0284 | 0.0369 |
| 4800 | 286 | 286 | 0.0260 | 0.0380 |
| 5200 | 308 | 308 | 0.0240 | 0.0409 |
| 5600 | 312 | 312 | 0.0223 | 0.0415 |
| 6000 | 316 | 316 | 0.0208 | 0.0420 |
| 6500 | 323 | 323 | 0.0192 | 0.0429 |
| 7000 | 338 | 338 | 0.0178 | 0.0449 |
| 8000 | 348 | 346 | 0.0156 | 0.0460 |
| 9000 | 349 | 361 | 0.0139 | 0.0480 |
| 10000 | 374 | 369 | 0.0125 | 0.0490 |
| 11000 | 382 | 376 | 0.0114 | 0.0500 |
| 12000 | 392 | 384 | 0.0104 | 0.0510 |
| 13500 | 400 | 391 | 0.0092 | 0.0520 |
| 15000 | 411 | 399 | 0.0083 | 0.0530 |
| 17000 | 420 | 206 | 0.0073 | 0.0540 |
| 19000 | 431 | 414 | 0.0066 | 0.0550 |
| 21000 | 440 | 421 | 0.0059 | 0.0560 |
| 23000 | 450 | 429 | 0.0054 | 0.0570 |
| 26000 | 460 | 436 | 0.0048 | 0.0580 |
| 29000 | 468 | 440 | 0.0043 | 0.0585 |
| 32000 | 477 | 444 | 0.0039 | 0.0590 |
| 35000 | 485 | 448 | 0.0036 | 0.0595 |
| 38000 | 498 | 454 | 0.0033 | 0.0603 |
| 42000 | 504 | 455 | 0.0030 | 0.0645 |
| 46000 | 517 | 459 | 0.0027 | 0.0610 |
| 50000 | 522 | 460 | 0.0025 | 0.0611 |

TABLE G.1 Example Calculation of pore size distribution

# APPENDIX H MICROHARDNESS PROFILES

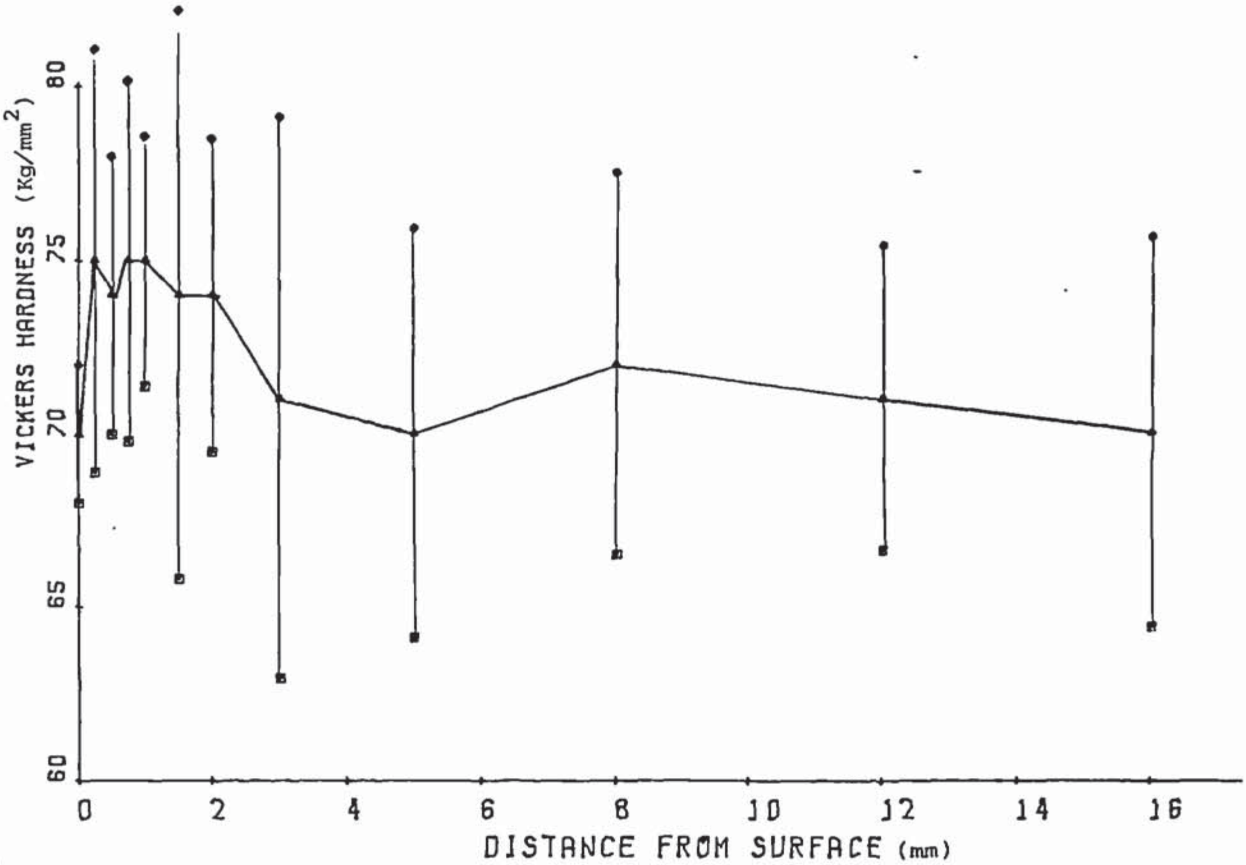



FIGURE H.1 Microhardness Profile for Concrete Mix B4, H.F Sample

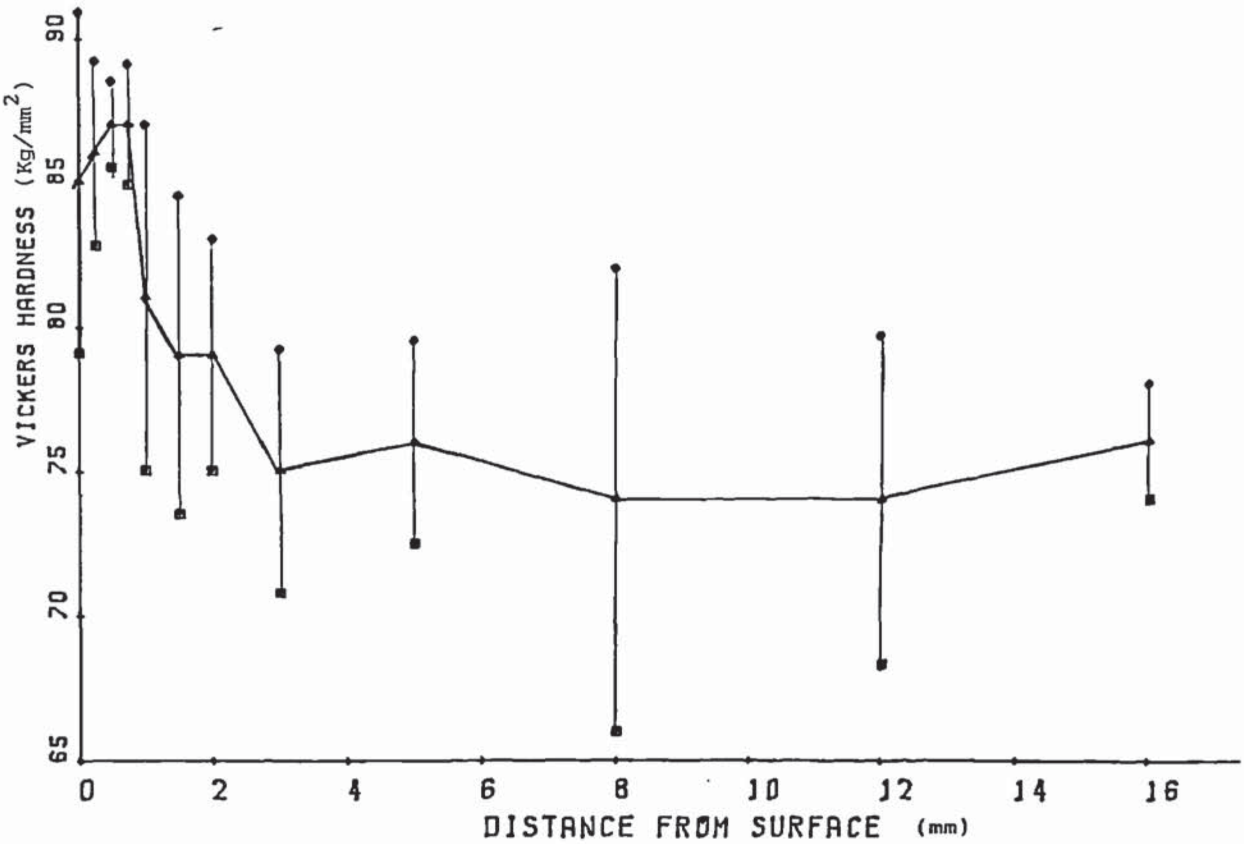



FIGURE H.2 Microhardness Profile for Concrete Mix B4, P.F Sample

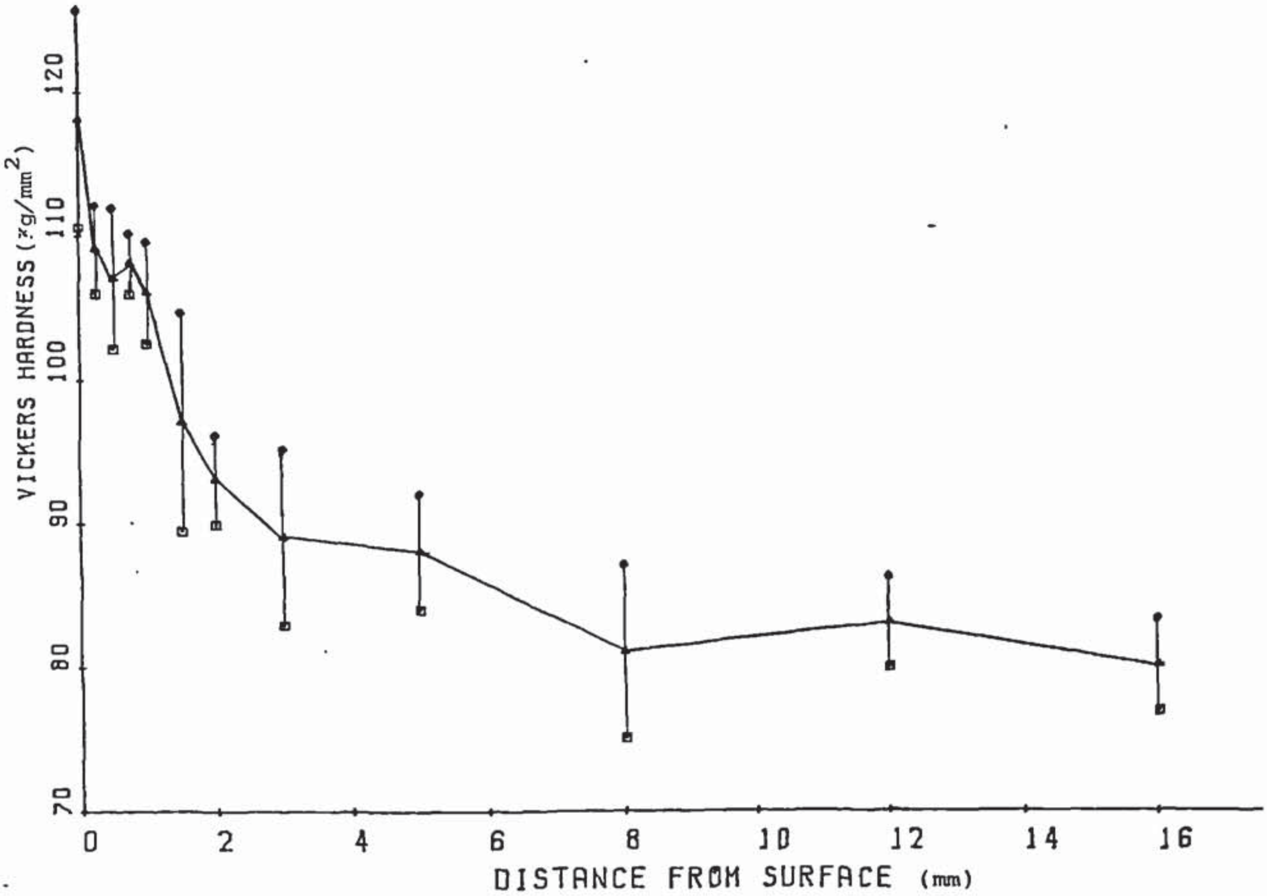



FIGURE H.3 Microhardness Profile for Concrete Mix B4, R.P.F Sample

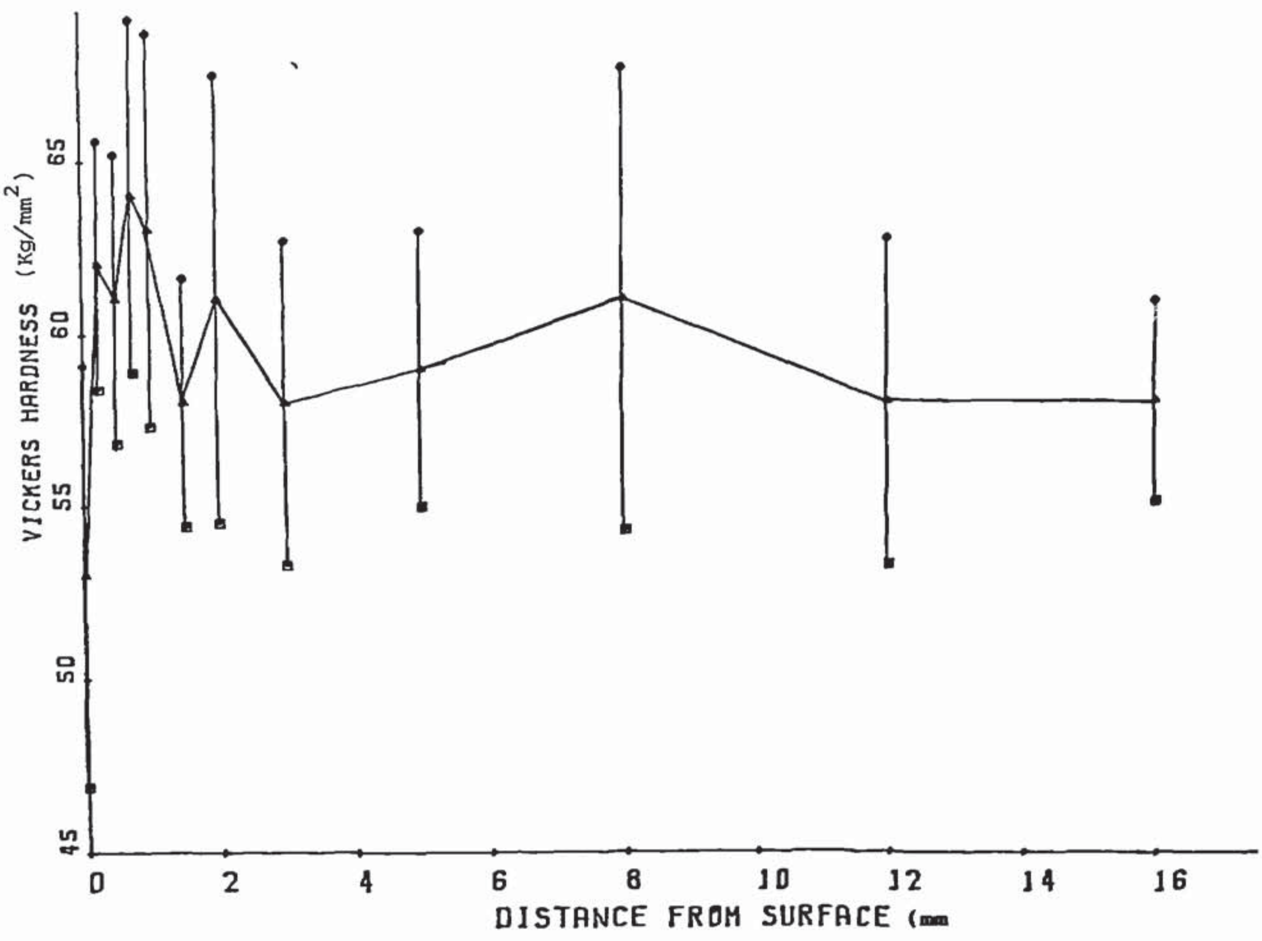



FIGURE H.4 Microhardness Profile for Concrete Mix B5, H.F Sample

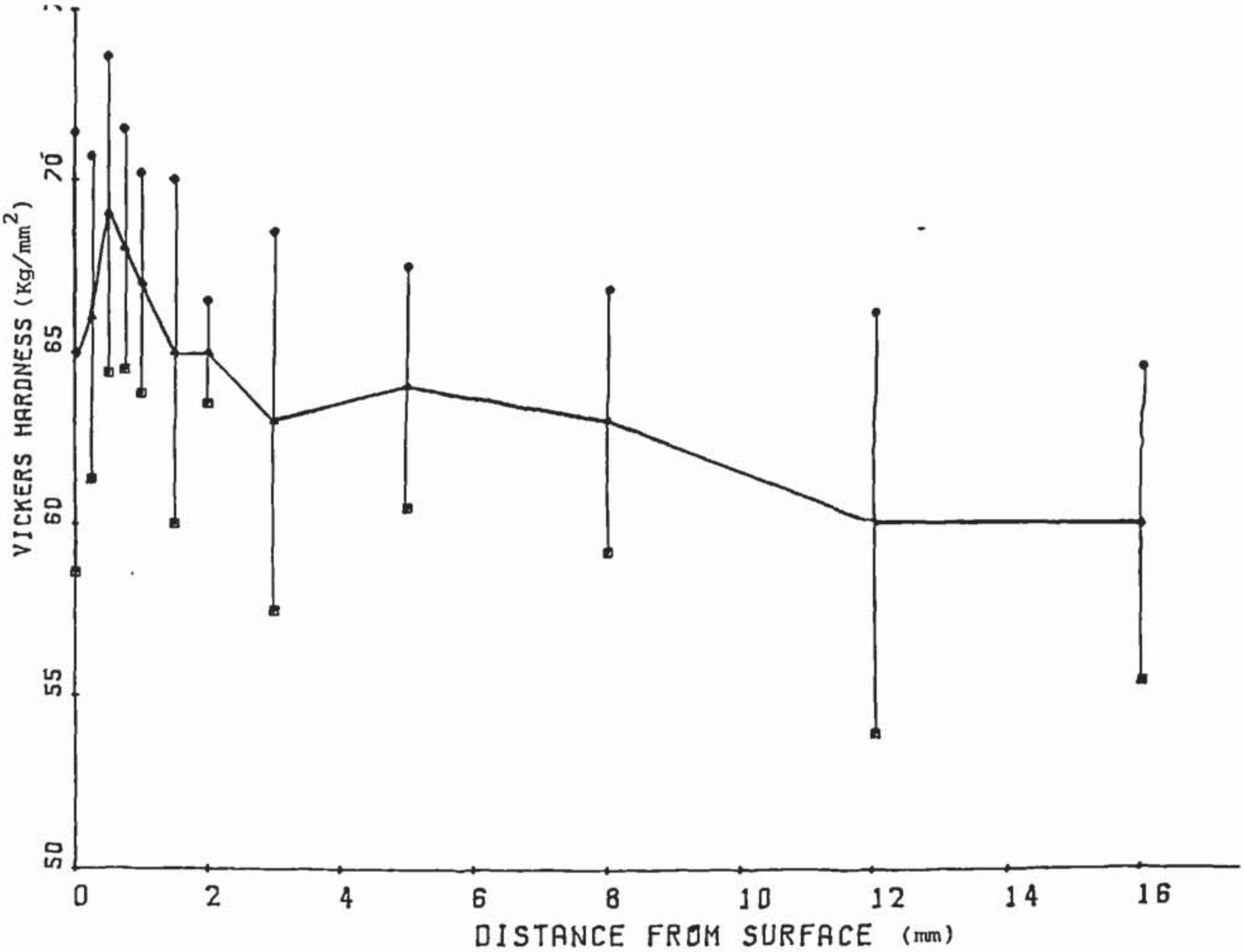



FIGURE H.5 · Microhardness Profile for Concrete Mix B5, P.F.Sample

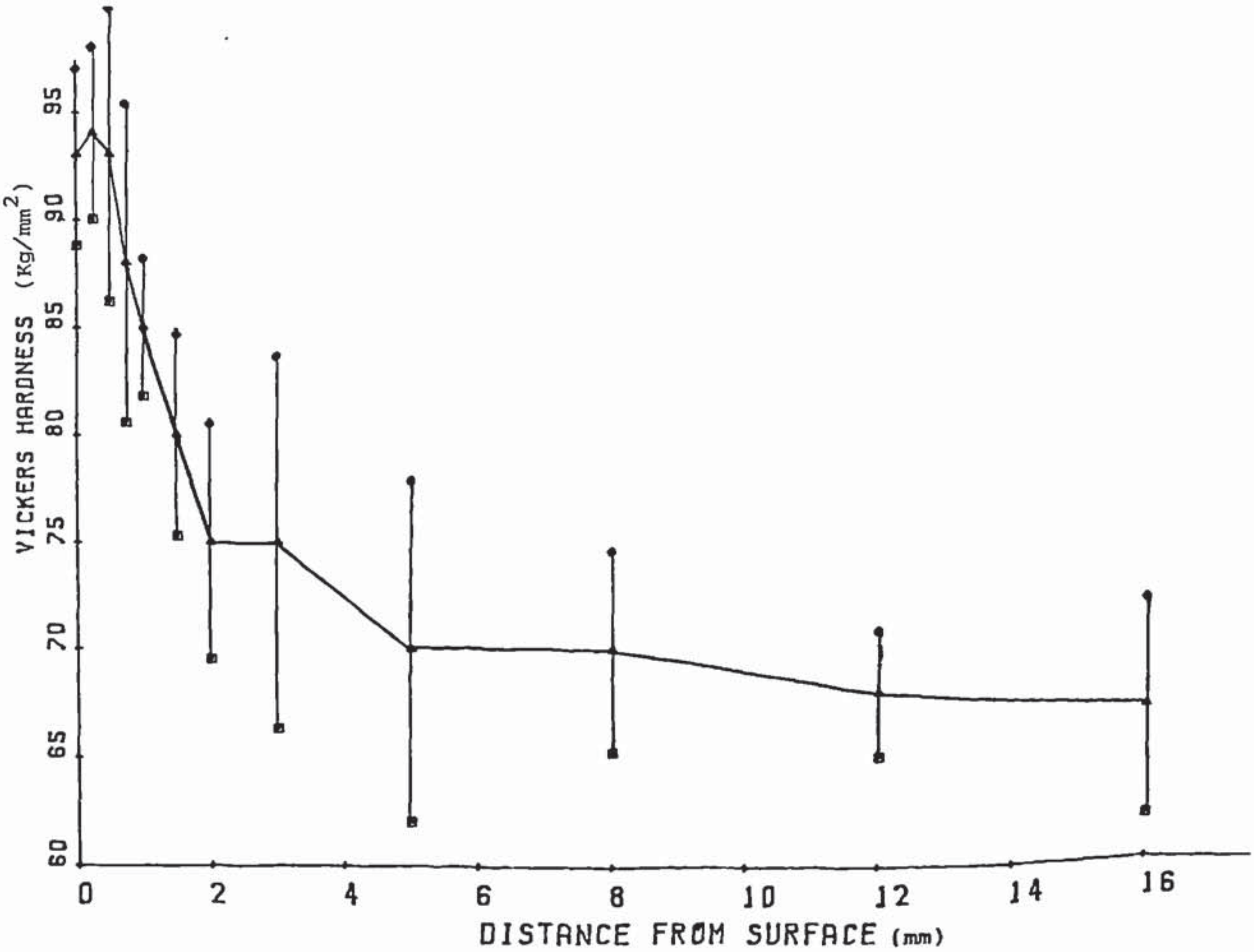



FIGURE H.6 Microhardness Profile for Concrete Mix B5, R.P.F Sample

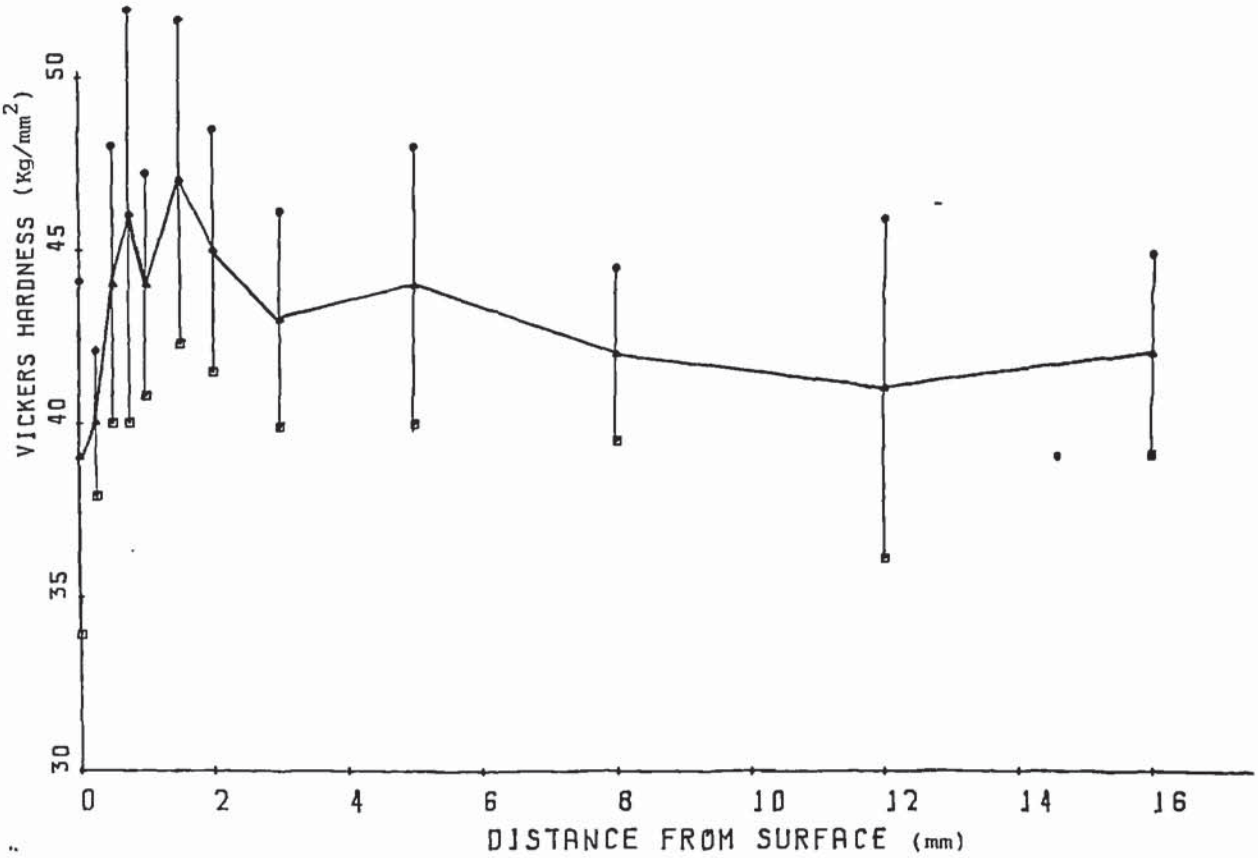



FIGURE H.7 Microhardness Profile for Concrete Mix B6, H.F Sample

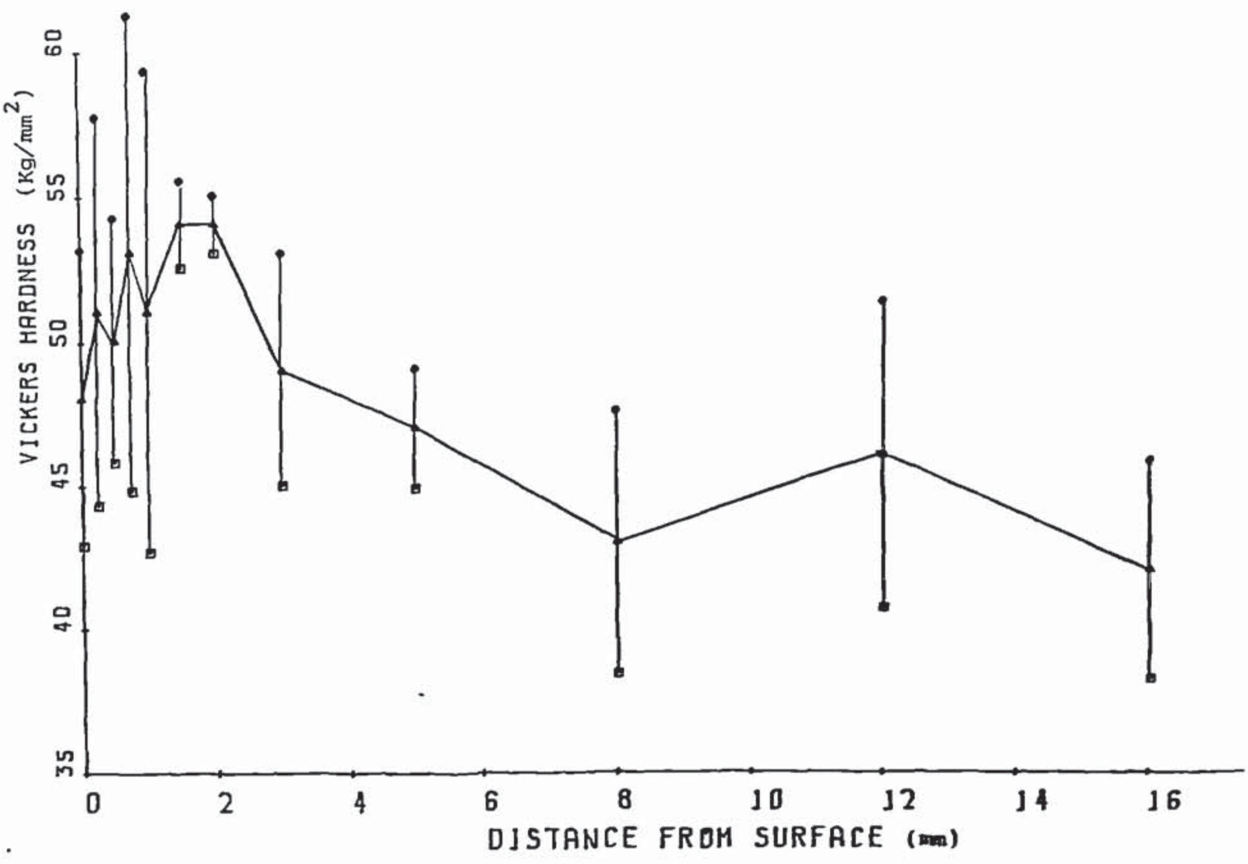



FIGURE H.8 Microhardness Profile for Concrete Mix B6, P.F. Sample

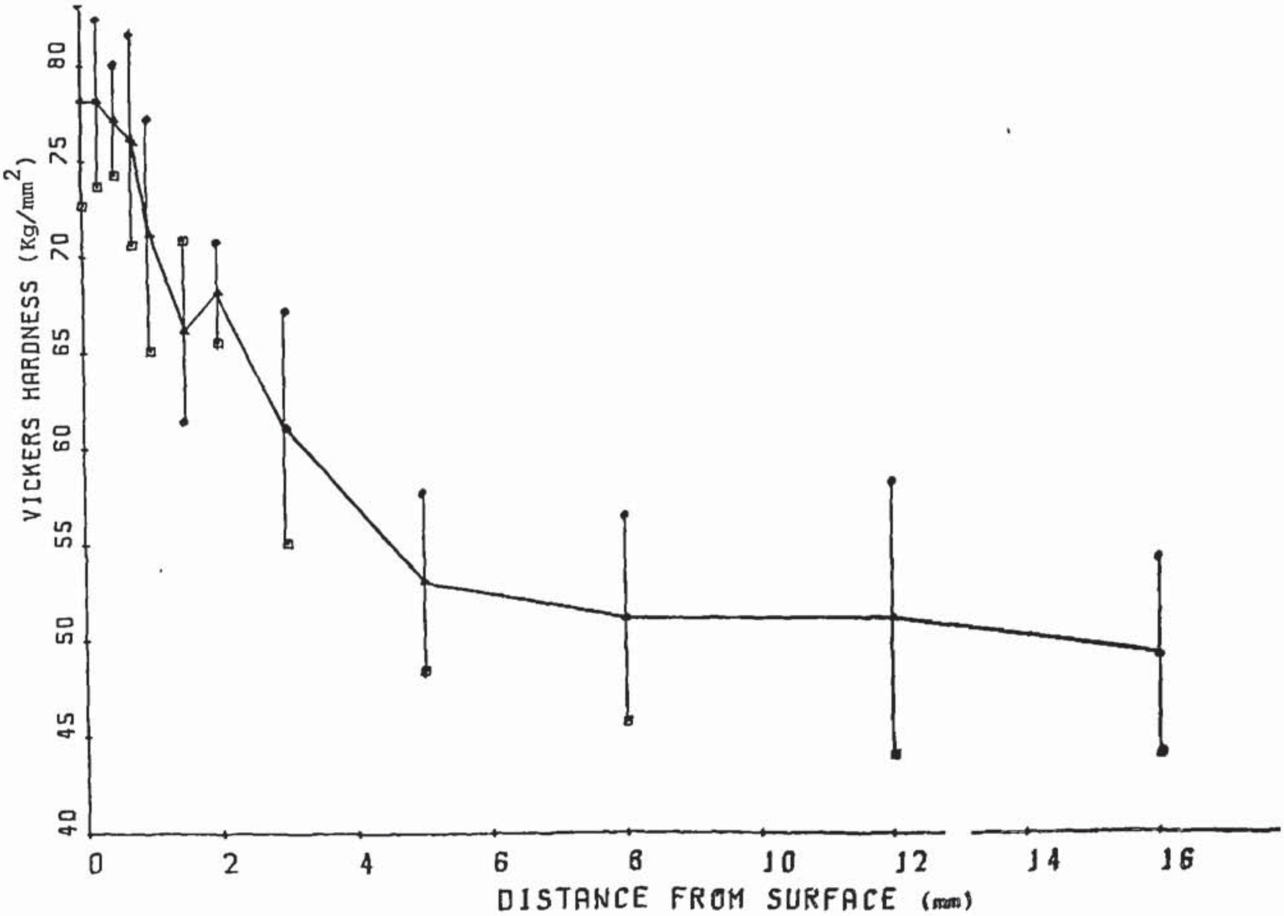



FIGURE H.9 Microhardness Profile for Concrete Mix B6, R.P.F Sample

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