

THE INFLUENCE OF CURING AND SURFACE PREPARATION ON THE ADHESION OF PROTECTIVE COATINGS ON CONCRETE

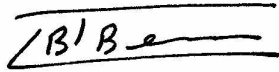
Bernard Thomas Benn

A Research Report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg in partial fulfilment of the requirements for the degree of Master of Science in Engineering

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DECLARATION

I declare that this project is my own unaided work. It is being submitted for the conversion of the Graduate Diploma in Engineering to the degree of Master of Science in Engineering from the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

A handwritten signature in black ink, appearing to read 'B T Benn', is enclosed within a rectangular box. The signature is written in a cursive style with a long horizontal stroke at the end.

B T Benn

On this 18th day of December 2008.

ABSTRACT

In cases where concrete has to be repaired or protected due to exposure to an aggressive environment, a protective coating is often used. The guidelines referenced on the subject of repairs and coatings of concrete require the substrate must be clean, dry and free from loose material but no mention is made of a preferred method of surface preparation.

This research report presents details of an investigation in which concrete was subjected to different curing regimes in order to induce different qualities of surface concrete. The different surface qualities were prepared using four alternative surface preparation methods prior to coating. After an initial investigation, five different coatings were chosen in order to cover a broad spectrum of coatings available to the construction industry.

Once the applied coatings had cured they were tested using a pull-off testing device to determine the adhesion properties. The mode of failure was determined by visual examination. In addition, surface characteristics were determined using an optical microscope and the water sorptivity test.

Results indicate that preparing the surface before application of coatings does improve adhesion. The preparation that was easiest to carry out, and which also gave the best adhesion results, was the wire brushing technique. Considering the practicality for site application, the mechanical method would be most appropriate. From the findings, aliphatic coating exhibited the best adhesion properties, while epoxy resin and cementitious-based materials also gave satisfactory results.

Elastomeric coating with lower adhesion strengths at early ages may be suited to surfaces that are expected to crack, as the elastic nature of the material will bridge the gap. Masonry paint, which was only used for comparative purpose did not perform as well as expected and had the lowest bond strengths. Where the removal of defective concrete is likely to result in a rough surface the cementitious material may be preferable.

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ORGANISATION OF THE DISSERTATION

The report has been organised into the following chapters. The Introduction states the problem, the proposed investigation and the limitations. The Literature Review refers to technical papers on the subject of adhesion of coatings to concrete that were read with particular reference to the two RILEM conferences on adhesion between polymers and concrete. The chapter on the Experimental Details includes information on the concrete materials used, the coatings, preparation of specimens and the test methods used during the investigation.

The Results and Discussions sections present each set of test results with the aid of tables, statistical analysis, graphics and photographs. This is followed by the Conclusions and Recommendations for Further Work. Finally the References, Bibliography and Appendices are included.

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Chapter 1: INTRODUCTION

1.1 Statement of the Problem

In many instances where repairs are carried out or where structural concrete is exposed to aggressive environments, the original or repaired concrete is often painted with a protective coating. Data sheets on the protective coatings available from suppliers, as well as information published in technical journals [1] and by specifying bodies [2] usually mention that the substrate should be clean, dry and sound. None of them, however, suggest a preferred method of substrate preparation probably because in every instance where protective coatings are required the condition and/or quality of the concrete onto which the coating has to be applied will first have to be assessed. Once the initial investigation has been completed the substrate preparation, repair method and coating application specification can be issued such that it relates to the conditions prevailing at that particular site. Some, but not all, of the site conditions that would need to be considered are: soundness of the concrete, condition of the reinforcing, accessibility of the site, availability of utilities, health and safety of the general public and site workers and ambient weather conditions during the preparation and coating period. There are also no recommendations on the use of different surface preparation methods for different near-surface concrete qualities. The near-surface concrete quality will have been affected by the degree of curing, curing methods and curing conditions at the time of construction. Aggressive environments such as physical abrasion or chemical attack from agents such as soft water and acidic pollutants will also have affected the near-surface quality of the concrete. As described above, the complexity of assessing

repairs and areas that require protective coatings make it extremely difficult to cover every eventuality in a data sheet or specification.

This investigation aims to examine the effect of both different surface preparation methods and the influence of the near-surface concrete quality (induced by means of different wet curing regimes) on adhesion by evaluating the performance of different commercially available protective coatings.

1.2 Need for Further Data on Adhesion

The need for further understanding of the adhesion of protective coatings on concrete is based on both personal experiences, when employed in the protective coatings industry, as well private conversations [3, 4] held with the major suppliers of protective coatings.

The following aspects were evident:

- There is little information available on the damage done to the substrate by equipment used to prepare the surface.
- The suppliers are generally reluctant and cautious to specify a particular method of substrate preparation, mainly due to the variable quality of in-situ concrete.
- There is little data on how the type of surface preparation influences the adhesion properties of a coating.
- There is little or no data available on the effect of the near-surface concrete quality on the adhesion properties of a protective coating.
- In a majority of cases where failure of coating has occurred, these failures have been attributed to inadequate surface preparation by the contractor.

It is hoped that this investigation will provide information useful to specifiers, contractors and suppliers that is relevant to application of coatings on concrete surfaces in structures.

1.3 The Investigation

1.3.1 Specimens

Four sets of concrete beams 750 x 150 x 150 mm in size were made, and then subjected to different controlled curing conditions to produce distinctly different near-surface concrete quality in each set. The beams were then exposed to the prevailing Johannesburg Highveld climatic conditions for at least one year before preparation and coating. The twelve batches of concrete were made in the Alpha Cement Concrete Laboratory (now AfriSam) from locally available coarse and fine aggregates, with four 50 kg bags of cement collected from a single pallet to ensure it was from the same production run. From each beam six specimens were cut to size. Four specimens were cut to nominal sizes 160 x 150 x 150 mm and two were cut to 50 x 150 x 150 mm. The latter (small) specimens were used for examination by optical microscope and for the sorptivity test. Three of the larger specimens were subjected to three different methods of surface preparation while the one remaining specimen coated as cast, without any surface preparation.

1.3.2 Coatings and Primers

From the list of potential suppliers, sourced from the Library at the Cement and Concrete Institute (C&CI), four readily available propriety concrete surface coatings were selected because they were accepted as high quality products by the construction industry. They also contain the most commonly used raw materials in

their formulation. The different coatings were brush applied and allowed to cure in accordance with manufacturers' instructions before adhesion tests were carried out.

Primers, usually packaged as separate products, are recommended when the adhesion of the protective coating to the concrete substrate without a primer is not considered adequate by the manufacturer. Primers bond either physically and/or chemical with the concrete substrate while the coating bonds chemically to the primer. The combination, of primer and coating, provides a monolithic protective layer to the concrete. Three of the propriety coatings were used with the primer recommended by the manufacturer, while the fourth coating and the masonry paint were applied without a primer. The latter was included in the investigation to compare adhesion characteristics and because it is normally, used without any primer, for decorative not protective purposes it was applied without a primer. The aim of the investigation was to assess propriety coatings as used in practice with different substrate preparations on concrete substrates of differing quality and thus it was outside the scope of the investigation to assess the affect of primers on those coatings that normally do not require primers

1.3.3 Test Methods

The particle size distribution and relative density of both coarse and fine aggregates were determined but the loose and compacted bulk density was only ascertained for the coarse aggregate. The consistency of each fresh concrete mix was obtained by means of the slump test, the wet density determined and the compressive strength of the hardened concrete measured at various ages.

After the specimens had been cut and prepared, sorptivity tests were carried out to assess the effect of the different methods of preparation on the near-surface concrete. Optical microscopic examination using thin slices was carried out to determine the extent to which the different methods of preparation had damaged the “sound” concrete that would be coated.

After the specified curing period for the coating had elapsed, the adhesion of the coating to the various concrete surfaces was determined using an “Elcometer” adhesion tester as described by Judge et al. [5]. The pull-off test was carried out by gluing a 20 mm diameter stud to the coating using a two-part epoxy glue, and then applying a direct tensile force. This force was applied until the coating was torn from the concrete surface and the magnitude of the stress measured was recorded in N/mm^2 (MPa). On completion of the test, the stud was visually examined to determine if the failure had occurred at the interface or in the substrate.

1.4 Limitations of the Investigation

As mentioned in the previous section, the C & CI Library has a comprehensive database of suppliers for the building and construction industry. From a possible 21 suppliers, the investigation was limited to four propriety products and one, readily available, masonry paint. The four propriety coatings were selected because they are each manufactured with different basic raw materials but several other coatings not used in this investigation may have different performance characteristics. Based on the data available from the manufacturers the coatings used in this investigation can be used under all South African weather conditions and thus it has been accepted that the affect of moist conditions on the polymers has been considered by the

manufacturer and therefore was not investigated as part of this study. There are many permutations regarding the 28-day characteristic strengths that could be specified for a structure. In this study only one water/cement ratio (w/c) was used and only four mixes were made. Each mix was subjected to a different controlled curing regime, which was expected to give different surface qualities of concrete.

Although coatings are formulated to last several years before maintenance may be necessary, long-term testing was not practical for the purposes of this investigation. The initial adhesion test was carried out at four weeks as the Product Data Sheet for the cementitious coating quoted the 28-day bond strengths. The second series of adhesion tests were carried out three months after the initial tests, approximately sixteen weeks after application of the coating in order to assess if any changes in the adhesion properties had occurred during the intervening period.

The size of the test specimens also limits the investigation, as they are significantly smaller than an actual structure. When a structure is coated, all the exposed surfaces are normally coated to provide total protection and to prevent delamination of the coating due to the build up of moisture under the coating, whereas the test specimens were only coated on one side. In order to prevent moisture ingress to beneath the coating by being absorbed through the uncoated sides of the specimens, and thus creating a vapour pressure that would disrupt the adhesion of the coating [6]), the samples were kept indoors for a month before coating and were kept under the same conditions after the coatings had been applied.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

The limitation of assessing protective coatings in a laboratory investigation is the difficulty of simulating the conditions most likely to occur on a site and the number of possible coatings. The broad classification of the protective coatings available for concrete in South Africa has been based on the descriptions given in the Product Data Sheets and includes:

- Polymer modified cements.
- Polymer dispersions including ethylene copolymers, elastomeric acrylics and aliphatic acrylics.
- Epoxy resins including pitch (tar) extended epoxies.
- Bitumen emulsions.
- Polyurethanes and polyurethane modified cements.

This means that interpretation of results of laboratory based test methods should take into consideration that:

- Surface preparations carried out in the laboratory may be difficult to replicate on site.
- The test methods used may be more difficult to utilise on site than in the laboratory.
- Actual coating should ideally be carried out under site conditions.

The most comprehensive information on the subject of “The adhesion of coatings to concrete” was contained in publications:

1. The Concrete Society Technical Report No. 50 [1].

2. The proceedings of the International RILEM Symposium on “Adhesion between Polymers and Concrete”, Aix-en-Provence, France, September 1986 [7].
3. Proceedings of the Second International RILEM Symposium on “Adhesion between Polymers and Concrete”, Dresden, Germany, September 1999 [8].

Much of the review focuses on these three publications as they represent the “State of the Art” up to the time this study was undertaken.

2.2 Science of Adhesion

Coatings may have a thickness that ranges from 100 μm to several millimetres. To fulfil the expected function satisfactorily over an extended period there must be a strong bond between the near-surface concrete and the coating. The surface condition required for concrete to accept a coating is just as important to the success and longevity of the coating as the foundation is to a structure [9]. Surface defects that will affect adhesion include tie holes, honeycombing and fins.

The presence of water must be recognised at all times [6] whether present as a liquid or vapour under varying degrees of relative and absolute humidity. Not only is the moisture present on the surface, air, soil but also on or in the concrete that is to be protected. Protective coatings are based on organic compounds, while concrete is inorganic and thus there is little or no physical or chemical affinity between the two. Therefore, obtaining satisfactory adhesion obviously poses some problems and these are complicated by the presence of water. Coatings will normally interrupt and stop the equilibrium reactions with respect to the “exchange” of water between the near-surface concrete and the ambient air. The result is an increase of moisture

content immediately underneath the coating, at the contact interface, that can cause inadequate curing of the coating and subsequent loss of adhesion.

Cardon and Hiel [10] argue that in the case of a thin layer, the properties of the transition zone are the fundamental control elements of the realised adhesion whereas for a thick adhesive layer, the properties of the bulk adhesive are the control elements.

Peier [11] describes two types of failure, shown in Figure 1, that can occur as shrinkage stresses develop in the coating layer after application

1. Cohesive failure (cracking) if:

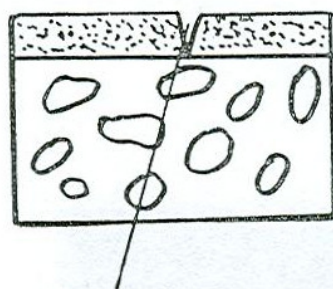
1. The adhesive strength $>$ shrinkage stresses and
2. The shrinkage stresses $>$ cohesion

2. Adhesion failure if:

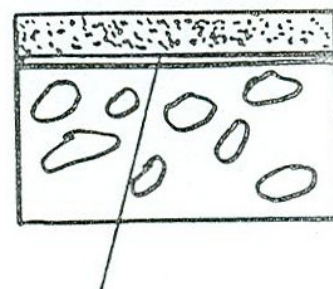
The adhesive strength $<$ shrinkage stresses

For the system to remain intact the following two conditions must be satisfied:

1. Adhesive strength $>$ shrinkage stresses and
2. Cohesive strength $>$ shrinkage stresses



cohesion failure (crack)



adhesion failure

Figure 1: Failure types [11]

A different description of how failure occurs, shown in Figure 2, was given by Ohama, et al. [12] who classified the modes of failure found when testing the adhesion of polymer-modified mortars to ordinary cement mortar as follows:

- Adhesive failure “A” when the failure was in the interface
- Cohesive failure “M” in the polymer-modified mortar
- Cohesive failure “S” in the substrate

The respective approximate extent of A, M and S failures as a percentage of the total cross-section area are expressed as suffixes for A, M, and S. For example if 80% of the failure was at the interface and 20% in the substrate the result would be recorded as A8S2. Theoretically, failure will occur at the weakest point of adhesion of the coating to the substrate. If an interface failure is obtained, the bond strength can be taken as the failure stress. If, however the failure occurs elsewhere, the result is more difficult to interpret, as the strength at the interface may be equal to the failure stress but it may also be greater. It is therefore important to compare the pull off tests with the interface failures [13]. The problem is that the number of interface failures may be small, making the conclusions inherently uncertain.

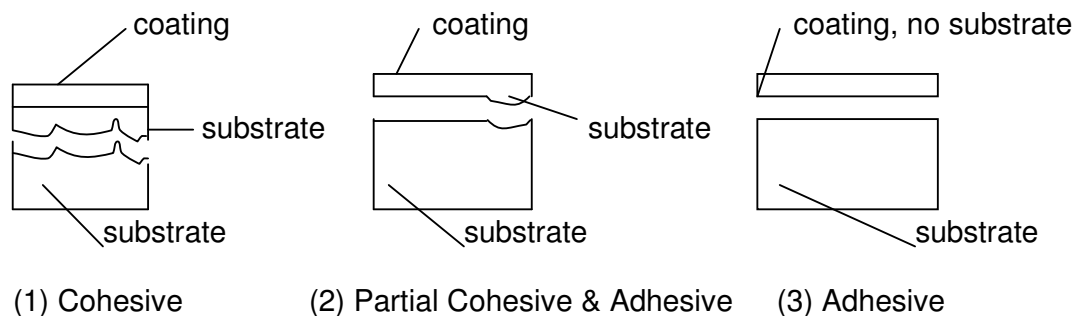


FIGURE 2: Modes of failure

Figure 2 illustrates the following failure modes:

- (1) Cohesive failure in the concrete substrate

(2) Partial cohesive and adhesive failure

(3) Adhesive failure at the interface of the coating and the concrete surface

It is relatively easy to coat a surface with a correctly formulated protective coating if this surface is sound, well cleaned and accessible. Of importance is the magnitude of adhesion that is related to the dynamic wetting of the concrete surface (adherent) by the coating (adhesive) [14] and is affected by:

- Potential adhesion between the coating and the adherent
- Roughness of the adherent
- Dynamic viscosity of the coating
- Spreading accuracy of the coating on the adherent

The results of blister-tests carried out by Günter [15] indicated that if the near-surface concrete is prepared (e.g. by sand blasting), the pressure required to cause delamination is greater than if no preparation is carried out. The results also showed that as the coating thickness is increased, the pressure required to produce delamination is also increased but that as temperature increased lower pressure is required to cause blisters. Courard [16] considered thermodynamic properties of solids and liquids in relation to adhesion and although this may be of value it was beyond the scope of this investigation to consider the thermodynamic aspects.

2.3 Surface Properties of Concrete Substrates

Gaul [9] refers to four general types of barriers/coatings and suggests that the surface requirements will depend on the type of coating and its specific characteristics. Table 1 indicates the surface condition required for the different coatings and was consistent with the requirements listed in the Product Data Sheets

of the protective coatings reviewed at the start of this investigation. The near-surface concrete is usually required to be dry when the coating or primer is applied, however Bundies [17] demonstrates that even in the dry concrete surface exposed to ambient conditions, there is 20 to 30 g/m² of water within the top 0.5 mm of concrete.

TABLE 1: Required conditions for barrier products [9]

Type of barrier	Concrete surface condition			
	Clean	Dry	Free of Laitance	Strength below surface of concrete
Decorative paint	Yes	Some	No	No
Damp proof	Yes	Some	No	No
Waterproof	Yes	Yes	Some	Some
Protective	Yes	Yes	Yes	Yes

The applicator should therefore carefully follow the standards and limits laid down in the job specification and in the suppliers' technical literature. Concrete surfaces that are used as a substrate may cause problems that are not necessarily present with other materials:

- Concrete surfaces are often very rough and have partly open air voids.
- Concrete surfaces are adsorbent to varying degrees.
- Concrete surfaces may be dusty and friable.
- Formed and floated surfaces commonly have a thin and relatively weak layer (laitance).
- Formed surfaces can contain significant amounts of adhered release agent.
- Surfaces with irregularities due to casting or shrinkage can lead to variable thickness of the coating layer.

2.4 Properties Affecting Bond

The International Concrete Repair Institute (ICRI) document [18] states that repair materials should not be specified until the properties that will best satisfy overall project objectives are identified. This principle, along with many of the properties mentioned in the ICRI document, is applicable to coatings.

2.4.1 Permeability of Substrate

Previous studies have found that after application of a coating to a concrete surface, stresses may develop in this composite system that are caused by various chemical and physical properties of both the coating and the near-surface concrete. Work carried out by Günter and Hilsdorf [19] showed that a concrete surface treated with an epoxy coating or some of the commonly used primers will have semi-permeable properties. Experiments have shown that osmotic pressure can reach up to 45 bars, which is approaching the bond strength between the near-surface concrete and the coating. This pressure is much less if the coating is flexible or if blisters have formed. Local defects in the coating or at the concrete-coating interface may lead to local stress concentrations that may cause delamination or damage at lower than normally expected stresses. Table 2 summarizes the various mechanisms leading to stress development together with the type of damage and the conditions under which they are likely to occur. The adhesion of a coating to a concrete surface, may be affected by the age of the concrete, concrete strength, aggregate grading and the salt content of the near-surface concrete [13].

TABLE 2: Stresses acting at the coating-concrete interface [19]

Cause of stresses	Conditions under which stresses may occur	Types of damage
Chemical attack and saponification	• Compounds which can be saponified (turn soapy) by reacting with an alkali • Pore solution in hydrated cement paste that is aggressive to coating	• Delamination • Dissolution
Capillary suction and compression of air in concrete pores	• Pores, partially filled with air • Water adsorption	• Delamination • Blisters
Water and solvent vapour pressure	• Pores, partially filled • Temperature increase	• Delamination • Blisters
Osmotic process	• Water soluble compounds in the coating • Semi-permeable membranes • Pore solution in hydrated cement paste	• Folding • Delamination • Blisters
Internal stresses and restraint	• Temperature change • Differences in thermal swelling or shrinkage properties of coating and of substrate	• Folding • Cracks • Delamination

2.4.2 Environmental Aspects

The prevailing temperature and humidity, after the near-surface concrete has been prepared can affect the adhesion of a coating [13]. This is influenced by free water and moisture content of the substrate, and the moisture gradient. It is thus advisable to avoid extremes in ambient temperature conditions. As mentioned previously Bundies [6] illustrates in his paper that even a dry surface could contain a considerable amount of water at its surface. Changes in ambient weather conditions can cause considerable variations in the moisture or water content of the near-surface concrete. Littmann [20] also suggests from his results that curing temperature during the days immediately after application have a decisive influence on the quality of adhesion.

2.4.3 Physical Effects Affecting Bond

To obtain a good bond it is necessary to consider the uniformity of the surface, the cleanness (dust, oil), release agents, curing compounds and cracks. These aspects are important because release agents migrate to surface during casting, while curing membranes based on waxes and resins are film formers that need to be mechanically removed. Cracks that are greater than 2 mm in width need to be investigated to ascertain if they are still active then treated appropriately.

Dimensional behaviour of a coating will be affected by drying shrinkage, modulus of elasticity, and restrained shrinkage. Drying shrinkage of protective coatings and repair mortars will occur and the rate of shrinkage depends on:

- Ambient temperature.
- Rate of evaporation of any volatile material.
- Thickness of the coating.
- Ambient relative humidity.
- Relative humidity of the substrate.

Any restraint to shrinkage that occurs when a coating is applied to a concrete surface will produce tensile stress in the coating, which is not easily measured but must be considered because of the possibility of cracking or tearing of the coating which then negates the desired protection. Durability of a coating will also be affected by permeability, water vapour transmission, weather conditions and compatibility with the near-surface concrete. The permeability of the coating to chlorides and atmospheric carbon dioxide (CO₂) will dictate the suitability of the coating for certain applications as these two chemicals are largely responsible for the onset of corrosion of the steel reinforcing in structural concrete. Also, for dimensional compatibility, the

modulus of elasticity and thermal coefficient of a coating that is to be applied to a structural member should be similar to that of the substrate and for a non-structural application the modulus of elasticity of the coating should be lower than that of the substrate [18].

Both hot and cold weather can affect the bond strength but hot weather also has an adverse affect on the drying shrinkage and surface finish. The bond at the interface between a coating and the concrete substrate can be influenced by micro cracks, roughness, surface preparation, pre-wetting, other treatments (curing membranes, de-icing salts, etc.) and the surface moisture at the time of coating [13]. In the work reported by Littmann [20] the characteristic strength of the concrete did not influence the adhesion as much as the type of cement did and it appeared that blast furnace slag cement was more appropriate for concrete in a humid environment.

2.5 Adhesion of Thin Coatings to Concrete

2.5.1 Repair Mortars

Cleland et al. [21] evaluated repair mortars on three different surface preparations by measuring the tensile and shear bond strengths. They noted that it was important to understand and follow the manufacturer's instructions in order to achieve the properties expected from pre-packed proprietary products. They also found that a brushed or lightly sand-blasted surface gave a sound rough surface that resulted in better bond strength, due to the increase in bond area and mechanical keying effects. To achieve this, it was important to prevent air voids by trapping air around the protrusions during application. Chiselling or bush hammering the surface can induce large stresses that can leave the aggregates and some matrix particles loose.

If the strength of this weakened layer is lower than the bond strength between itself and the repair material failure can occur along this weak plane.

2.5.2 Thin Coatings

During the process of rehabilitating concrete structures, proper surface preparation of the substrate and bonding of the protective coating materials, are both important factors affecting the success of the repair [22]. Similarly, the successful application of a thin coating, whether protective or aesthetic, over a patch repair depends on the attention paid to the following factors that affect the strength of adhesion between the repair material and the substrate [21]:

- Characteristics of the original concrete, the surface condition and its preparation.
- Characteristics of the coating material.
- Workmanship.
- Environmental conditions.

2.6 Available Test Procedures

Various sample methods and test techniques have been suggested or described in the following referenced literature:

- The ASTM - D4263-83 [23] describes the test for indicating moisture in concrete by using the plastic sheet method.
- Dusty surfaces can be identified by wiping the concrete with a dark cloth. If a layer of whitish powder is found on the cloth, the surface is too dusty [2].
- Oily surfaces can be identified by sprinkling water onto the dried surface. If water beads and does not spread out immediately, the surface is probably contaminated [2].

- Excessive laitance is considered to be present if a quantity of loose powdery material is observed or easily removed from the surface when the concrete is scraped with putty knife [2].
- The RILEM document AAC15.1 details how to determine the adhesion of mortars and other surface coatings [24].
- The ICRI document [18] describes three methods of testing bond strength. In Figure 3 below the “direct tensile bond test”, “shear bond test” and the “slant shear bond test” are illustrated.

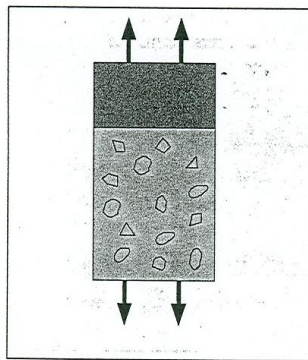


Figure 3.1. Direct tensile bond test.

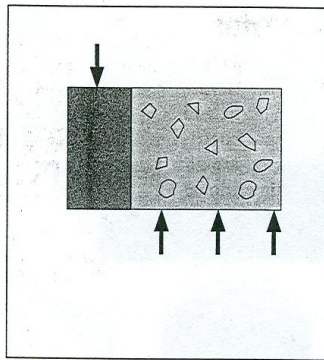


Figure 3.2. Shear bond test.

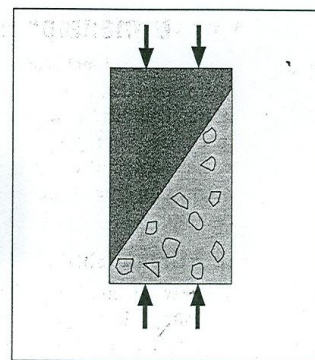


Figure 3.3. Slant shear bond test.

FIGURE 3: Methods of testing bond strength [18]

- Oba et al [25] reported on the possibility of using an infrared-thermograph for the site evaluation of a coating. Although this test method still has to be optimised, the thermal images obtained for a freshly applied coating indicated areas of poor membrane adhesion due to differences in the surface temperatures.
- For thin layer mortars, Peier [11] suggests minimum requirements for the adhesive tensile strength after 28 and 90 days of a mean strength greater or equal to 1500 kPa (1.5 MPa) with no single test value to be less than 1000 kPa (1.0 MPa). These values may be considered applicable to protective coatings.

Naderi et al. [26] describes two insitu test methods for shear bond and tensile bond strength respectively, shown in Figure 4. In these tests cores of 50 mm diameter

were drilled through the repair material and extended about 5 mm into the substrate concrete.

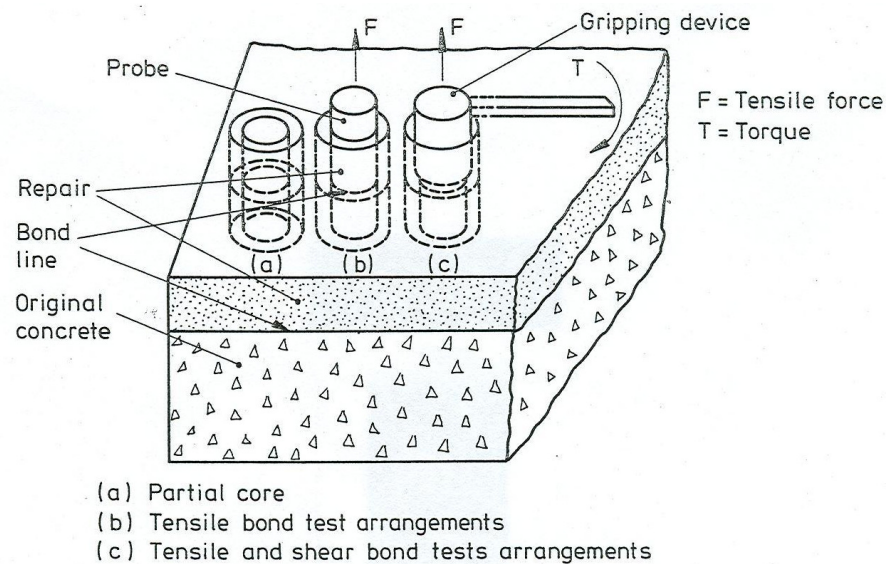


FIGURE 4: In situ bond strength test arrangement [26]

For the tensile test, a stud was glued to the top of the core and a tensile force applied until failure occurred. For the shear test a special apparatus is fitted on top of the core and is clamped to it, a torque is applied through a handle until failure.

Although the pull-off test has been generally accepted as a suitable method to determine the adhesion strength because of its easy use on site, Günter [15] suggests that the blister-test would be more suitable for studying bond properties.

Briefly, the blister-test involves setting up artificial defects at the interface of a concrete surface and the coating material. These defects are created at points where steel tubes, plugged with wax at the one end, have been inserted through the concrete. A circular area of the concrete surface and the end of the steel tubes are coated with a thin layer of beeswax and paraffin approximately $2a_0$ in diameter, see Figure 5. After the application and hardening of the protective coating, that is to be tested, the wax is removed from the end of the steel tube and air pressure is applied to the lower side of the coating at a controlled rate of 8.5 bar/min. This area is

recorded as A_0 . At the start of delamination, the pressure is recorded as p_0 and is then reduced to zero to prevent an uncontrolled increase in the delamination. The area of the delamination is measured and recorded as A_1 . Pressure is again applied until delamination commences at pressure, p_1 . After reducing the pressure to zero, the size of the defect is recorded as A_2 . The process is repeated for up to 30 values of the critical pressure p_i and the defect area A_i .

From graphical and regression analysis, it was evident that there was a non-linear decrease in the critical pressure with an increasing radius of defect. An analysis of the results using fracture mechanics can give values of adhesion fracture toughness which can be used to characterise the resistance of a protective coating against delamination or the formation of blister.

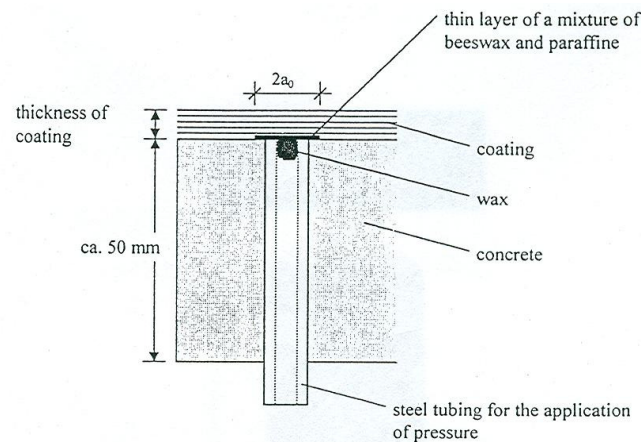


FIGURE 5: Blister test, creating a local defect in a specimen [15]

Günter [15] suggests that the commonly used test methods can be divided into two groups:

- A. Continuous application of external forces that directly apply stresses to the coating/concrete interface until failure occurs. Direct tension, flexural tension, torsion or shear forces could induce failure stresses.

B. Long term exposure of the coating/concrete interface to conditions that may cause changes to the physical or chemical properties at the interface region. The changes in the bond strength due to these exposures may be measured using the experimental methods mentioned before.

Various researchers [11, 15, 25, 26] have shown that there are a number of different test methods that can be used to determine the bond strength between a coating or repair material and a concrete substrate. In this investigation testing was limited to direct pull-off tests on concrete specimens stored indoors without exposure to outdoor environmental conditions. Although environmental factors may influence the bond strength of different coatings when applied to different surface characteristics, they are not considered particularly important in ranking the effectiveness of different methods of surface preparation.

2.7 Preferred Properties

A number of published papers and some technical committee reports have made suggestions regarding the preferred properties of coatings and repair systems. The following section sets out those properties of more relevance to coatings. For epoxy repair mortars, the ACI Committee 503 stipulates a minimum pull-off strength of 100 psi (0.69 MPa) [27]. In order to ensure the best possible long-term adhesion the following are of equal importance:

- The condition of the substrate at its surface.
- The environmental conditions when the primer or coating is applied.
- The chemical reaction inside any two-part coating.
- The chemical reaction of the coating with substrate.

Bordado [28] lists the advantages of the thermosetting type materials that are also desirable in other types of coating systems:

- Very low shrinkage.
- High resistance to acids and alkalis.
- Barrier properties against water, salt, and gases.
- Good durability under varied service conditions.
- Excellent adhesion, even under damp conditions.

Sasse and Stenner [29] highlighted some important sections of a new series of CEN standards, EN 1504 series Parts 1 to 10 [30]. In particular, ENV 1504–9, 1996, Table 3 “Principles and Method Related to Defects in Concrete” indicates that coatings can be used for the following reasons:

- Protection against ingress of aggressive agents.
- Controlling the moisture content of concrete.
- Increasing the resistance of concrete surface to chemical attack.
- Increasing the electrical resistivity of concrete.
- Creating conditions for cathodic control.

An extract from Table 1: of EN 1504–2: “Surface Protection Systems for Concrete Structures” [30] indicates that it is mandatory to carry out a pull-off test to determine the adhesion of the coating relevant to protection against the ingress of aggressive agents, moisture control of the concrete, physical resistance of the concrete to mechanical attack and resistance to chemicals.

The new EN 1504 Parts 1 to 10 [30] might become an important reference document when repairing and coating concrete structures.

2.8 Surface Preparation

ASTM D 5295–92 [2] recommends that if grinding techniques are utilised, it is important to avoid polishing the surface as this can affect the adhesion. It also suggests that it is important to avoid sanding, as this drives dust particles into the pores creating a de-bonding layer. For acid etching, ASTM D 5295 suggests that a 10% or 20% solution of hydrochloric acid at a coverage rate of 1l/m^2 may be used with surface pre-dampening to obtain a more even etch. However, where the use of chlorides is inadvisable (due to the long-term effect on reinforcing steel), a 15% phosphoric acid solution could be considered.

Hindo [22] examined two different methods of preparing a concrete surface for repair and concluded that hydro-demolition (water blasting) might be preferred over jack hammering because the latter causes a “bruised” concrete layer, that contains micro cracking, up to about 9 mm deep. The advantages of the water blasting technique were:

- Lack of the “bruised” layer.
- Irregular wavy surface profile.
- Increased number of micro-pores.
- Greater surface area for adhesion.

Undoubtedly, an important property for the structure is durability and if it is accepted that the coating is effective, then durability aspects become easier to handle, at least as regards the following principles [14]:

- Mechanical and thermo-mechanical behaviour: this relates to the resistance of a composite system against creep under load, and its fatigue life within the service temperature range.
- Physico-chemical behaviour: this includes the wet strength of coatings in the pH-range occurring at the interfacial zone, as well as chemical ageing during service and under fire conditions.

Often there is an implicit acceptance that concrete will provide sufficient protection for reinforcing steel and thus its durability will be acceptable. It is accepted that this concrete should be of an appropriate strength grade, is well proportioned to facilitate full compaction and is properly cured. These properties are also important when it is necessary to repair and apply protective coatings. From literature, it is evident that adhesion of a coating to concrete is affected by concrete strength [13] both compressive and tensile, which is directly related to w/c ratio and curing. In addition, compaction and curing influence the porosity and permeability of the near-surface concrete.

Chapter 3: EXPERIMENTAL DETAILS

3.1 Introduction

This chapter contains details on the materials used in concrete mixes and how the fresh and hardened concretes were tested. Curing regimes used to achieve different near-surface concrete qualities are explained. Surface preparation methods and the coating application are detailed as are the test methods used.

3.2 Concrete Materials

3.2.1 Cementitious Material

The cement used was a factory blend of Portland cement and siliceous fly ash (FA) at a nominal ratio of 65/35%. The cement satisfied the MC22.5 X category of SABS ENV 413-1:1996 (now SANS 50413-1:2004) [31, 32]. It was obtained from Alpha Cement (now AfriSam) factory in Roodepoort, and at the time when the specimens were made was sold to the construction industry as “Multi Purpose Cement”. The relatively high FA cement (approximately 35%) was selected, so that poor early-age curing can be used to produce a lower quality concrete particularly at the surface. Four 50 kg bags of cement were used to manufacture specimens. To reduce the possibility of variation within the cement, all bags were collected from the same pallet to ensure that the cement came from the same production run.

3.2.2 Aggregates

The aggregates used were not specially selected but were all collected from the laboratory stockpile on the same day then stored in lab conditions until used. Both coarse and fine aggregates were representative of the quarry material and the type

of materials that would normally be supplied to the ready-mix and construction industries. The coarse aggregate was a Meta–Mela Andesite of the Ventersdorp Supergroup from the Eikenhof quarry near Johannesburg. The fine aggregate was decomposed Halfway House granite from the Jukskei quarry.

The aggregates were air dried prior to mixing. The typical physical properties are given in Table 3.

TABLE 3: Typical physical properties of the coarse and fine aggregates

SIEVE SIZES	% PASSING	%PASSING
Material	Andesite stone	Granite sand
26.0	100.0	
22.4	89.1	
19.0	71.6	
13.2	8.2	
9.5	1.4	
6.7	0.4	
4.75		100.0
2.36		82.0
1.18		62.0
0.60		44.0
0.30		29.0
0.15		18.0
0.075	0.0	11.5
Fineness modulus		2.7
Relative Density	2.89	2.65
Loose bulk density	1467	
Compacted bulk density	1676	

3.2.3 Water

Potable tap water, as supplied by Rand Water, was used in all the mixes.

3.3 Mix Details

3.3.1 Mix Proportions and Specimens

The mix proportions detailed in Table 4 were not specifically designed for the investigation but were based on the typical mix used by the ready-mix industry when

using these particular aggregates. Four sets of specimens were made with each set consisting of six 750 x 150 x 150 mm beams and nine 100 x 100 x 100 mm cubes. Three 40 litre batches of concrete were used to produce one set of specimens, with two beams and three cubes made from each batch.

TABLE 4: Mix proportions

MATERIALS	%	kg/m³	40 litre batch (kg)
“Multi Purpose Cement” MC 22.5 X	13.5	330	13.2
22/19-mm Andesite stone	44.0	1080	43.2
Decomposed granite sand	34.9	855	34.2
Water	7.6	187	7.48
TOTAL MASS		2452	

3.3.2 Concrete Manufacture

Four sets of specimens, labelled A, B, C and D were made at intervals of one week in order to facilitate their production for the different curing regimes. Three batches were needed to make up a set of specimens and these batches, designated batch numbers A1, A2, A3, B1, B2, B3 etc., were made on the same day. The mixing was carried out at the Alpha Cement (now AfriSam) Group Concrete Laboratory, which was situated at the Roodepoort Cement factory. A 50 litre Eirich mixer was used for mixing and each batch was mixed for two and a half minutes. Both fine and coarse aggregates were air-dried overnight prior to being weighed on the day of mixing. An unopened 50 kg bag of cement was used for each of the four sets of specimens. Mix water was weighed just prior to the mixing cycle. The materials were added in the following order: coarse aggregate, cement, fine aggregate and finally, water. Water was added immediately after the mixer had been started and the mixing time was measured from the time water was introduced. After the batch of concrete had been mixed for two minutes the mixer was stopped and the slump measured. The sample

of concrete used for the slump was returned to the mixer and the concrete mixed for a further 30 seconds then two beams and three cube specimens made.

3.4 Testing of Concrete

3.4.1 Introduction

The physical properties of each batch of concrete were measured in order to ensure the mixes were consistent across the twelve batches needed for the four sets of specimens. The physical properties measured were fresh wet density (FWD), slump and unconfined compressive strength.

3.4.2 Fresh Concrete

The tests that were carried out on the fresh concrete were:

- FWD in accordance with SABS Method 1245:1994 [33] except that a 100mm cube mould was used as the measuring vessel.
- Slump in accordance with SABS Method 862-1:1994 [34].

The fresh wet density was used as a control measure of control for batching, while the slump was used to ensure that similar workability was obtained for each of the three mixes that made up a single set of specimens bearing in mind that the quantity of water added to each batch was kept constant.

3.4.3 Hardened Concrete

Three cube specimens were made from each batch, then cured and tested in accordance with SABS Method 863:1994 [35]. The cubes were placed in the curing room maintained at a temperature of 22 to 25 °C and a relative humidity of 90% to

95% for the first 24 hours. After demoulding, the cubes were stored under water in the curing room at 22 to 25 °C until crushed on a 3000 kN Amsler compression testing machine in the Roodepoort laboratory. The 7-day and 28-day compressive strengths of each set of specimens were determined by crushing one randomly selected cube from each batch that made up a particular set. The compressive strengths of these four sets of specimens were compared to confirm that the wet cured concretes were of a similar strength grade at 28 days. The remaining three cubes from each set of mixes were crushed at one day (set B), three days (set A), 56-days (set C) and 90-days (set D).

3.5 Curing Regime for the Beams

During the first 24 hours, each set of six beams was handled in the same manner as the cubes. Immediately after casting, the beams were placed in the curing room maintained at a temperature of 22 to 25 °C and with a relative humidity of 90% to 95%.

The beams were removed from the moulds after 24 hours and then subjected to the following curing regimes:

- Set A: Stored underwater for 27 days at a temperature of 22 to 25 °C. After removing the beams from the curing tank, they were placed outdoors where they were exposed to the prevailing weather conditions for one year
- Set B: After 6 days in the curing tank, the beams were placed outdoors
- Set C: After 2 days in the curing tank, the beams were placed outdoors
- Set D: After demoulding at 24 hours, the beams were immediately placed outdoors

The outdoor weather conditions had a daily average winter to summer temperature range of 0 to 20 °C and an average relative humidity range of 10% to 60% during the 12 months before the specimens were cut and prepared for coating application.

3.6 Specimen Preparation

3.6.1 Climatic Exposure

The prepared sections were exposed to ambient weather conditions for 12 months prior to being cut and coated as per the schedule set out in Table 5. Before the prepared surfaces were coated, they were stored inside the laboratory for six months to allow them to dry out.

3.6.2 Cutting the Beams

Columns one to three of Table 5 detail how each beam was cut into sections, using a wet-blade diamond saw, to the following approximate sizes, (also shown in Figure 6):

- 50x150x150 mm: two samples; for optical microscopy and water-sorptivity tests
- 150x150x150 mm: four samples; for surface preparation and coating tests.

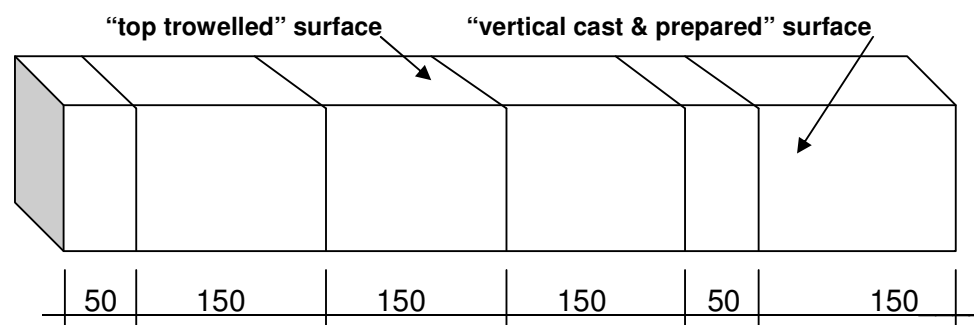


FIGURE 6: Sketch of the beam sections (not to scale)

The procedure involved cutting a 50 mm section off the end of the beam prior to preparing the surface. Once the surface preparation was complete, another 50 mm

section was cut from the middle of the prepared beam and used for microscopic examination.

TABLE 5: Summary of adhesion test programme

Beam	Slice	Typical length (mm)	Preparation	Coating Type	Test
1	1	50	None	None	Microscope
	2	175	None	Elastomeric	Pull-off
	3	175	None	Aliphatic	Pull-off
	4	150	None	Epoxy Resin	Pull-off
	5	150	None	Cement Based	Pull-off
2	1	50	None	None	Microscope
	2	150	Mech. Wire brush	Elastomeric	Pull-off
	3	150	Mech. Wire brush	Aliphatic	Pull-off
	4	50	Mech. Wire brush	None	Microscope
	5	150	Mech. Wire brush	Epoxy Resin	Pull-off
	6	150	Mech. Wire brush	Cement Based	Pull-off
3	1	50	None	None	Microscope
	2	150	Hand wire brush	Elastomeric	Pull-off
	3	150	Hand wire brush	Aliphatic	Pull-off
	4	50	Hand wire brush	None	Microscope
	5	150	Hand wire brush	Epoxy Resin	Pull-off
	6	150	Hand wire brush	Cement Based	Pull-off
4	1	50	None	None	Microscope
	2	150	Bushing tool	Elastomeric	Pull-off
	3	150	Bushing tool	Aliphatic	Pull-off
	4	50	Bushing tool	None	Microscope
	5	150	Bushing tool	Epoxy Resin	Pull-off
	6	150	Bushing tool	Cement Based	Pull-off
5	1	50	None	None	Microscope
	2	175	None	Paint	Pull-off
	3	175	None	None	Water-sorptivity
	4	150	Mech. Wire brush	Paint	Pull-off
	5	150	Mech. Wire brush	None	Water-sorptivity
6	1	50	None	None	Microscope
	2	175	Hand wire brush	Paint	Pull-off
	3	175	Hand wire brush	None	Water-sorptivity
	4	150	Bushing tool	Paint	Pull-off
	5	150	Bushing tool	None	Water-sorptivity

3.6.3 Surface Preparation

Although the literature referred to the damaging effect of jack hammering [22] laboratory constraints only permitted three different surface preparations to be investigated. These consisted of a light manual wire brushing, a heavier mechanical wire brushing and the use of a bushing tool that was very similar to a jack hammering technique. One vertically cast face of each beam was prepared as per the schedule in Table 6 and the differences obtained with the various preparation techniques can be seen in photograph shown in Figure 7.

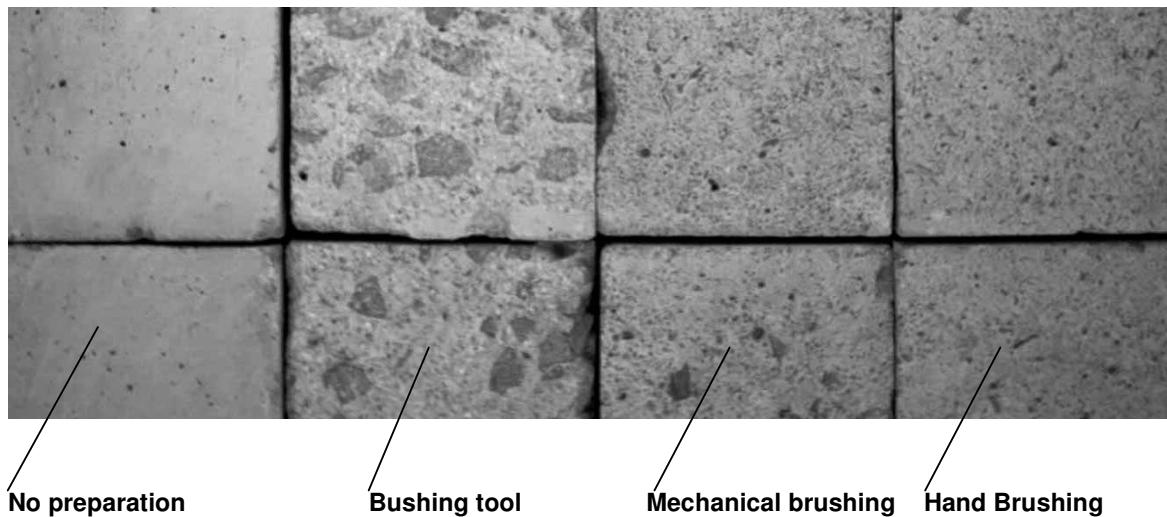


FIGURE 7: Photograph of the concrete surfaces obtained when using different preparation techniques

The mechanical wire brushing was carried out using a circular wire-brush, shown in Figure 8, that was fitted into the chuck of a rotary hand held electric drill. The rotating wire brush was applied to the surface of the concrete for 15 minutes to remove the surface laitance and expose a small amount of the aggregate. A close-up view of this surface finish is shown in Figure 9.



FIGURE 8: Mechanical Wire Brush

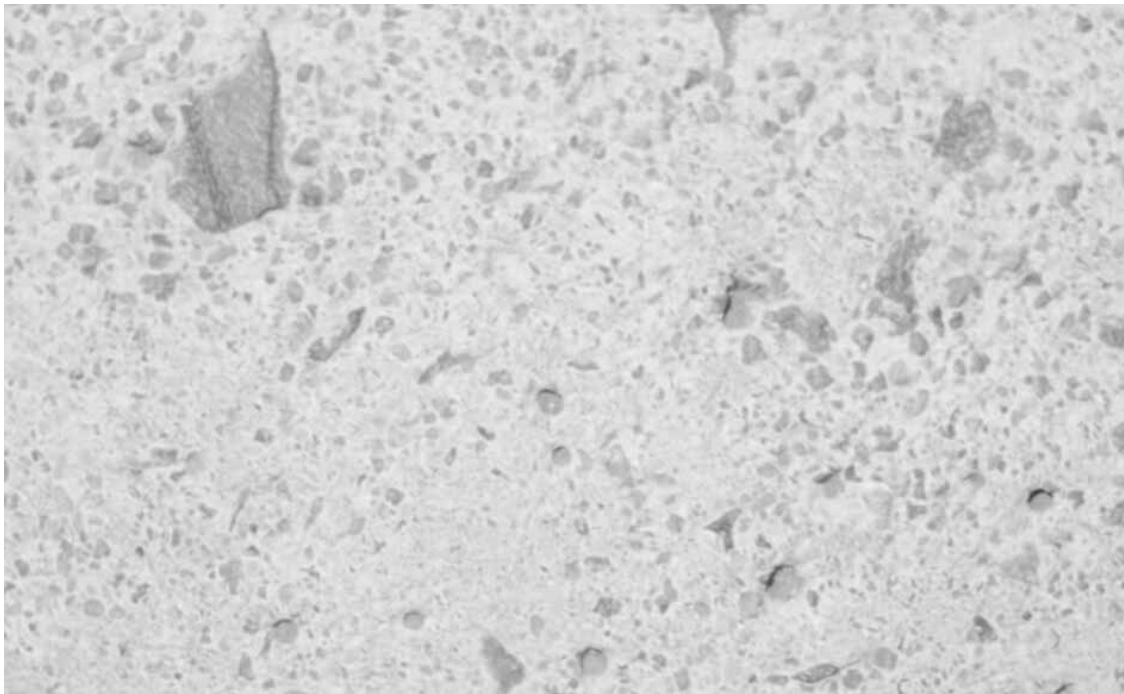


FIGURE 9: Surface after preparation by mechanical wire brush

For manual wire brushing a hand held wire brush, shown in Figure 10, obtainable from most hardware shops was used to remove as much of the surface laitance as

possible. The manual brushing was applied for 15 to 20 minutes, which, as seen in Figure 11, exposed very little of the coarse aggregate.



FIGURE 10: Hand held Wire Brush

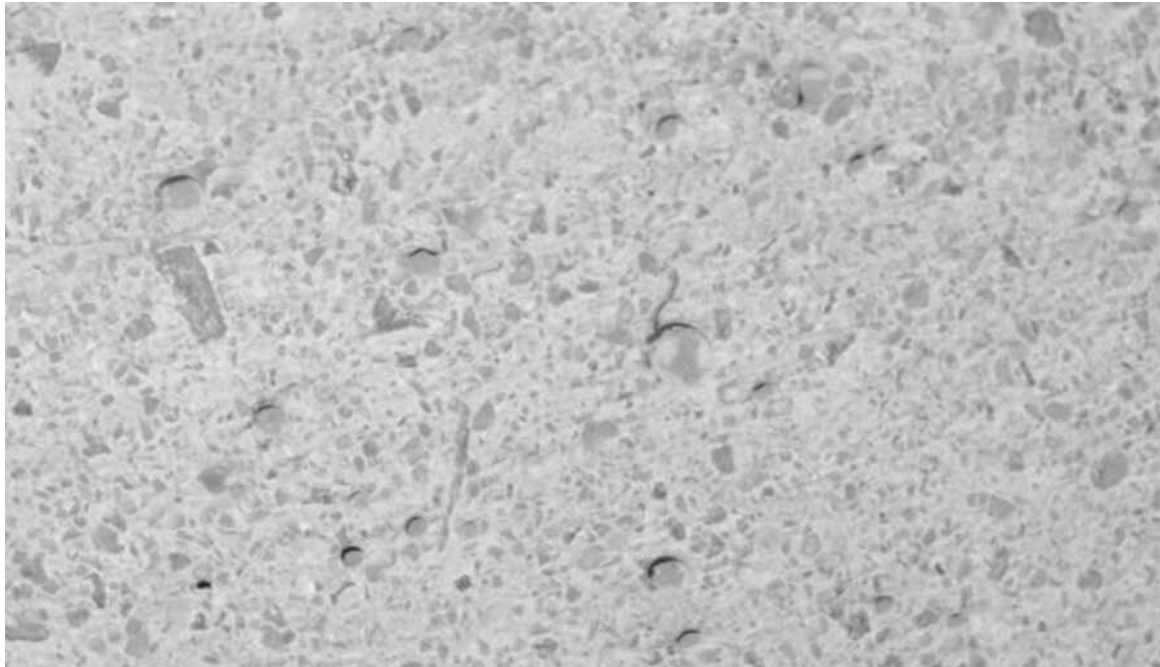


FIGURE 11: Surface after preparation by hand held wire brushing technique

The bush hammering was carried out using the bushing tool, shown in Figure 12, with a 40 x 40 mm blade width was attached to a mechanical combi-hammer. The blade was applied to the surface until the entire surface laitance and some of the concrete matrix had been removed, as shown in Figure 13.



FIGURE 12: Bushing Tool

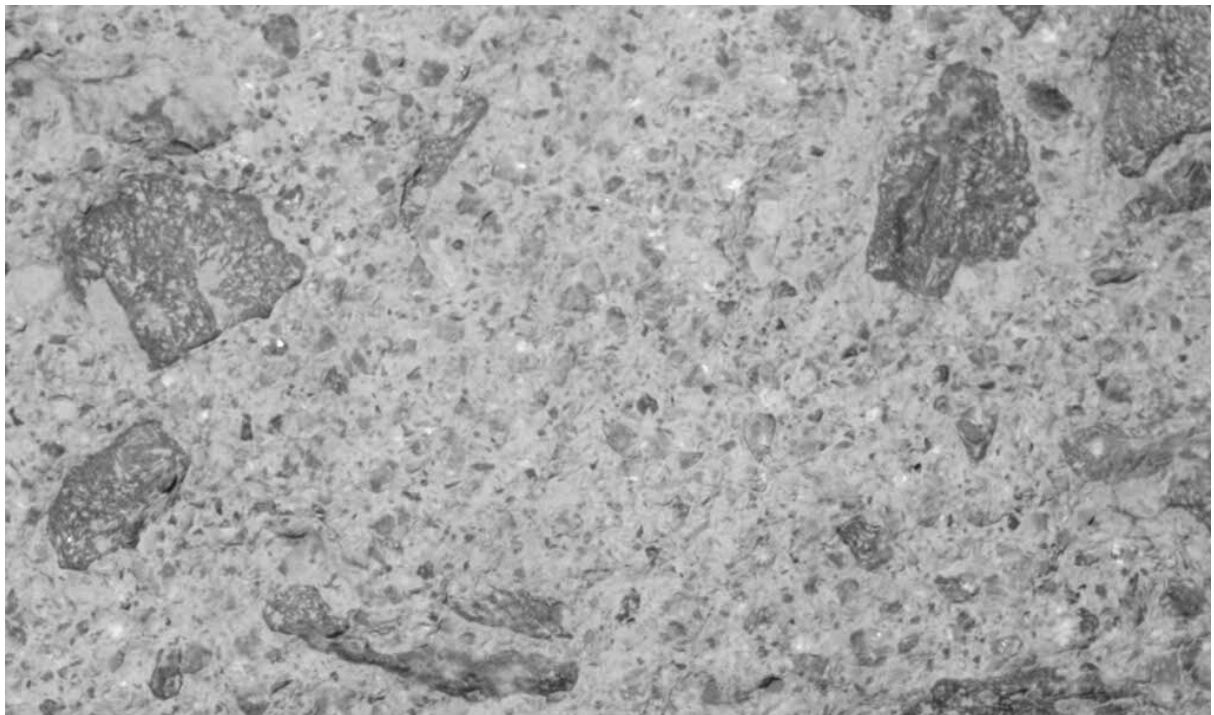


FIGURE 13: Surface after preparation with bushing tool

Specimens that were not subjected to surface preparation were wiped with a damp cloth. The typical specimen surface with some blow holes caused by trapped air pockets can be seen in Figure 14.

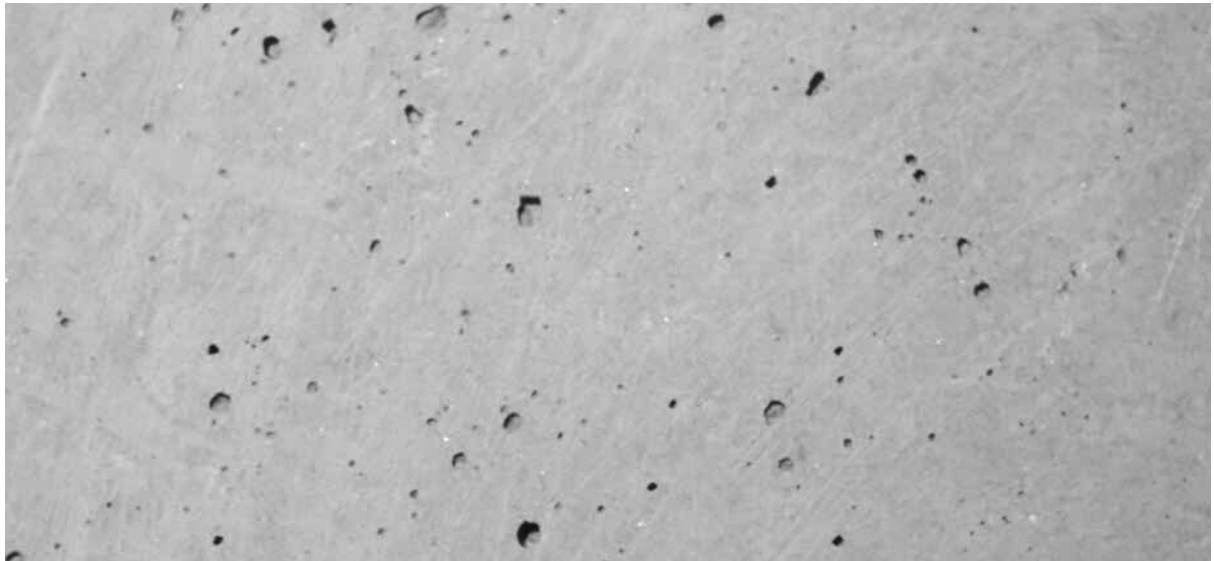


FIGURE 14: The unprepared concrete surface

3.7 Coating of Surface

3.7.1 Introduction

In preparing for coating, specimens were placed on a bench in the laboratory before the onset of the summer rains. After six months, the specimens were first swept very lightly with a soft brush then vacuum cleaned to remove any remaining dust. The moisture at the near-surface was evaluated by sticking a 50 x 50 mm square piece of plastic to the surface for 24 hours prior to coating. This was to ensure that no trapped moisture would cause a hydrostatic pressure under the coating [23]. The coatings used for this investigation are listed, in Table 6, along with a summary of their technical details. These details were extracted from the manufacturers' data sheets or through direct communications with the manufacturer [36].

TABLE 6: Summary of coatings and technical details

Type	Elastomeric	Aliphatic	Epoxy Resin	Cement Based	Paint [36]
Number of components	One	One	Two	Two	One
Primer requirements	Yes, solvent	Yes, silane	No	Yes, water	No
Number of coats	2	2	2	2	2
Minimum thickness per coat	Not stated	150 µm	175 µm	Not stated	Not stated
Suggested final thickness	Not stated	300 µm min.	350 µm min.	2mm max.	Not stated
Over-coating time	8 hours min.	6 hours	24 hours	2-6 hours	4 hours
Coverage rate	3-5 m ² /ℓ	3 m ² /ℓ	5.5-7 m ² /ℓ	2 kg/ m ² /mm	6 m ² /ℓ
Curing time	Not stated	Not stated	7 days	28 days	24 hours
Minimum concrete temperature	5 °C	2 °C	5 °C	5 °C	Not stated
Application Type	Brush/spray	Brush	Brush/spray	Brush/spray	Brush

3.7.2 Coating Application Procedure

Where required by the manufacturer, the recommended primer was applied and where allowed to cure as necessary before the coatings were applied. The coatings were all brush applied in accordance with the manufacturers' instructions. The thickness of each coating, as detailed in Table 7, was also in accordance with the recommendations given on the manufacturers' instructions. The thickness was measured as a wet film thickness using a "Wet Film Thickness Gauge" obtained from

Fosroc International Ltd. The coated specimens were kept indoors on the laboratory bench out of any drafts and not exposed to the sun while the coating was curing. The test specimens were small compared to an actual structure and in order to prevent the coating from being damaged by the penetration of moisture through the uncoated sides of the specimens or by frost the specimens were kept inside the laboratory for the duration of the testing.

TABLE 7: Wet film thickness and over-coating time

Coating	Wet Film Thickness (micron)	Over-coating time (hours)
Elastomeric	400	48
Aliphatic	175	48
Epoxy resin	175	72
Cementitious	1000	24
Masonry paint	175	24

3.7.3 Controlling Film Thickness

The Wet Film Thickness Gauge used consists of a hexagonal aluminium plate (see Figure 15 and Figure 16), which is 1 mm thick with a series of six spigots cut into each side between the corners. The spigots are manufactured such that each will leave a predetermined gap between the surface and the end of the spigot when the corners are pressed firmly onto the surface.

The gap size varies from a minimum of 25 microns to a maximum of 2 000 microns. The gauge is used, by pressing the corners firmly into the wet coating until they rest against the substrate. The thickness of the coating is determined by removing the disc and visually inspecting the spigots to determine which one has been covered with the coating. For example: if the 175 micron and 200 micron spigots are coated but the 225 micron spigot is not, then the wet film thickness is recorded as 200 microns.

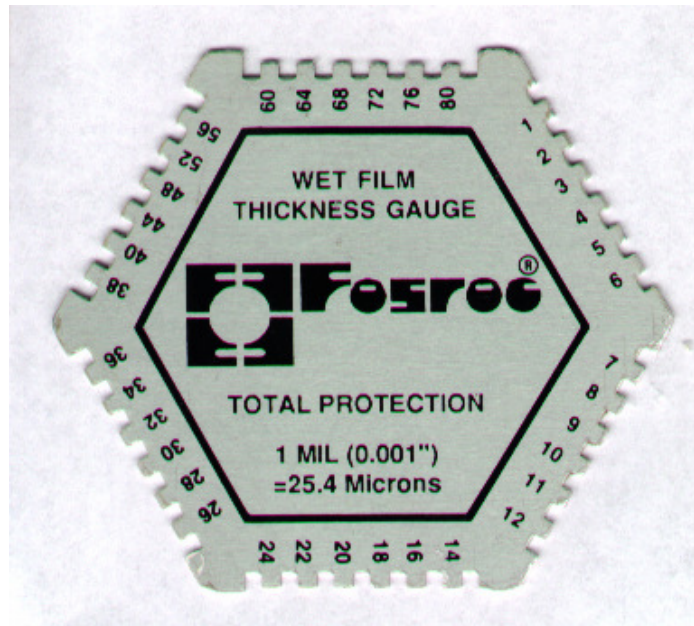


FIGURE 15: Wet Film Thickness Gauge (front view)

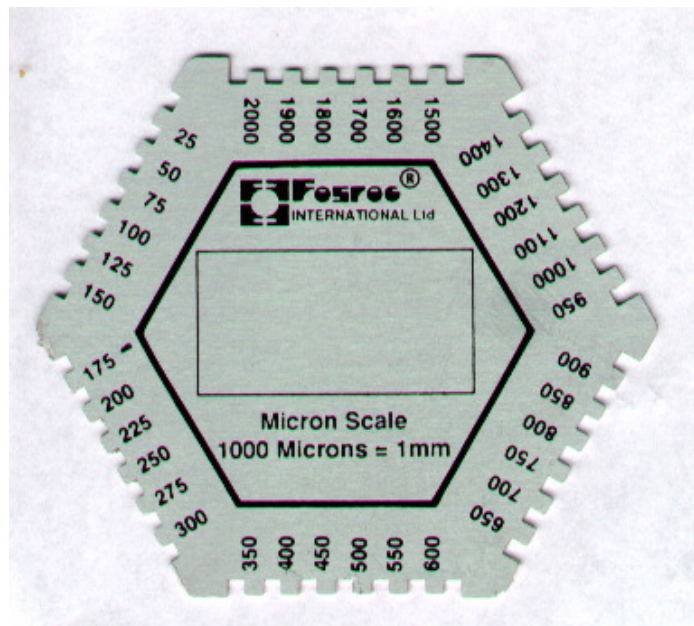


FIGURE 16: Wet Film Thickness Gauge (rear view)

3.7.4 Elastomeric Coating

The coating is a water-based ethylene co-polymer dispersion that is used in conjunction with a solvent based primer. It is supplied as a single pack system that

only has to be thoroughly stirred before applying to the primed prepared surface. It is an elasto-plastic material capable of crack bridging and is claimed to give excellent adhesion and resistance to UV radiation.

3.7.5 Aliphatic Coating

The material is an aliphatic, water-based protective coating that is normally used in conjunction with a single component deep penetrating silane-siloxane primer. It is claimed to have outstanding resistance to aggressive elements and UV radiation.

3.7.6 Epoxy Resin Based Coating

This coating is a pitch extended two-part epoxy resin system with high build thixotropic properties and contains inert fillers and blended solvents. The two components should be mixed with a slow-speed mixer for about four minutes until a uniform consistency is obtained. The coating does not require a primed surface and is claimed to have good chemical and abrasion resistance.

3.7.7 Cementitious Based Coating

This material is a two component, polymer-modified, cement-based waterproofing slurry, which only requires that the concrete substrate be primed by thoroughly wetting the concrete with water. This is to prevent moisture from being sucked out of the coating that would prevent the proper hydration of the cementitious materials in the coating. It is reported to have excellent adhesion properties, is waterproof and can seal fine cracks that are not subject to movement.

Mixing procedure requires the powder component be added to the liquid component while mixing with a slow-speed mixer until a smooth homogeneous mortar is

obtained. When brush applied, the second coat is applied at 90 degrees to the direction of application of the first coat.

3.7.8 Masonry Paint

The acrylic, water-based paint was readily available from most hardware stores, was advertised as having good adhesion properties and does not require a primer.

3.8 Water Sorptivity Test

In order to assess the near-surface concrete the specimens were made Multi Purpose Cement (MC 22.5 X) containing a approximately 35% percentage fly ash and were subjected to different curing regimes to influence both the compressive strength and the quality of the near-surface concrete. The water sorptivity test was used to characterise the quality of surface concrete before and after preparation of the surfaces. The results were also used to provide a basis for comparison of the pull-off strengths in relation to the initial surface quality. Tests, using samples 68 mm diameter by 25 mm thick, were carried out as per the method statement set out in Alexander M.G. et al. [37] "Concrete durability index testing manual". Figure 17 shows a sketch of the test arrangement. The test method consists of measuring the mass of water absorbed over time through the surface of a sample, having sealed the sides of the sample before commencing the test.

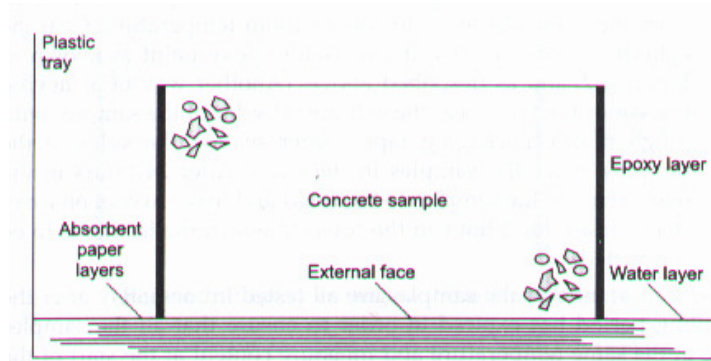


FIGURE 17: Water sorptivity test arrangement [37]

The sorptivity is given by:

$$S = \frac{\Delta M_t}{t^{1/2}} \times \frac{d}{M_{sat} - M_0}$$

where S = Sorptivity

ΔM_t = change of mass with respect to the dry mass (g)

M_{sat} = saturated mass of sample (g)

M_0 = oven dry mass of sample (g)

d = thickness of sample (mm)

t = time of absorption (hours)

3.9 Microscopic Evaluation

The university's MEIJI ML.POL-T Petrographic Microscope with a maximum 40x magnification was used to examine the surfaces of prepared concrete specimens for evidence of cracks or delamination in the near-surface concrete, thin sections of each surface were prepared by the university for examination under the microscope. The sections were taken normal to the surface so that the microscope slide presented a cross section through the surface zone.

3.10 Adhesion Testing

3.10.1 Adhesion Tester

The adhesion tests were carried out using an Elcometer 106 Adhesion Tester, which consists of aluminium studs and adhesion tester.

The aluminium studs, 20 mm in diameter and 14 mm high are shown in a schematic diagram, Figure 18.

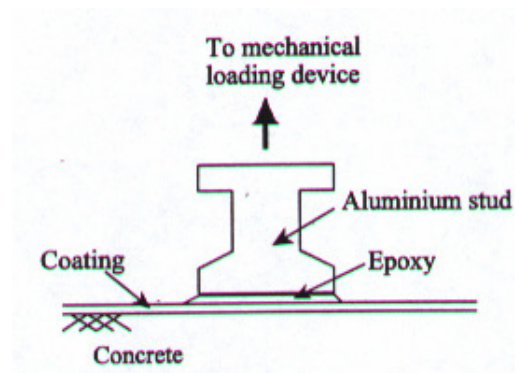


FIGURE 18: Adhesion stud [38]

The Elcometer adhesion tester, shown in Figure 19, consists of a truncated cone with three adjustable feet at the larger end of the cone. The upper smaller end of the cone consists of a barrel that houses a spring arrangement. The spring applies a lifting force to the stud when the hand-operated circular disc is turned clockwise at a loading rate of 1 N/mm^2 per minute. Between the feet is a slotted jaw that is engineered to precisely slide over the stud ensuring axial loading. The testers are available with different scale ranges engraved onto the barrel in N/mm^2 . The maximum force that could be recorded on the Elcometer used in this investigation was 7 N/mm^2 .

3.10.2 Method of Operation

A two-part Pratley Quickset Clear Glue was selected because the tensile strength was stronger than both the substrate and the coating. This glue has rapid setting

characteristics, gelling within three minutes and reaching final set in approximately eight minutes at 23 °C. Full tensile strength is obtained in about one hour and the glue is sufficiently cured in 24 hours.



FIGURE 19: Elcometer Adhesion Tester [5]

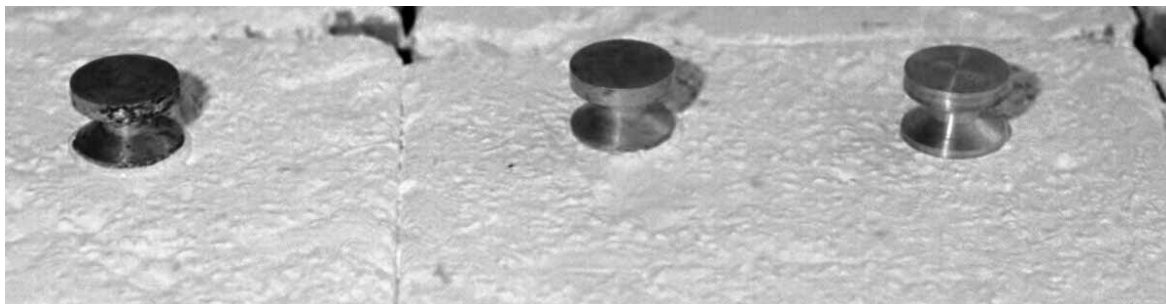


FIGURE 20: Test Studs attached to coating before testing

The studs were glued to the coatings as shown in Figures 18 and 20. After 24 hours the tester was positioned such that each stud was pushed hard up against the back of the jaw; this ensured that the pull-off load was applied axially through the stud. The

handle was then turned clockwise to apply a tensile load to the stud. As load is applied, the barrel is forced downwards and the indicator needle upwards until the adhesion between the coating and the near-surface concrete fails. When the coating fails, the force is released allowing the barrel to spring upwards leaving needle to indicate the force applied at the time of failure. The reusable studs were visually inspected to record the mode of failure, described below, before they were cleaned of the glue and any coating.

Adhesion failure at the interface of the coating and the substrate may include a clean break with no substrate attached to the coating or a small amount ($< 30\%$ of the stud area) of the substrate may be attached to the coating. Cohesive failure occurs if between 30% and 60% of the stud area has pieces of the substrate attached to the coating. Substrate failure occurs when more than 70% of the coating is covered with substrate.

Chapter 4: RESULTS AND DISCUSSION

4.1 Introduction

The results of the different tests conducted, together with a discussion of these results, are reported in this chapter. The batch weights, concrete test results and the statistical calculations on the test results are detailed in Table A1 and Table B1 in the Appendix. As a limited number of samples were tested in this investigation the mean, standard deviation and coefficient of variation were used to assess if there were significant difference between the sample sets.

4.2 Fresh Concrete

4.2.1 Fresh Wet Density

The average FWD of the 12 batches was $2446 \pm 27.6 \text{ kg/m}^3$, detailed in Table 9 and Table B1 in the appendix, which indicated that the mixes had been consistently weighed, as the FWD measure did not differ by more than 50 kg/m^3 from the theoretical batch mass. The average FWD of Set D was lower than the other three sets and the slump of this set of mixes was similar to Set A and Set B therefore additional water was probably not the reason for the lower density but most likely this was due to less compaction effort when making the cubes. To a lesser extent, a change in the particle shape and the combined grading of the coarse aggregate and sand caused by segregation during weighing in the laboratory may also have contributed to the difference in FWD between Set D and the other sets of results.

4.2.2 Slump

The consistence, as measured by the slump test, for each of the 12 mixes was within ± 10 mm of the target slump of 90 mm (target range was 80 mm to 100 mm), as seen in Table 9. This was within the suggested tolerance of 25 mm or $\pm 1/3$ of specified slump [39] for representative samples so no adjustments were made to the mixes. The average slump of Set C was different to the other average slump values. As due care was taken in batching mix materials it is unlikely that an error was made in the measuring of the water and based on Figure B1 extracted from Concrete Technology, A South African Handbook [40] a change in slump from 85 mm to 95 mm would require between 40 ml/batch (1 l/m^3) and 80 ml/batch (2 l/m^3), a quantity that was unlike to have gone unnoticed. The fresh wet density and masses of the cubes also indicate that additional water was not the probable cause. However it was possible that there was sufficient slurry left in the mixer after the first mix to have impacted on the slump of the subsequent mixes. It is also possible that a larger proportion of material greater than 13.2 mm in size was included during the weighing of the coarse aggregate. This may have been the result of segregation caused during the handling of the material in the laboratory. An increase in the amount of the larger fraction could have reduced the surface area of the aggregates just enough to affect the slump.

4.3 Hardened Concrete

4.3.1 Long-term Exposure Conditions

Concrete beams were left outside the laboratory where they were exposed to typical Highveld conditions. Based on monthly averages, shown in Table 8, as reported by

Table 8: Average temperature and rainfall for Johannesburg [41]

Month	Temperature [°C]		Rainfall [mm]
	Average Daily Maximum	Average Daily Minimum	Average Monthly
January	26	16	125
February	25	14	90
March	24	13	91
April	21	10	54
May	19	7	13
June	16	4	9
July	17	4	4
August	19	6	6
September	23	9	27
October	24	11	72
November	24	13	117
December	25	14	105

the South African Weather Service over a 30-year period, the typical temperature range for this period varied between 4 °C in winter and 26 °C in summer. The relative humidity based on the average monthly rainfall was as low as 10% in winter to 100% during the wetter months of summer.

4.3.2 Compressive Strength

As mentioned in Section 3.4.3, three cubes were made from each batch and their individual cube masses and strengths determined as shown in Table 9. To assess whether the compressive strength across the 12 batches of concrete were similar, two cubes from each batch were selected at random for testing at 7-days and 28-days respectively. The remaining cube from each batch was used to make up another set of three cubes that were tested at 1-day for Set B, 3-days for Set A, 56 days for Set C and 90 days for Set D in order to obtain an indication of the

compressive strength development of well cured concrete containing a high fly ash content up to three months after casting.

Unfortunately due to an administrative error only two cubes of Set C were crushed at 56 days and the other was crushed at 90 days. This result was combined with the results of the three cubes from Set D to indicate the 90 day strength. At each age, the three tested cubes satisfied the 15% acceptance requirement of SABS Method 863:1994 [35]. The compressive strength at 28 days of each batch of concrete exceeded the target strength of 20 MPa but a comparison of the results indicated that both Set C and Set D have lower strengths than Set A and Set B. The lower strength obtained in Set C, Table 9, coincided with a higher slump but the FWD and the masses of the cubes were similar to both Set A and Set B. As discussed in Section 4.2.2 the quantity of water required to change the slump was unlikely to have gone unnoticed, which tends to indicate that neither the water content nor aggregate content changed. If the 15% acceptance requirement [35] is applied to the nine cubes of Set A, Set B and Set C then the values obtained in Set C are valid and the results can be considered as part of the overall set, with the difference probably due to testing variation during crushing.

The lower strengths in Set D, Table 9, failed the 15% acceptance requirement [35] when all 12 cubes were considered as part of the same set. These lower strengths could well be related to the lower FWD and lower cube masses, which indicates that either the water content or combined aggregate grading changed, or that the cubes were not properly compacted. As the slump of Set D was not significantly different it is unlikely that the water content or combined grading was the cause but the most probable reason for the lower strengths was inadequate compaction of the cubes, which were generally lower in mass than all the other seven and 28 day cubes.

The average compressive strength and standard deviation for 7-day and 28-day tests, based on 12 samples (see Appendix, Table C1) taken across the batches, were 14.5 ± 1.0 MPa and 23.5 ± 1.5 MPa respectively. The average compressive strength of the four sets exceeded 30 MPa after 56 days and 35 MPa after 90 days. Table 9 also shows the mass of each individual cube and these masses compared favourably with the FWD obtained at the time of mixing.

TABLE 9: Physical properties of concrete as measured for each batch

Set		A			B			C			D		
Batch		1	2	3	1	2	3	1	2	3	1	2	3
Property	Unit	Fresh Concrete Tests											
Slump	mm	80	85	80	85	85	80	90	95	95	85	90	85
FWD	kg/m ³	2468	2464	2473	2458	2437	2480	2412	2443	2473	2433	2397	2414
Cube Masses and Compressive Strength Tests (100 mm cubes)													
1-day	kg				2444	2443	2449						
	MPa				4.5	5.0	5.0						
3-day	kg	2467	2394	2429									
	MPa	10.5	10.5	10.5									
7-day	kg	2464	2452	2470	2446	2471	2463	2441	2445	2436	2416	2397	2413
	MPa	15.0	15.0	15.0	15.0	15.5	15.5	13.0	13.0	13.5	13.5	14.0	13.0
28-day	kg	2394	2451	2446	2449	2488	2459	2412	2449	2434	2387	2422	2414
	MPa	25.5	24.5	24.0	25.0	24.0	25.0	23.5	22.5	23.0	22.0	21.0	21.5
56-day	kg							2440	2466				
	MPa							30.0	32.0				
90-day	kg									2434	2432	2446	2441
	MPa									40.0	36.0	38.5	37.0

The strength development curve shown in Figure 21 indicates that with sustained moist curing, fly ash contributes significantly to strength development after 28 days. By wet curing the cubes, strength increased from 23.5 MPa at 28 days to 38 MPa (increase of $\pm 61\%$) at 90 days. This substantiates the premise that by varying the moist curing of the concrete beams, concrete of differing quality would be produced.

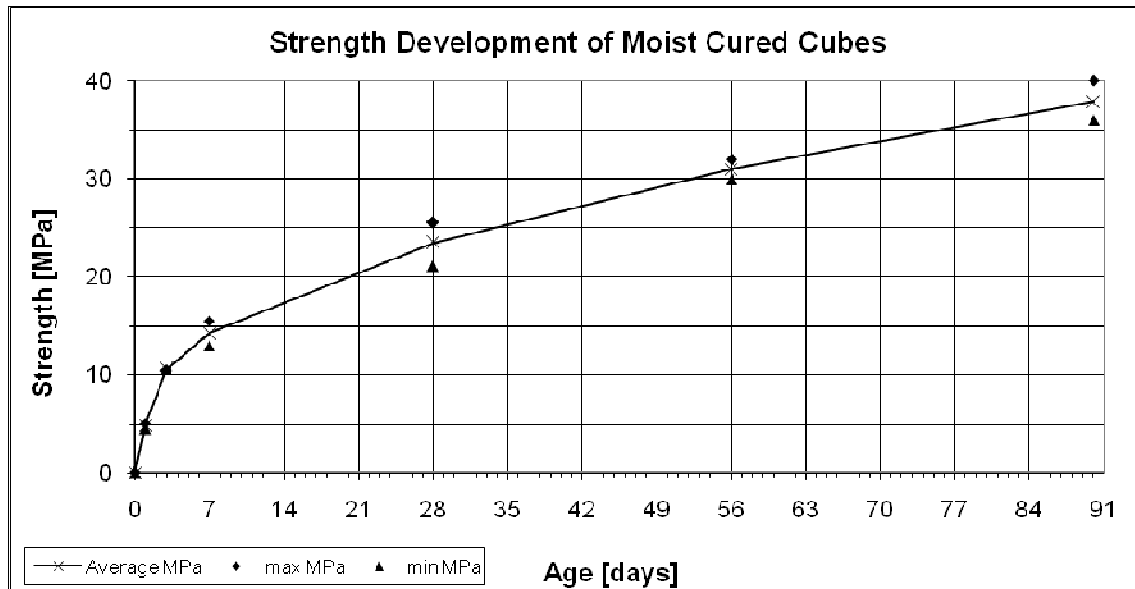


FIGURE 21: Strength development curve

4.4 Water sorptivity

4.4.1 Summary of Results

Water sorptivity tests [37] were carried out on samples cut from each set of beams that had been subjected to the different curing regimes. Both the prepared and unprepared surfaces were tested twice but as the first results were erratic only the second set of test results have been included in Table 10.

TABLE 10: Water sorptivity results

	Initial water curing period			
	28 days	7 days	3 days	1 day
Surface preparation \ Units	[mm/hr ^{0.5}]	[mm/hr ^{0.5}]	[mm/hr ^{0.5}]	[mm/hr ^{0.5}]
None (original surface)	8.84	9.89	12.73	16.37
Mechanical wire brush	9.80	10.47	14.62	17.02
Hand (manual) wire brush	10.06	11.65	13.46	13.23
Bushing tool	7.15	10.54	13.14	14.62

Table 10 gives details of results obtained with the second test and are arranged from left to right in order of decreasing curing time and from top to bottom in order of increasing mechanical effort in surface preparation.

4.4.2 Analysis of Results

The results shown in Figure 22 indicate that, there was little or no correlation between the wet curing period and the method of surface preparation at a particular age after curing. It would have been expected that the “no preparation” sample would show the highest sorptivity due to the weak layer of surface concrete while the hand brushing and mechanical wire brushing would give lower sorptivities as the poor near-surface concrete was removed. The bushing tool could be expected to give variable results as shown due to the possibility of concrete “bruising” as mentioned in various papers [12, 16].

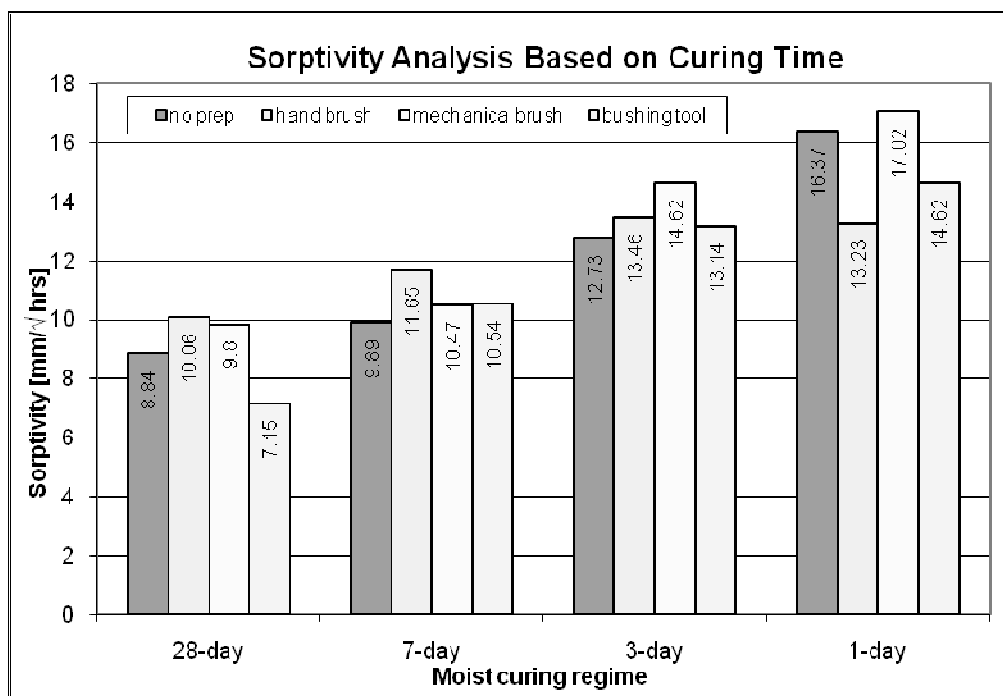


FIGURE 22: Chart of Sorptivity and Curing Time

Figure 23 shows that for a particular preparation method there was a strong correlation between the length of curing and the reduction in the sorptivity even after the surfaces had been prepared.

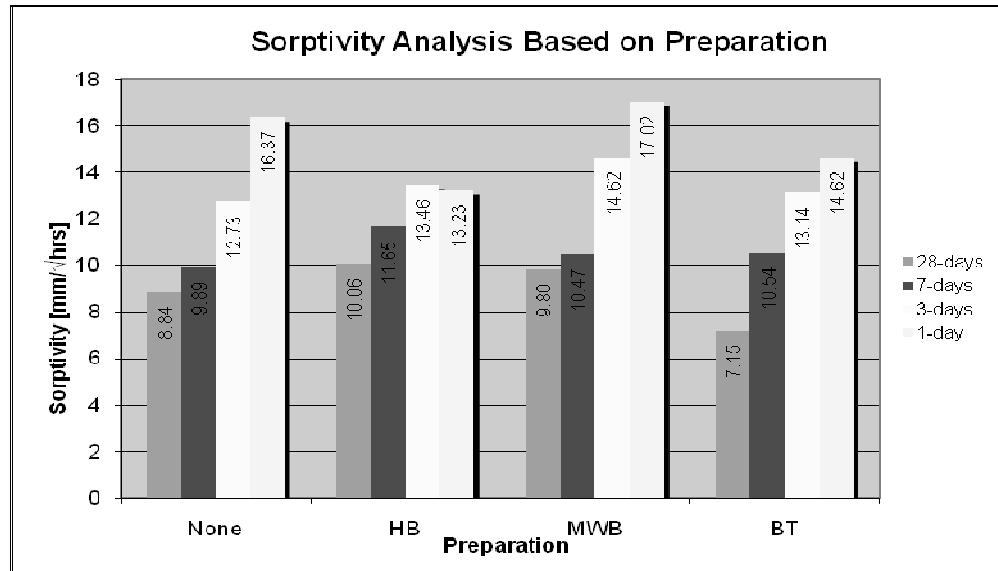


FIGURE 23: Chart of Sorptivity and Preparation Method

The results of the “unprepared” surfaces, which were subjected to different wet curing regimes, agree with the findings of Alexander et al. [42], who showed that wet cured concrete had lower sorptivity values than moist-cured or dry-cured concrete, as illustrated in Figure 24. The only anomaly to the trend was the one-day cured, hand brushed sample that would have been expected to have a higher sorptivity but it is possible that this sample was not adequately prepared and was left with excess amounts of the poor near-surface concrete.

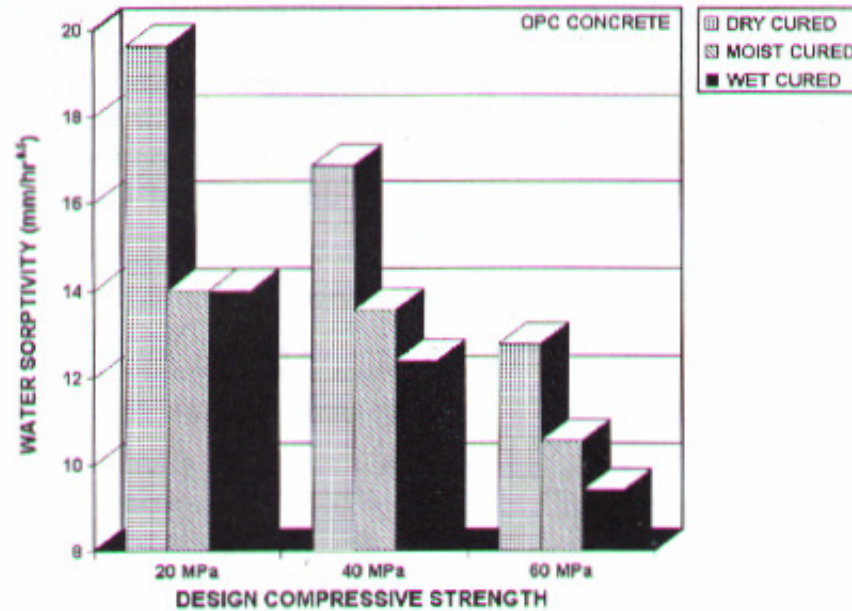


FIGURE 24: Water sorptivity of OPC concretes with different curing regimes [42]

Calculations of the water sorptivity values and their correlation coefficient for the linear regression are detailed in the Appendices. The correlation coefficient of linear regression analysis on the water sorptivity results was greater than 95% for all results as detailed in Table 11.

The results of the tests on the unprepared surfaces that had been subjected to different wet curing regimes, together with previous work carried out by Alexander.M.G et al. [42] strongly suggest the water sorptivity test can be used to index the quality of the surface concrete of a structure.

TABLE 11: Correlation coefficient for water sorptivity test results

Wet Curing	Surface Preparation			
	None	Mechanical Wire Brush	Hand Wire Brushing	Bushing tool
28 days	0.988	0.995	0.990	1.000
7 days	0.994	0.993	0.992	0.969
3 days	0.987	0.996	0.978	0.990
1 day	0.984	0.977	0.976	0.995

4.5 Application of Coatings

4.5.1 General Assessment

Based on the assessments made during application of the coatings, the following was noted:

- The more viscous the material, the more difficult it was to ensure an even thickness of coating.
- On an uneven surface, it was very difficult to apply an even thickness of coating.
- If coatings are to be applied effectively and in particular over a large surface area, a spray application may be preferable.

5.5.2 Elastomeric Coating

The elastomeric coating on different surfaces is shown in Figure 25 with the bushing tool preparation on the left, mechanical wire brushed surface in the centre and hand wire brushed surfaces on the right. Spraying this material would not pose a problem if the appropriate equipment (recommended by the supplier) were used.

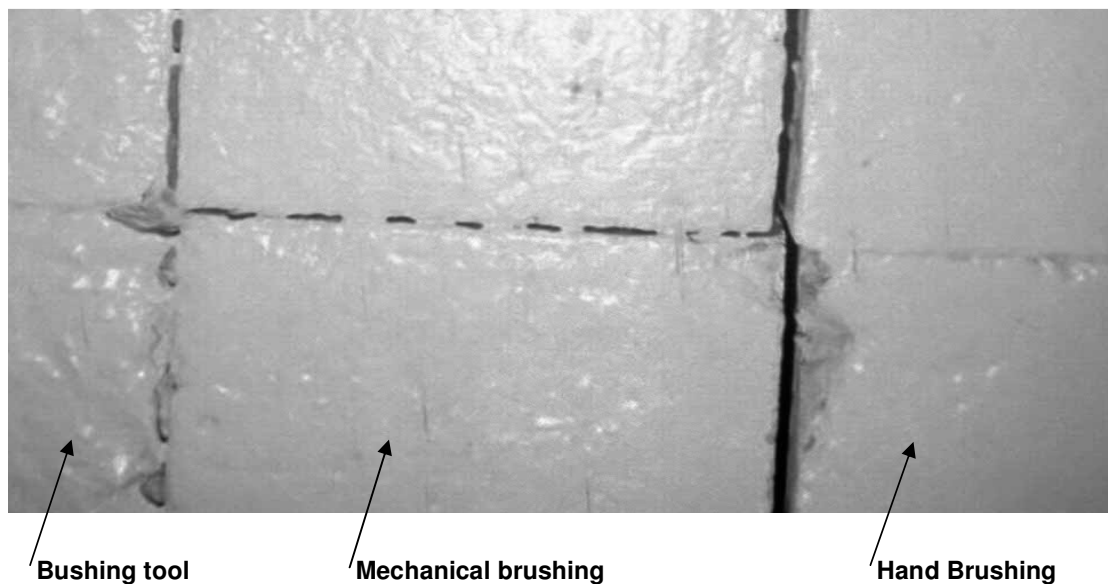


FIGURE 25: Specimens coated with elastomeric coating

4.5.3 Aliphatic coating

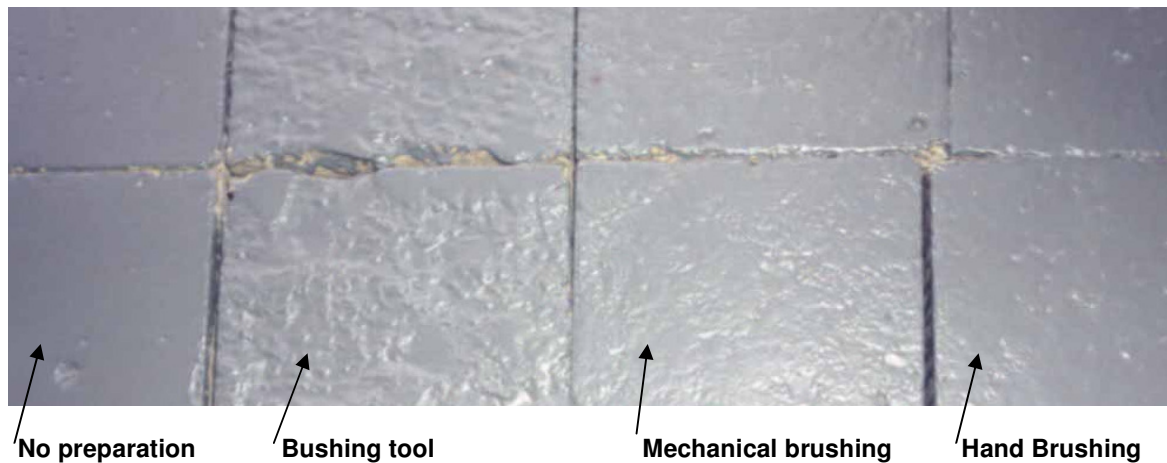


FIGURE 26: Specimens coated with aliphatic coating

In Figure 26, the unprepared surface is shown on the left followed by the bushing tool preparation, mechanical wire brushing and hand wire brushing on the right. This material tended to dry more quickly than the elastomeric coating but was easy to apply with a brush and will also spray without difficulty.

4.5.4 Epoxy Resin Based Coating

This two-part system was difficult to mix, as the pack had to be split for economic reasons and the viscous nature of the materials required considerable effort even with a mechanical mixer. Application by brush was not difficult, although it was necessary to work quickly as the mixed material exhibited a short pot-life. However, spraying on site may be a problem unless specialised equipment was available. In Figure 27 coated surfaces are shown with unprepared surface on the left followed by the bushing tool preparation, mechanical wire brushing, and hand wire brushing on the right.

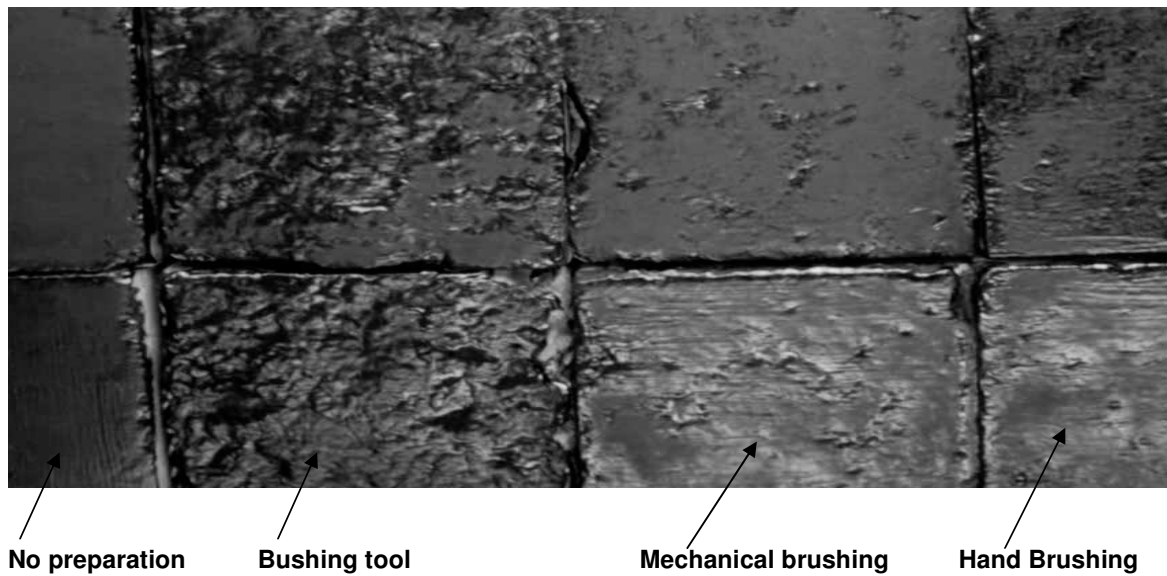


FIGURE 27: Specimens coated with epoxy resin based coating

4.5.5 Cementitious Based Coating

This two-part material was much easier to mix than the epoxy resin based material and was also easier to apply by brush to the recommended thickness. The two coats resulted in a thick coating that tended to bridge the gaps between specimens as can be seen in Figure 28. Spraying with suitable equipment should not pose a significant problem.



FIGURE 28: Specimens coated with cementitious based coating

4.5.6 Masonry Paint

Shown in Figure 29 is the masonry paint which was the easiest coating material to apply probably due to its low viscosity. It should be remembered that masonry paint is not designed as a protective coating and was only used in this study for comparing adhesion strengths with selected coatings.

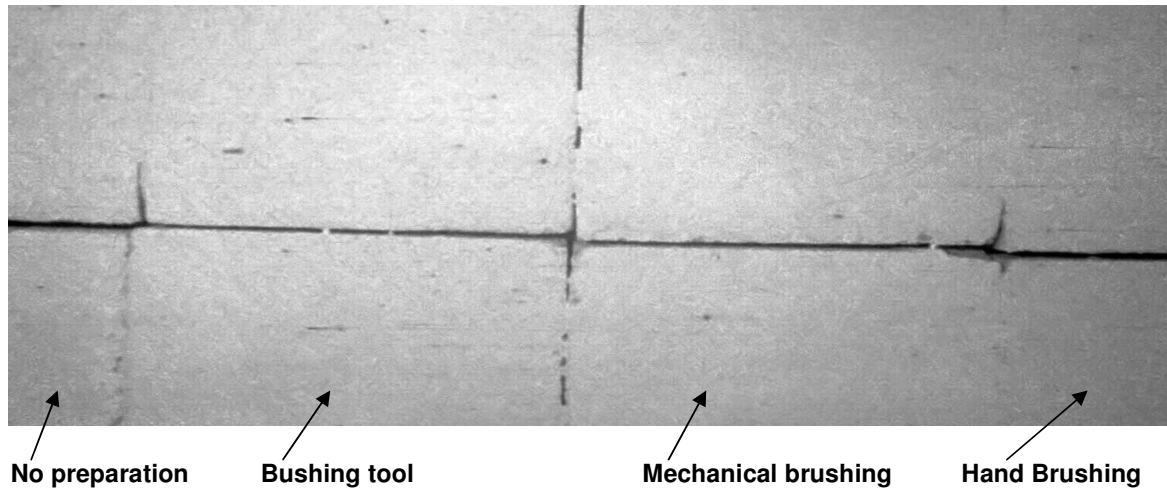


FIGURE 29: Specimens coated with masonry paint

4.6 Microscopic Evaluation

Thin sections of various prepared surfaces taken from concrete cured for one day and 28 days were examined under an optical microscope. The top edge of each specimen was examined at 40x magnification under plane-polarised light and cross-polarised light. Evidence of cracking, illustrated in Figures 30 and 31, was only found in one sample, that was cured for 28 days, and that had been prepared using the brushing tool. These cracks were probably caused by the heavy impact imparted by the brushing tool and are similar to evidence reported by Silfwerbrand [13] and Hindo [22]. From this examination, there does not appear to be a need for microscopic examination of samples obtained from the prepared surface on a site prior to coating, unless defective concrete has been removed using a jack-hammering technique.

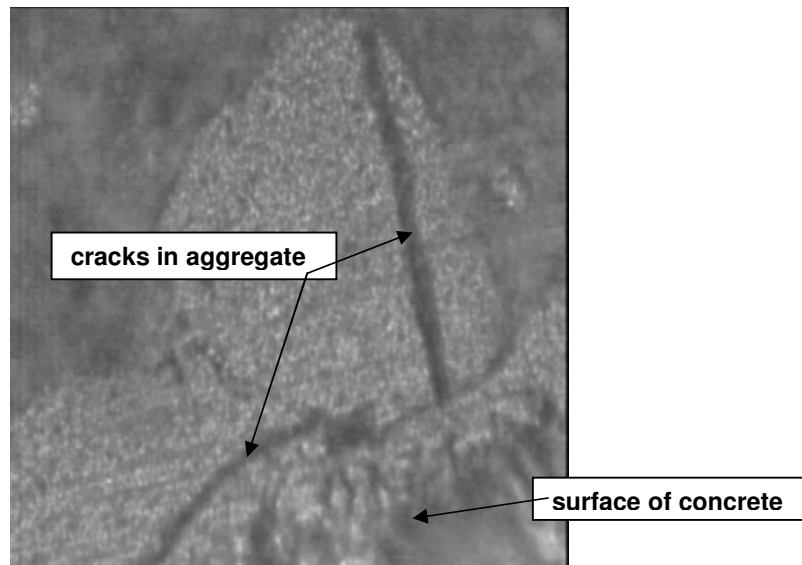


FIGURE 30: Cracking in the aggregate of concrete prepared with the bushing tool

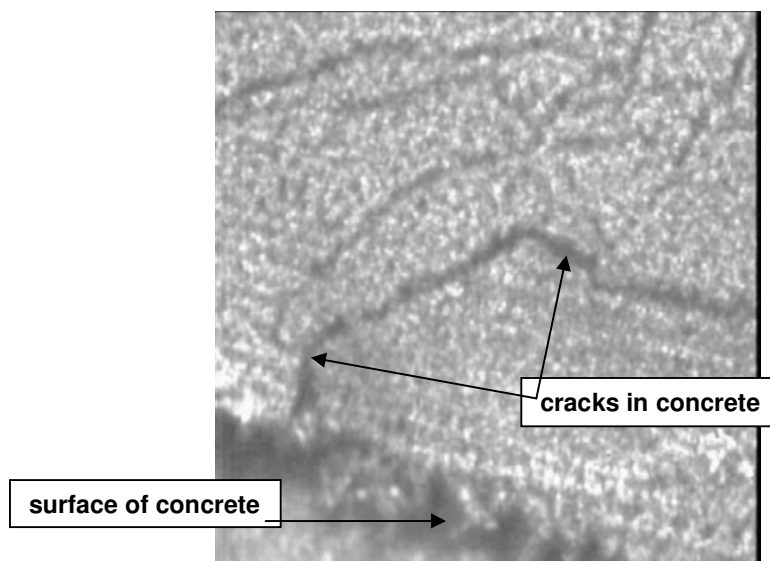


FIGURE 31: Cracking near the surface of concrete prepared with the bushing tool

4.7 Adhesion Tests

4.7.1 Introduction

Analyses of the mode of failure and tensile strengths obtained at four weeks and sixteen weeks after application of the coatings are detailed in the subsequent sections while the individual results are presented in the Appendices. The 4-week

results were based on an average of two tests and the 16-week results on an average of three tests. The ambient temperature and humidity conditions in the laboratory were not controlled and, between January and July, the period during which the application and testing was carried out, these were monitored indoors and varied from 20 to 27 °C during the day and between 10 to 18 °C at night, while the relative humidity varied from 55% to 65%. The relative humidity in the laboratory tended to be higher than the outside ambient conditions due to the curing tanks in the laboratory.

As mentioned in Section 3.7.2 the coated samples were cured inside the laboratory on a bench away from any drafts and direct sunlight. The first series of pull-off tests were carried out after four weeks to allow for a full cure of the cementitious coating. The second series of pull-off tests were carried out three months after the first tests, which was sixteen weeks after the application of the coating. A second set of tests was carried out to establish if there was any change in the adhesion of the coating to the concrete with time.

4.7.2 Mode of Failure

An assessment of the mode of failure, summarised in Table 12, indicates that where the concrete was wet-cured for at least 7 days, the mode of failure tends to be at the interface (33 of 200 results) whereas with the concrete wet-cured for three days or less there was a greater tendency (85 out of 200) for the failure to be in the substrate or partly in the substrate. The former is probably due to a higher tensile strength in the near-surface concrete obtained by well-hydrated cement in this area as opposed to only partial hydration caused by the premature loss of moisture from the near-surface concrete when the curing time is reduced.

The adhesion of coatings to the concrete improved with time after application, with twice as many failures (35% versus 17.5%) in the substrate after sixteen weeks compared to four weeks. This was more consistent for the aliphatic coating, epoxy resin coating and masonry paint, where the surface had been prepared using the brushing techniques. This increase in adhesive strength is likely due to the rough surface obtained by brushing that improves the mechanical bond between the coating and the concrete, as well as bonding surface area.

TABLE 12: Description of the mode of failure obtained during pull-off test

Coating		Elastomeric		Aliphatic		Epoxy resin		Cementitious		Masonry	
Interval between the coating application and the adhesion test		4 weeks	16 weeks	4 weeks	16 weeks	4 weeks	16 weeks	4 weeks	16 weeks	4 weeks	16 weeks
Concrete Curing Period	Surface Preparation	Mode of failure: I = at the interface S = in substrate I; I; S = mainly at the interface, with slight substrate failure I; S; S = mainly in the substrate, with slight interface failure C = coating failure									
28-day	None	I; I	I; S; S	S; S	S; S; S	S; S	I; I; S	C; C	I; I; I	S; S	I; I; I
7-day		I; I	I; I; I	I; I	I; I; I	S; S	I; S; S	C; C	I; I; I	I; I	I; I; I
3-day		I; I	I; I; I	I; I	I; I; I	I; I	I; I; I	C; C	I; I; I	I; I	I; I; I
1-day		I; I	I; I; I	I; I	I; I; I	I; I	I; I; I	C; C	I; S; S	I; I	I; I; S
28-day	Bushing tool	I; I	S; S; S	S; S	S; S; S	I; I	S; S; S	C; C	I; I; I	S; S	S; S; S
7-day		I; I	I; I; I	I; I	I; I; S	I; I	I; S; S	C; C	I; I; I	I; I	I; I; I
3-day		I; I	I; I; I	I; I	I; I; I	I; I	I; I; I	C; C	I; I; S	I; I	I; I; I
1-day		I; I	I; I; S	I; I	I; S; S	I; I	S; S; S	C; C	I; I; S	I; I	I; I; S
28-day	Mechanical wire brush	I; I	I; I; S	S; S	S; S; S	I; I	S; S; S	C; C	I; I; I	S; S	S; S; S
7-day		I; I	I; I; I	S; S	S; S; S	I; I	S; S; S	C; C	I; I; I	I; I	S; S; S
3-day		I; I	I; I; I	I; I	S; S; S	I; I	I; I; I	C; C	I; I; I	I; I	I; S; S
1-day		I; I	I; I; I	I; I	I; S; S	I; I	I; I; I	C; C	I; I; I	I; I	I; I; I
28-day	Hand wire brush	I; I	I; S; S	S; S	S; S; S	S; S	S; S; S	C; C	I; I; I	S; S	I; S; S
7-day		I; I	I; I; I	S; S	S; S; S	S; S	I; I; S	C; C	I; I; I	I; I	I; I; S
3-day		I; I	I; I; I	I; I	S; S; S	I; I	I; I; I	C; C	I; I; I	I; I	I; S; S
1-day		I; I	I; I; I	I; I	S; S; S	I; I	I; I; I	C; C	I; I; I	I; I	I; I; I

It was also noticeable that the cementitious coating itself failed at four weeks whereas after sixteen weeks the failure was at the interface. This suggests that as the cement in coating hydrated, the tensile strength of the coating increased to the

extent where it exceeded the adhesive strength between the coating and the concrete surface.

4.7.3 Test Results

Each coating type has been analysed individually in the following sections along with an overall assessment of the effect of the surface preparation on the different coatings.

4.7.3.1 Elastomeric Coating

The results shown in Figure 32 indicate that in general, the bond strength increases with time after application and as the moist curing period of the concrete was extended. Where no preparation was applied, the bond strength of the elastomeric coating to concrete substrates tends to plateau after 7 days of moist curing. This may indicate that the quality of the laitance did not improve significantly after 7 days of moist curing.

Where the bushing tool was used for preparing the surfaces there was a greater increase in the adhesion strength with concrete that was moist cured for longer than 7 days. The wire brushing techniques generally tend to give the highest bond strength, which may be the effect of removing near-surface laitance. The results indicate that 60% of the bond strengths measured after four weeks and 80% measured after sixteen weeks were equal to or greater than the 1500 kPa (1.5MPa). However, the increase in adhesion strength at sixteen weeks was significantly greater for the concrete that was subjected to less curing. This may have been caused by the mechanical surface preparation more easily removing the “weaker”

near-surface concrete resulting in deeper penetration of the coating into exposed concrete thus giving higher strengths.

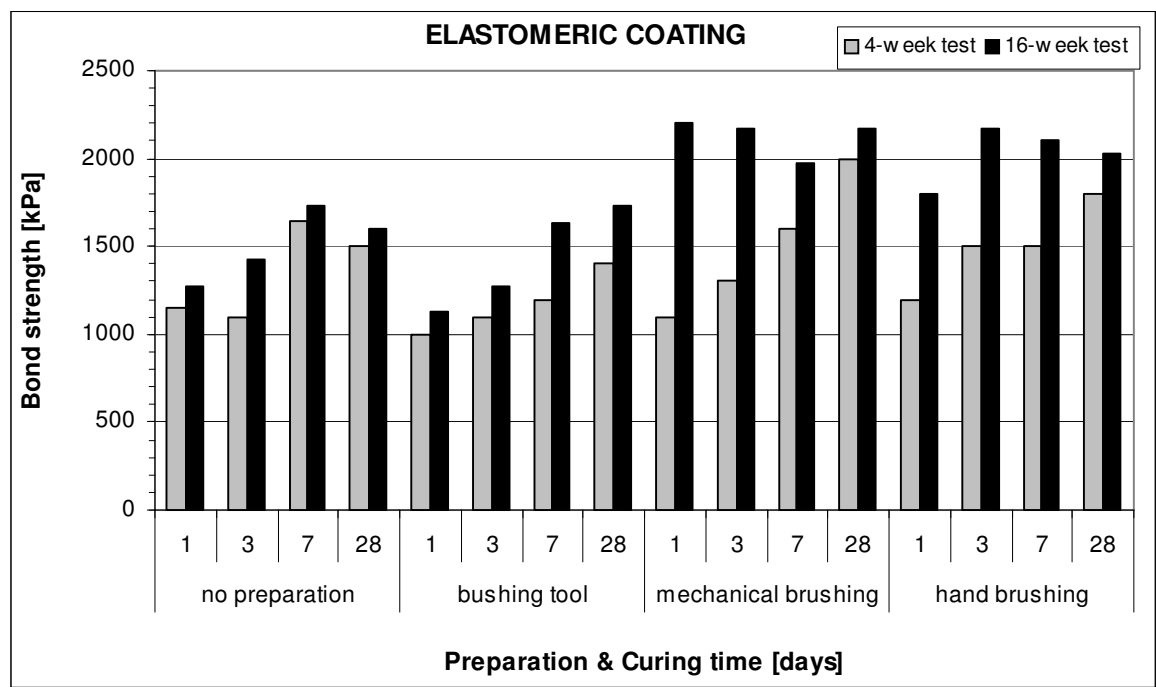


FIGURE 32: Adhesion strengths of the elastomeric coating at 4-weeks and 16-weeks after application

4.7.3.2 Aliphatic Coating

The results obtained using the aliphatic coating are shown in Figure 33. These indicate that when no preparation was carried out or where the bushing tool was used to prepare the surfaces, the bond strengths increase with longer curing times but flattened out after 7 days of concrete curing. Where the preparation was based on mechanical brushing or hand brushing there appeared to be very little increase in the adhesion strength with concrete curing age or with time after the coating application.

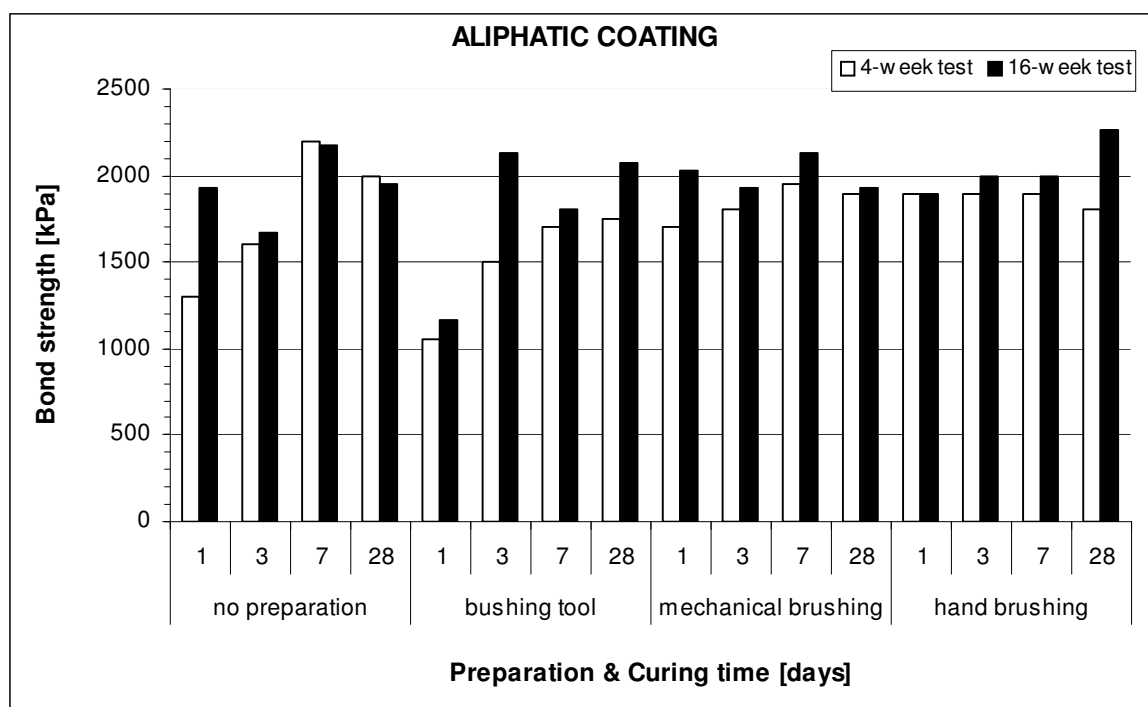


FIGURE 33: Adhesion strengths of the aliphatic coating at 4-weeks and 16-weeks after application

More than 90% of the adhesive strengths obtained were greater than 1500 kPa and the two brushing preparation techniques produced bond strengths greater than 1700 kPa, irrespective of the curing time. Similar adhesion strengths greater than 1700 kPa, were recorded for unprepared concrete surface and the concrete subjected to bushing tool that was cured for at least 7 days. The good adhesion strengths obtained on concrete that was prepared by brushing the surfaces was likely to be due to the removal of the relatively weak near-surface concrete. This allowed the coating to bond to a sound substrate and as a result most failures were in the substrate as can be seen in Table 12. These relatively high bond strengths may be due to the good adhesive properties of the coating used in combination with the deep penetrating silane-siloxane primer. As the use of a primer is specified by the coating

manufacturer the adhesion strength of the coating without a primer was not considered as part of this study.

4.7.3.3 Epoxy Resin Based Coating

The adhesion strengths of the epoxy resin coating are depicted in Figure 34 and show that when measured four weeks after application, the strengths did not increase with moist curing time and showed no obvious trend. However after sixteen weeks the bond strength improved with increasing curing time although sometimes, it was lower on the specimen cured for 28 days. This may be related to easier penetration of the coating into the pores of the concrete cured for 7 days or less compared to tighter pore structure of 28 day concrete. When tested at four weeks, the bond strengths between the epoxy resin and the concrete surface prepared with the bushing tool were similar regardless of the curing time.

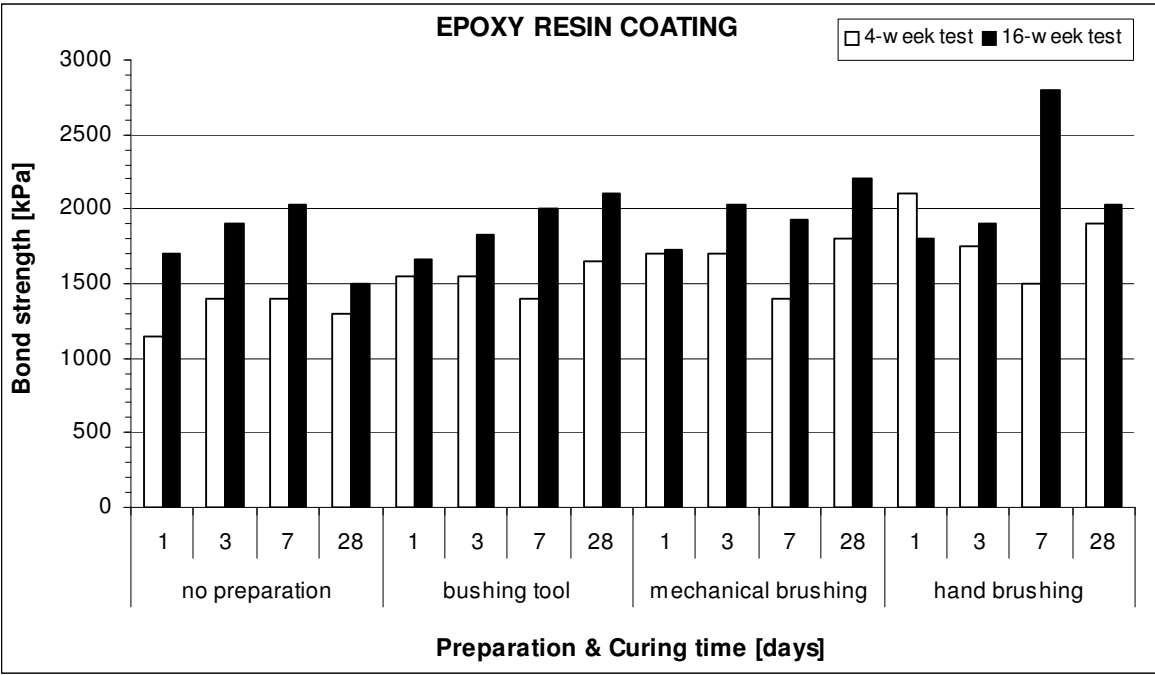


FIGURE 34: Adhesion strengths of the epoxy resin based coating at 4-weeks and 16-weeks after application

However, the strengths tend to increase linearly when tested at sixteen weeks. The results obtained from samples prepared by both mechanical and hand wire brushing did not show a clear trend of increase in bond strength with curing time of concrete.

The 16-week results were higher than the 4-week results, except for the hand brushed sample moist cured for 1-day. The erratic results may be due to inconsistencies in the preparation that may have removed varying amounts of the near-surface concrete. In general, bond strengths greater than 1500 kPa were obtained sixteen weeks after application for all ages of concrete and with all the different surface preparations. This is due to the slow but good adhesion properties of the epoxy type materials.

4.7.3.4 Cementitious Based Coating

The thickness of this coating was considerably greater than the other coating materials and it was evident that this had an affect on the mode of failure of the test results four weeks after application as all the failures occurred within the coating itself. Table 12 does indicate that after sixteen weeks however, the failure tended to occur at the interface between concrete and the coating. The bond strengths obtained after four weeks, shown in Figure 35, were within a fairly narrow range of 1350 kPa to 1850 kPa for all methods of preparation. One sample prepared by hand brushing the surface reached a strength of 2600 kPa. However, this result appears anomalous as the 16-week result was not correspondingly higher.

At sixteen weeks after application, the adhesive strengths are generally higher than the 4-week strengths indicating that the internal tensile strength of the coating had increased such that it exceeded the bond strength. The adhesion of the coating to

those surfaces prepared with the bushing tool were lower at sixteen weeks than at four weeks, the reason was not clear as the mode of failure was at the interface and did not appear to be related to a substrate failure. Neither the surface preparation nor the curing regime had a significant effect on the results, with 84% of the results exceeding 1500 kPa, it could be argued these aspects might not be that critical when using a cementitious based coating. Based on the results obtained with this material, it may have been better to test this coating using the techniques describe by Silwerbrand [13] and Hindo [22] but this was outside the scope of the investigation. The technique involves drilling a core through the repair mortar into the substrate to a depth of about 50 mm. A steel plate of the same diameter as the core is then glued to the mortar. Once the epoxy glue has cured an adjustable loading device is placed and levelled over the test area and an axial tensile force is applied until failure occurs. The stress is calculated and the mode of failure recorded.

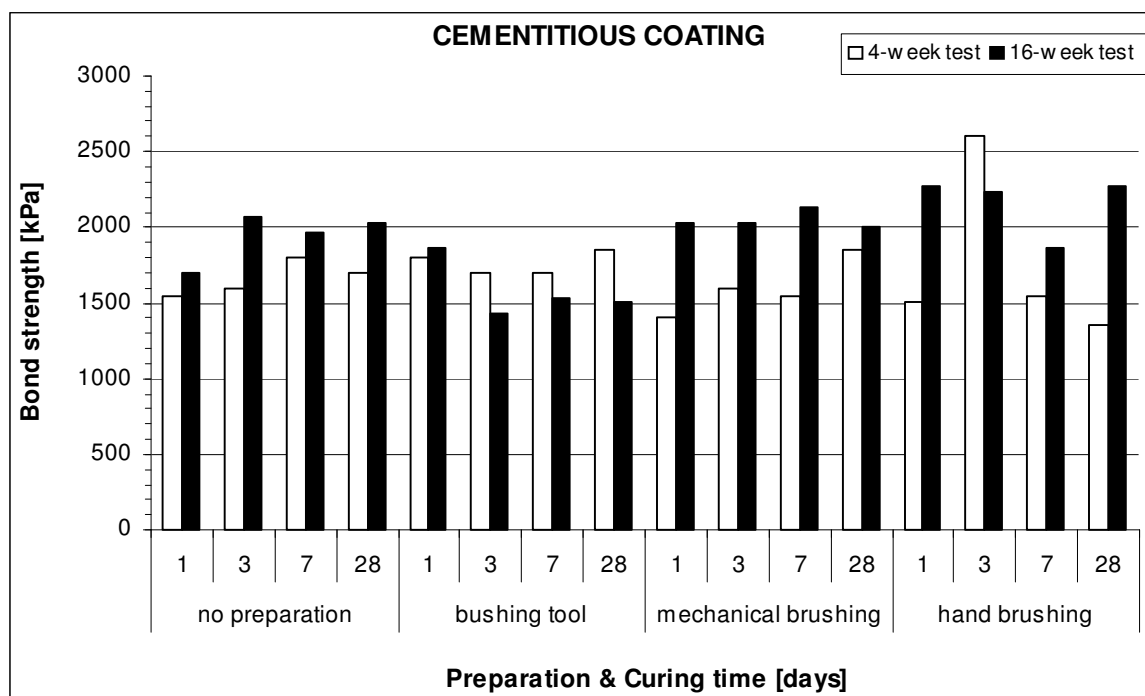


FIGURE 35: Adhesion strengths of the cementitious based coating at 4-weeks and 16-weeks after application

4.7.3.5 Masonry Paint

Results obtained when using the ordinary paint are shown in Figure 36. The results indicate that the adhesion to the wire brushed surfaces was better than that on the other surfaces at both test ages. More than 75% of the bond strengths were greater than 1500 kPa on the brushed surfaces compared to 50% or less for the other surface preparations. The bond strengths increased with moist curing when tested at four weeks and sixteen weeks, however the 16-week result for one 28-day moist cured sample, was marginally lower than the 4-week test result. This may indicate inconsistent preparation as both failures occurred at the interface. The surfaces prepared with the bushing tool were actually too rough to obtain an even coating or good seating of the adhesion stud.

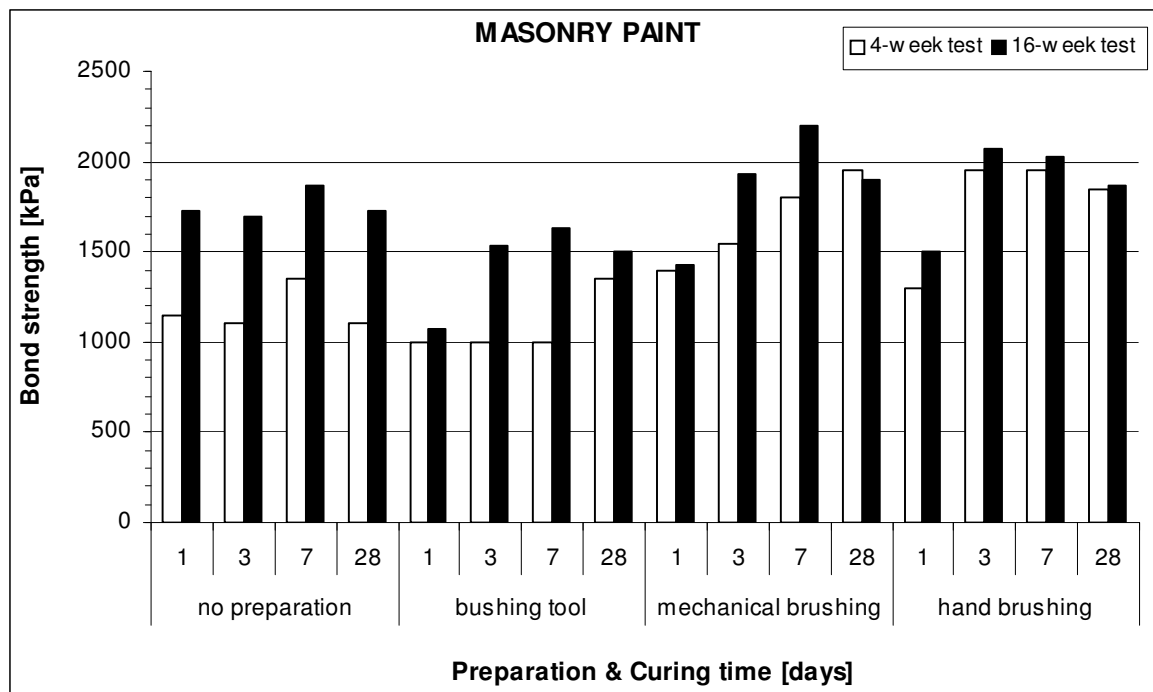


FIGURE 36: Adhesion strengths of the masonry paint at 4-weeks and 16-weeks after application

However, when no preparation was carried out and where a very rough finish was obtained with the bushing tool, the moist curing time did not significantly affect the bond strength. In general, when using the masonry paint, the duration of the moist curing did not appear to affect the strength of adhesion but the bond strength is generally less than when using propriety protective coating materials. Notwithstanding the latter, the bond strength did improve with the age after the application of the coating and it was evident that the greatest improvement was where there was no surface preparation.

4.7.4 Effect of Surface Preparation

To assess the effect of the surface preparation on the adhesion of the various coatings the minimum adhesion strength of 1500 kPa (1.5 MPa) as suggested by Peier [11] was used to establish which coating performed best irrespective of the preparation technique employed. In addition, a more conservative but arbitrarily selected minimum bond strength of 1750 kPa was also used to assess the coating performance. As can be deduced from Table 13, the aliphatic, cementitious based and epoxy resin based coatings performed better than the other two coatings when the minimum was set at 1500 kPa and the tests were carried out at four weeks. When the testing was carried out at sixteen weeks, all of the coatings gave satisfactory bond strengths. If the more conservative approach were to be adopted, with a minimum requirement of 1750 kPa, the aliphatic coating was better than the other coating materials at four weeks. There was no significant difference between the aliphatic coating, the epoxy resin and the cementitious-based coating when tested at sixteen weeks but these materials performed better than the elastomeric coating and the masonry paint.

TABLE 13: Percentage of samples exceeding selected minimum adhesion strengths

Time after application	4-weeks	16-weeks	4-weeks	16-weeks
Minimum kPa	> 1500 kPa	> 1500 kPa	> 1750 kPa	> 1750 kPa
Elastomeric	43%	75%	12%	50%
Aliphatic	87%	93%	62%	87%
Epoxy resin	62%	100%	25%	75%
Cementitious	87%	93%	25%	75%
Masonry paint	37%	87%	31%	43%

The charts in Figure 37 indicated that where no preparation was undertaken, the cementitious coating achieved adhesion strengths greater than 1500 kPa with all tests while the aliphatic coating exceeded this minimum in 85% of cases. This concurs with Fiebrich [43] who came to the conclusion that a mechanically abraded surface preparation was not necessary for long-term adhesion with acrylic coatings to concrete. The elastomeric coating performed better on concrete cured for seven days or more when tested at four weeks, whereas the adhesion after 16 weeks did not seem to be influenced as much by lack of concrete curing. The adhesion of epoxy resin and masonry paint was generally greater when tested at 16 weeks compared to the adhesion at four weeks.

When the concrete was prepared using the bushing tool the cementitious coating was again the more consistent performer with the aliphatic and epoxy resin materials also achieving satisfactory adhesion particularly at later ages. The elastomeric coating and the masonry paint only exceed 1500 kPa when the concrete was wet cured for at least seven days and if tested after sixteen weeks. The aliphatic coating

exceeded the minimum of 1500 kPa irrespective of the moist curing period if the surface was prepared by means of mechanical brushing. With this preparation technique the cementitious based coating and the epoxy resin material also achieved bond strengths in excess of 1500 kPa in more than 85% of cases. The elastomeric coating and masonry paint only exceeded the 1500 kPa requirement when applied to concrete moist cured for at least seven days or when tested sixteen weeks after application. By applying a light preparation, using the hand brushing technique on the surfaces, all the coating materials exceeded 1500 kPa when tested sixteen weeks after application.

The aliphatic and epoxy resin materials performed well when tested at four weeks while the elastomeric coating and masonry paint achieved satisfactory strengths when used on concrete cured for at least three days. The adhesion strengths of the cementitious based coating were difficult to assess when tested at four weeks. Although the results were all of the order of 1500 kPa, the failures had occurred in the coating itself. In some respects, this could be considered to be an advantage as despite being damaged, there was still coating material adhering to the concrete surface that would provide some degree of protection.

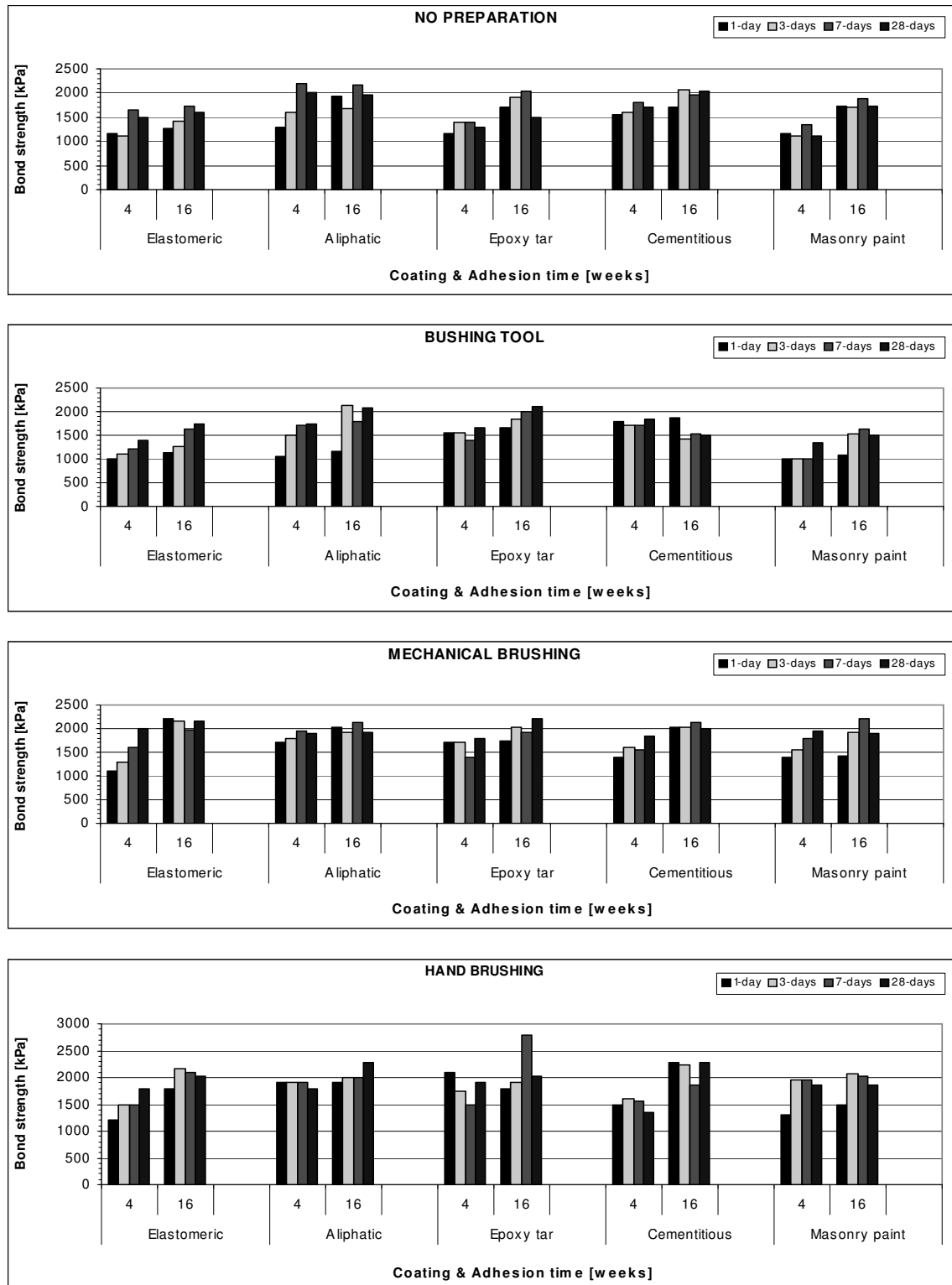


FIGURE 37: Graphical comparison of surface preparations and bond strengths

4.8 General Discussion

While being mindful of the small range of coatings assessed in this investigation, the following comments relate to the relative performance of the coatings:

- On unprepared surfaces or where the preparation produced a very uneven surface, the aliphatic, cementitious and epoxy resin materials gave the best adhesion irrespective of the quality of the near-surface concrete induced by the curing regime. This indicated that even on poor quality concrete surfaces induced by only one day of moist curing these coating could still be considered appropriate when long term protection is required.
- Preparation based on the wire brush techniques, consistently gave a better bond strength irrespective of the type of coating material used.
- With coatings applied in conjunction with specified primers the coating and primer act as a monolithic material. Any adhesion failures will take place at the concrete/primer interface because the chemical bond between the primer and coating is stronger than the physical bond between the substrate and the monolithic primer/coating material.

A failure will occur at the weakest section of the coating/concrete interface and in the literature review three type of failure [10] were described:

1. If an interface failure is obtained the bond strength can be defined as the failure strength,
2. If the failure is in the substrate then the bond strength is greater than the tensile strength of that section of the substrate,
3. If the failure is partly in the interface and partly in the substrate, it is more difficult to interpret, with the bond strength likely to be greater than the strength obtained with interface failure but less than the strength achieved with substrate failure.

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

- Coating adhesion strength generally improves with improved quality of the host concrete surface. This is best achieved through good quality curing of the concrete although there is only a marginal improvement in adhesion strength if the concrete is cured for longer than seven days.
- Mechanical brushing and manual brushing gave a surface texture, which resulted in the best coating adhesion for all the coatings used. This was mainly due to the even but rough surface that was obtained once the surface laitance had been removed.
- A microscopic examination of samples obtained from the prepared surfaces showed that heavy impact preparation causes microstructural damage in the prepared near-surface and this affects applied coatings.
- The aliphatic coating, cementitious based coating and epoxy resin type coating showed the best adhesion properties even to poor quality concrete surfaces. The cementitious material failed within the coating itself when tested four weeks after application and at the interface at sixteen weeks.
- The bond strengths obtained during this investigation, in conjunction with results reported in published literature, indicate that minimum strength of 1500 kPa is appropriate in most situations.

RECOMMENDATIONS FOR FURTHER WORK

- More extensive comparative testing using the water-sorptivity test should be carried on actual structures.
- Tests using the Elcometer Adhesion Tester should be carried out on actual structures during the rehabilitation of such structures.
- Research on the quality of surface preparation is essential to be able to specify quantitatively the expected performance.

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APPENDIX

A. Laboratory Batch Weights and Detailed Concrete Test Results

Table A1 below contains the actual details recorded at the time of mixing and testing of the fresh and hardened concrete. The fresh concrete test results and the data obtained during the testing of the cubes have been included in the body of the report in Table 9.

TABLE A1: Laboratory recordings of batch weights and concrete test results

Set		A			B			C			D		
Batch		1	2	3	1	2	3	1	2	3	1	2	3
Materials	Units												
Cement	kg	13.2			13.2			13.2			13.2		
Stone	kg	43.2			43.2			43.2			43.2		
Sand	kg	34.2			34.2			34.2			34.2		
Water	kg	7.48			7.48			7.48			7.48		
Fresh Concrete Tests Results													
Slump	mm	80	85	80	85	85	80	90	95	95	85	90	85
FWD	kg/m³	2468	2464	2473	2458	2437	2480	2412	2443	2473	2433	2397	2414
Cube Testing (100 mm) Data after 28 days of Wet Curing													
1-day	kg				2444	2443	2449						
	MPa				4.5	5.0	5.0						
3-day	kg	2467	2394	2429									
	MPa	10.5	10.5	10.5									
7-day	kg	2464	2452	2470	2446	2471	2463	2441	2445	2436	2416	2397	2413
	MPa	15.0	15.0	15.0	15.0	15.5	15.5	13.0	13.0	13.5	13.5	14.0	13.0
28-day	kg	2394	2451	2446	2449	2488	2459	2412	2449	2434	2387	2422	2414
	MPa	25.5	24.5	24.0	25.0	24.0	25.0	23.5	22.5	23.0	22.0	21.0	21.5
56-day	kg							2440	2466				
	MPa							30.0	32.0				
90-day	kg									2434	2432	2446	2441
	MPa									40.0	36.0	38.5	37.0
Curing Regime for Concrete Beams													
Beams	curing	28 days wet cure			7 days wet cure			3 days wet cure			1 day wet cure		

B. Analysis of slump difference

Figure B1 below was used to assess if the average slump of Set C was possibly due to additional water added by mistake to the concrete during mixing. The interpolation at the intersection of the dotted lines indicates how much additional water would possibly be required to alter the slump from 85 mm to 95 mm. As explained in more detail in the body of the report, Section 4.2.2, this does not seem to be the reason for the increase in slump.

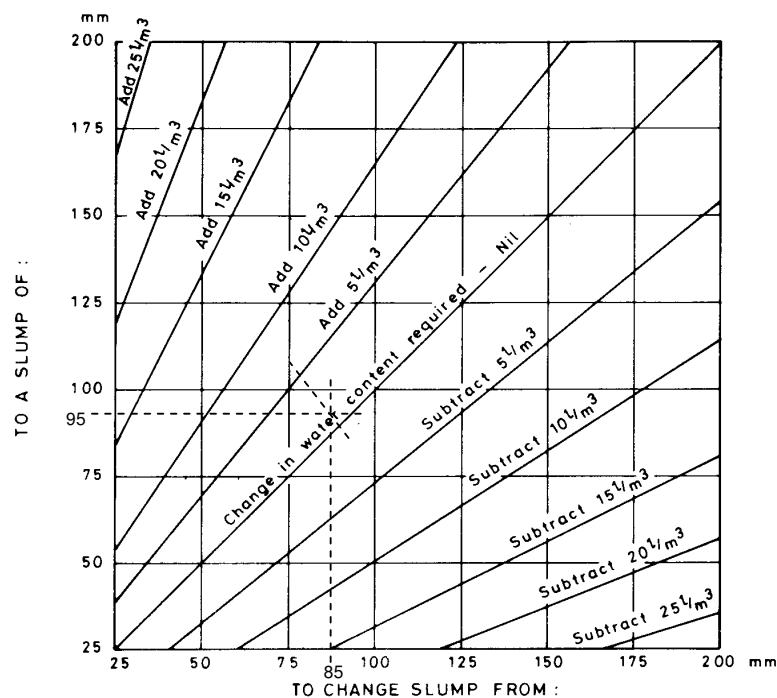


Figure B1: Change in water content required to change the slump [40]

C. Statistical Analysis of Laboratory Test Samples

The calculated values for the average, sample standard deviation and coefficient of variation for the wet and hardened test samples of the concrete used for the coating are listed in the Table C1 below. The coefficient of variation in all cases was less than 10%, which indicates that there was good control in the mixing and sample making process across the 12 mixes on which the properties measured.

TABLE C1: Statistical analysis of the wet and hardened properties of the concrete

Property	units	Number of samples	Average	Sample standard deviation	Coefficient of variation
Units					%
Slump	mm	12	86	5.3	6.1
Fresh wet density	kg/m ³	12	2446	27.6	1.1
Cube mass at 7 days	kg	12	2443	23.8	1.0
Cube strength at 7 days	MPa	12	14.0	1.0	7.1
Cube mass at 28 days	kg	12	2434	29.0	1.2
Cube strength at 28 days	MPa	12	23.5	1.5	6.3

D. Water Sorptivity Calculations

The calculations and regression analysis of the water-sorptivity results are detailed below from Page V to Page XX inclusive. These pages indicate the calculated sorptivity values as well as the correlation coefficient [R^2]. These values have been calculated at both t_{12} and t_{20} time intervals and the sorptivity value used to assess the quality of the near surface concrete is the value that had the highest [R^2] as in some case it was evident from the chart that some of the samples had partial saturation by the end of the test. The Charts show typical graphs of the regression analysis and the sorptivity curves are plotted as “square root of time” against “water absorption” for calculated values with the highest [R^2] value. The abbreviations used in these tables are:

- None = no preparation was carried out
- MWB = Mechanical wire brush preparation
- HB = Hand brush preparation
- BT = Bushing tool preparation

Sorptivity Calculations

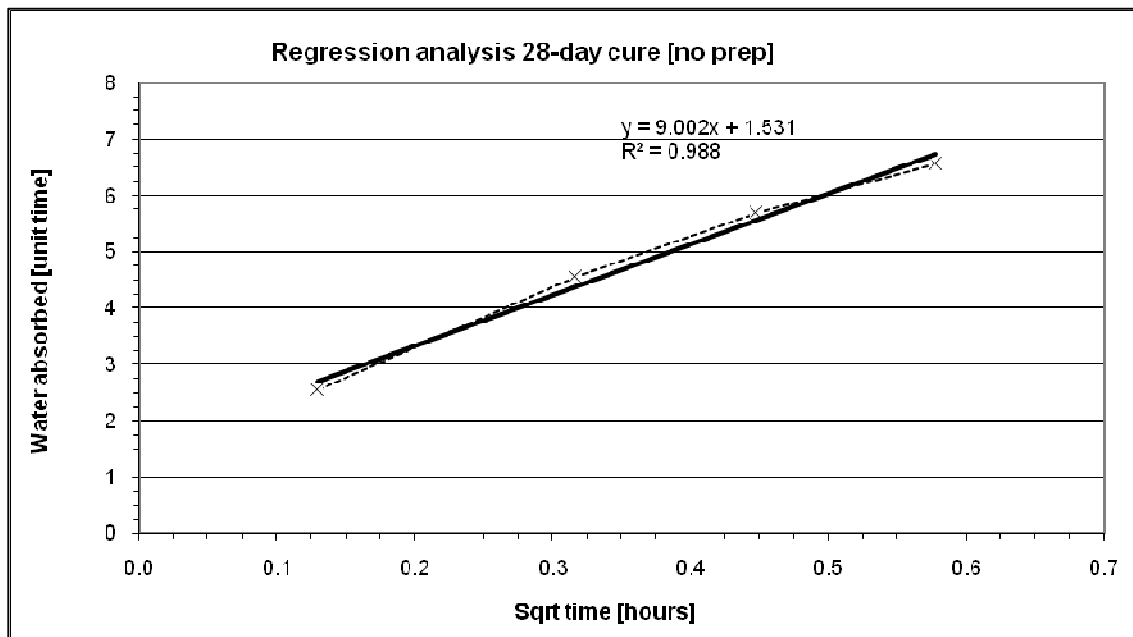
Water – Sorptivity calculations on concrete cured for 28 days

Preparation	none				
Test date	12.04.99				
Sample ID	1.3.3				
Sample thickness [mm] d =	24.6				
	24.3				
	24.4				
	24.7				
Average thickness [mm] d =	24.5				
Oven dry mass [g] Mo =	527.67				
Sat. wet mass [g] Msv =	555.31				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	527.79				
1	530.34	0.1	2.55	0.1	2.55
6	532.35	0.3	4.56	0.3	4.56
12	533.48	0.4	5.69	0.4	5.69
20	534.35	0.6	6.56		
Slope [g/ $\sqrt{\text{hrs}}$] F =		9.00		9.93	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		8.01		8.84	
Correlation coefficient R ² =		0.988		0.996	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



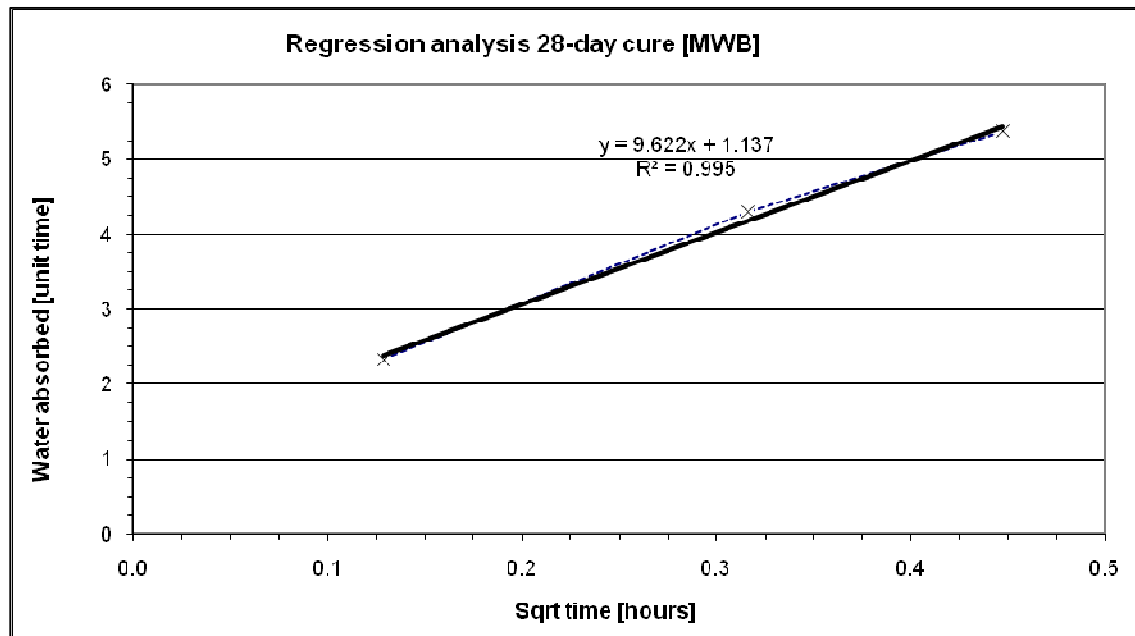
Water – Sorptivity calculations on concrete cured for 28 days

Preparation	Mechanical Wire Brush				
Test date	12.04.99				
Sample ID	1.3.6				
Sample thickness [mm] d =	25.5				
	25.3				
	25.2				
	25.3				
Average thickness [mm] d =	25.3				
Oven dry mass [g] Mo =	517.02				
Sat. wet mass [g] Msv =	542.01				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	517.15				
1	519.48	0.1	2.33	0.1	2.33
6	521.45	0.3	4.30	0.3	4.30
12	522.52	0.4	5.37	0.4	5.37
20	523.46	0.6	6.31		
Slope [g/ $\sqrt{\text{hrs}}$] F =		8.89		9.62	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		9.06		9.80	
Correlation coefficient R ² =		0.992		0.995	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



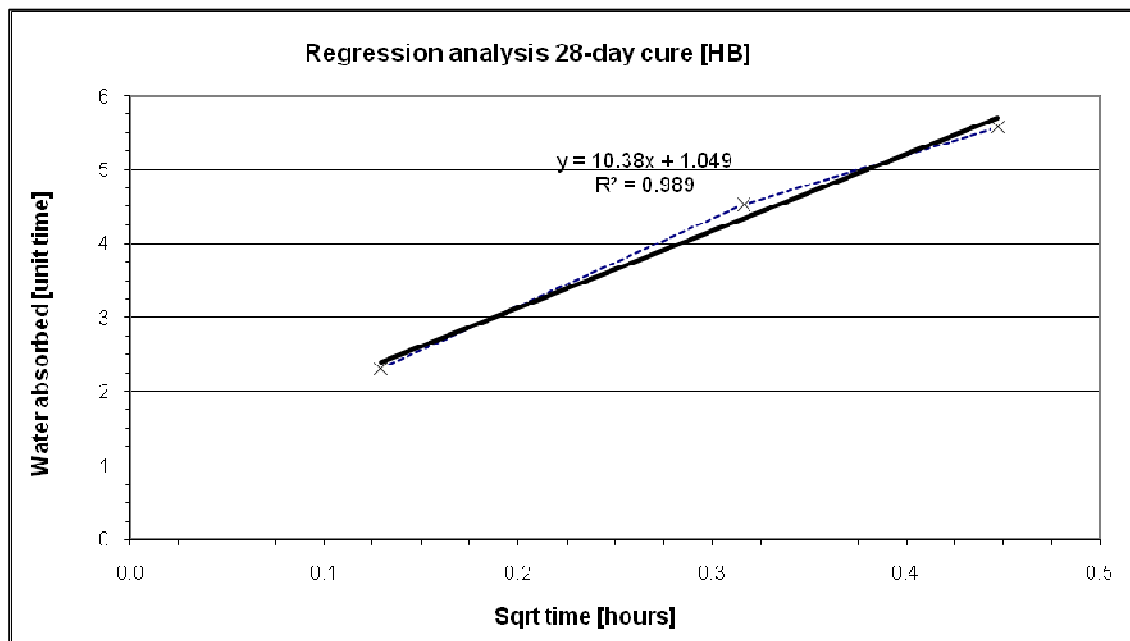
Water – Sorptivity calculations on concrete cured for 28 days

Preparation	Hand (Manual) Wire Brush				
Test date	12.04.99				
Sample ID	1.5.3				
Sample thickness [mm] d =	23.9				
	25.3				
	24.7				
	24.6				
Average thickness [mm] d =	24.6				
Oven dry mass [g] Mo =	513.70				
Sat. wet mass [g] Msv =	539.21				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	513.79				
1	516.10	0.1	2.31	0.1	2.31
6	518.32	0.3	4.53	0.3	4.53
12	519.37	0.4	5.58	0.4	5.58
20	520.24	0.6	6.45		
Slope [g/ $\sqrt{\text{hrs}}$] F =		9.25		10.39	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		8.96		10.06	
Correlation coefficient R ² =		0.981		0.989	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



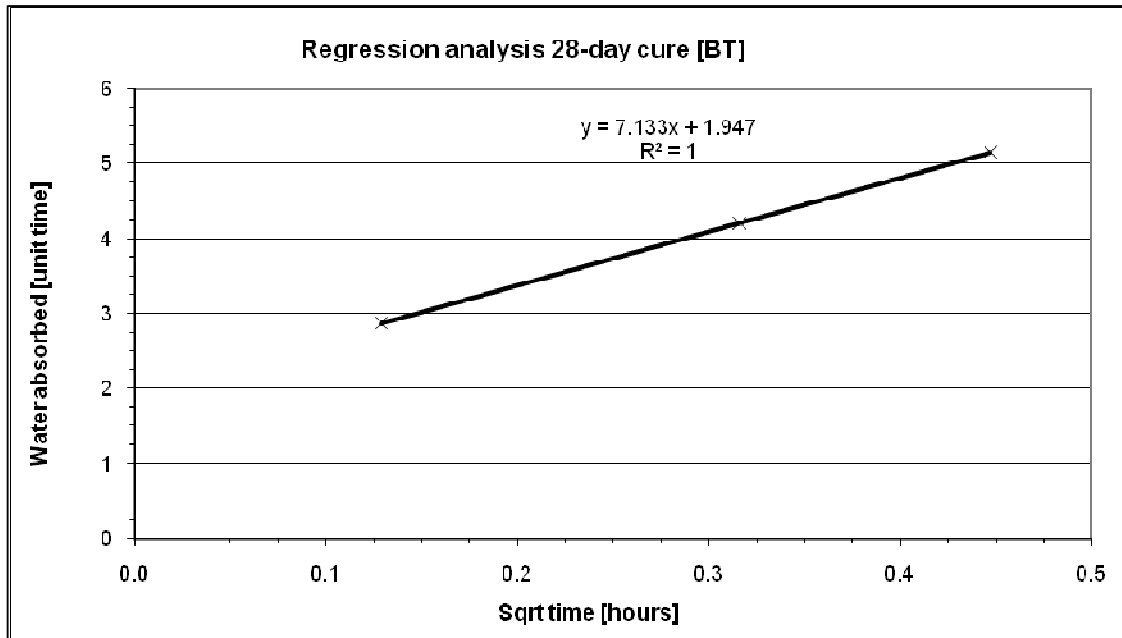
Water – Sorptivity calculations on concrete cured for 28 days

Preparation	Bushing Tool				
Test date	13.04.99				
Sample ID	1.5.6				
Sample thickness [mm] d =	25.4				
	25.5				
	24.4				
	25.1				
Average thickness [mm] d =	25.1				
Oven dry mass [g] Mo =	504.42				
Sat. wet mass [g] Msv =	529.52				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	504.48				
1	507.35	0.1	2.87	0.1	2.87
6	508.68	0.3	4.20	0.3	4.20
12	509.62	0.4	5.14	0.4	5.14
20	510.22	0.6	5.74		
Slope [g/ $\sqrt{\text{hrs}}$] F =		6.51		7.13	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		6.53		7.15	
Correlation coefficient R ² =		0.992		1.000	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



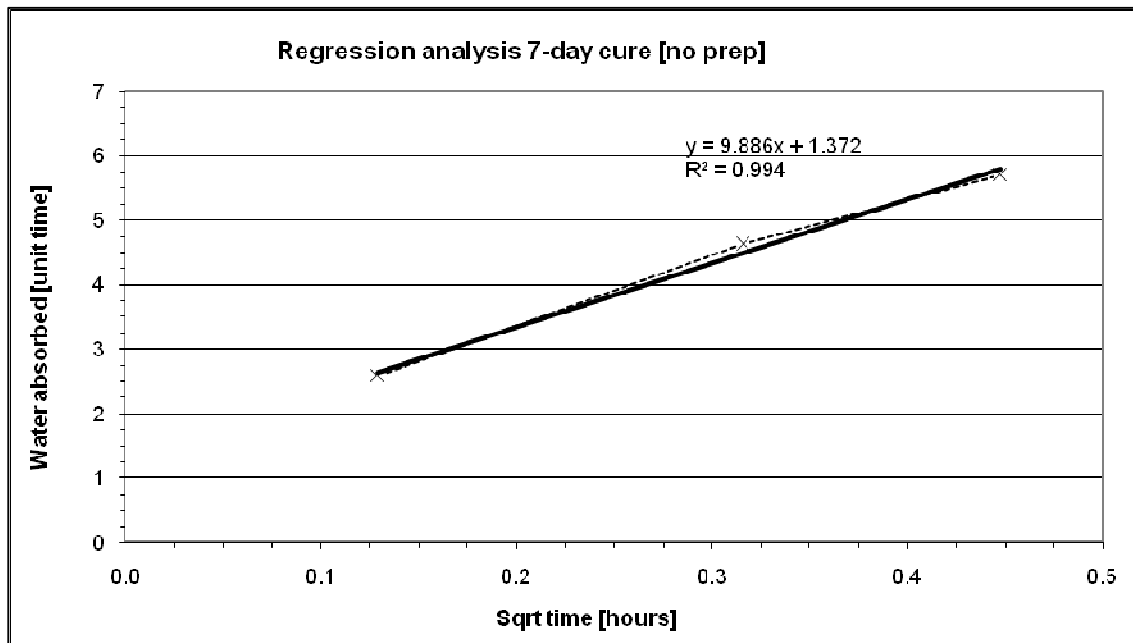
Water - Sorptivity calculations on concrete cured for 7 days

Preparation	none				
Test date	12.04.99				
Sample ID	2.2.3				
Sample thickness [mm] d =	24.5				
	24.8				
	24.9				
	23.9				
Average thickness [mm] d =	24.5				
Oven dry mass [g] Mo =	469.70				
Sat. wet mass [g] Msv =	494.34				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	469.82				
1	472.41	0.1	2.59	0.1	2.59
6	474.46	0.3	4.64	0.3	4.64
12	475.53	0.4	5.71	0.4	5.71
20	476.4	0.6	6.58		
Slope [g/ $\sqrt{\text{hrs}}$] F =		8.93		9.89	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		8.93		9.89	
Correlation coefficient R ² =		0.987		0.994	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



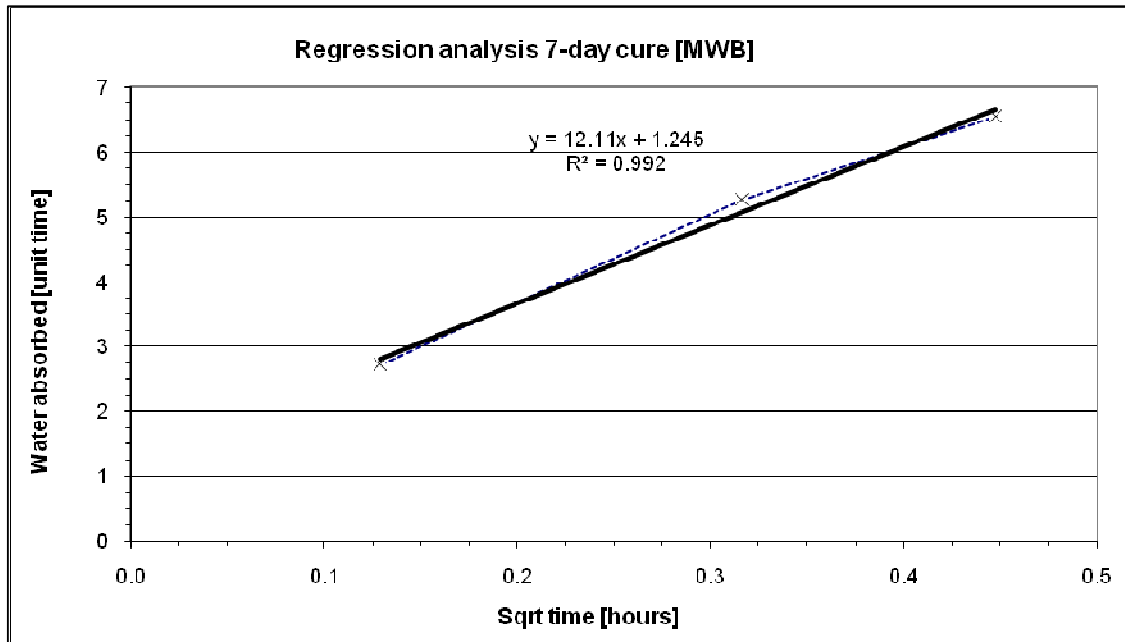
Water - Sorptivity calculations on concrete cured for 7 days

Preparation	Mechanical Wire Brush				
Test date	12.04.99				
Sample ID	2.2.6				
Sample thickness [mm] d =	24.5				
	24.3				
	25.0				
	25.0				
Average thickness [mm] d =	24.7				
Oven dry mass [g] Mo =	501.95				
Sat. wet mass [g] Msv =	530.67				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	502.08				
1	504.81	0.1	2.73	0.1	2.73
6	507.35	0.3	5.27	0.3	5.27
12	508.63	0.4	6.55	0.4	6.55
20	509.50	0.6	7.42		
Slope [g/ $\sqrt{\text{hrs}}$] F =		10.55		12.12	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		9.11		10.47	
Correlation coefficient R ² =		0.977		0.992	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



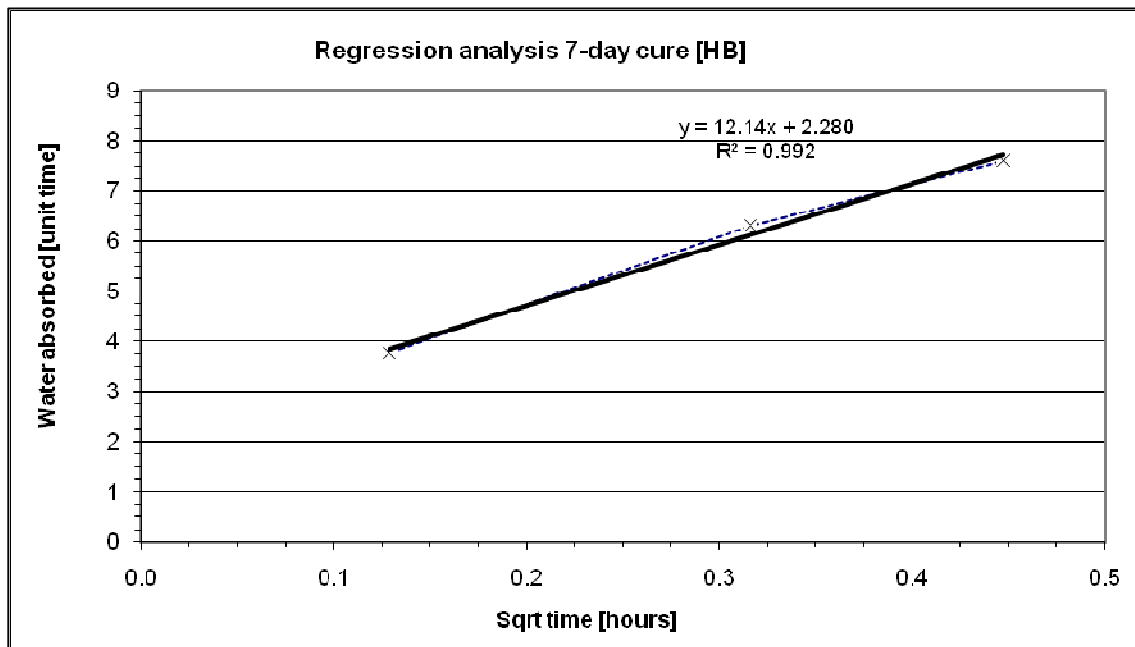
Water - Sorptivity calculations on concrete cured for 7 days

Preparation	Hand (Manual) Wire Brush				
Test date	13.04.99				
Sample ID	2.6.3				
Sample thickness [mm] d =	25.1				
	25.1				
	24.8				
	25.1				
Average thickness [mm] d =	25.0				
Oven dry mass [g] Mo =	537.30				
Sat. wet mass [g] Msv =	563.49				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	537.41				
1	541.18	0.1	3.77	0.1	3.77
6	543.72	0.3	6.31	0.3	6.31
12	545.01	0.4	7.60	0.4	7.60
20	545.82	0.6	8.41		
Slope [g/ $\sqrt{\text{hrs}}$] F =		10.46		12.14	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		10.04		11.65	
Correlation coefficient R ² =		0.974		0.992	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



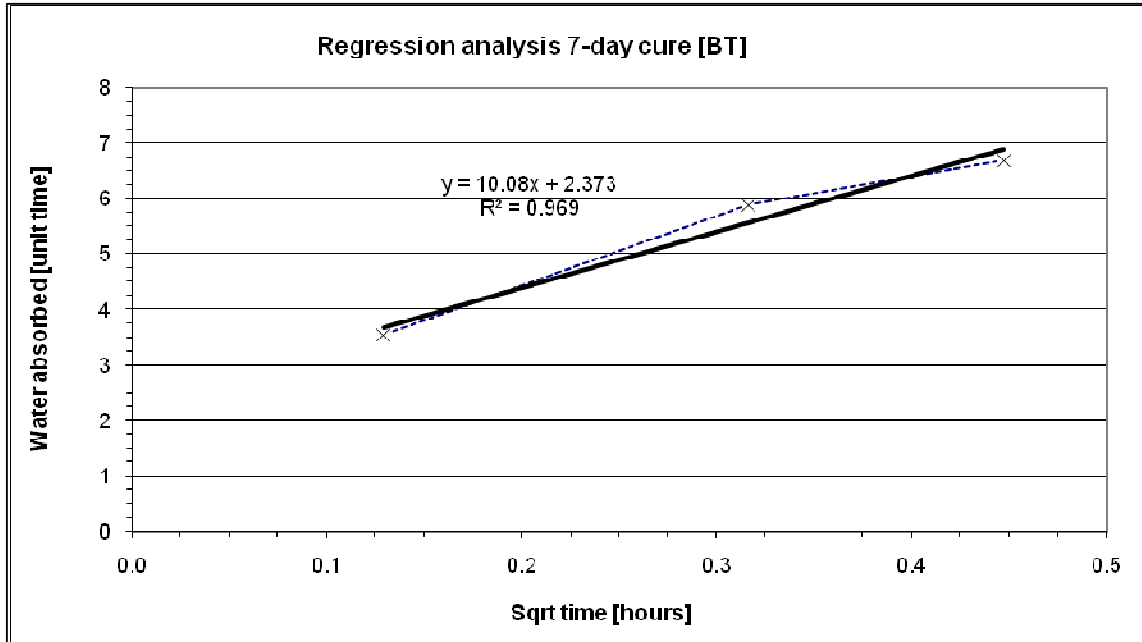
Water - Sorptivity calculations on concrete cured for 7 days

Preparation	Bushing Tool				
Test date	13.04.99				
Sample ID	2.6.6				
Sample thickness [mm] d =	25.8				
	25.8				
	25.7				
	25.7				
Average thickness [mm] d =	25.8				
Oven dry mass [g] Mo =	511.75				
Sat. wet mass [g] Msv =	536.44				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	511.81				
1	515.35	0.1	3.54	0.1	3.54
6	517.70	0.3	5.89	0.3	5.89
12	518.50	0.4	6.69	0.4	6.69
20	519.46	0.6	7.65		
Slope [g/ $\sqrt{\text{hrs}}$] F =		9.04		10.08	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		9.45		10.54	
Correlation coefficient R ² =		0.971		0.969	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



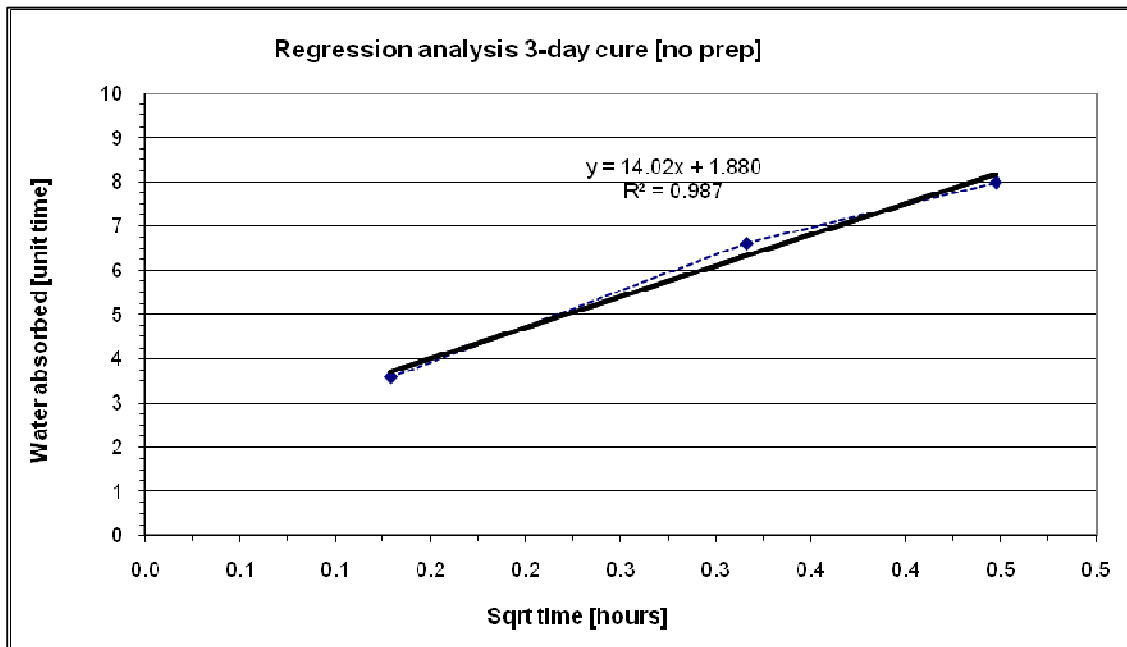
Water - Sorptivity calculations on concrete cured for 3 days

Preparation	none				
Test date	12.04.99				
Sample ID	3.3.3				
Sample thickness [mm] d =	24.1				
	24.7				
	24.3				
	24.5				
Average thickness [mm] d =	24.4				
Oven dry mass [g] Mo =	506.30				
Sat. wet mass [g] Msv =	533.33				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	506.45				
1	510.02	0.1	3.57	0.1	3.57
6	513.06	0.3	6.61	0.3	6.61
12	514.43	0.4	7.98	0.4	7.98
20	515.14	0.6	8.69		
Slope [g/ $\sqrt{\text{hrs}}$] F =		11.56		14.03	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		10.50		12.73	
Correlation coefficient R ² =		0.954		0.987	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



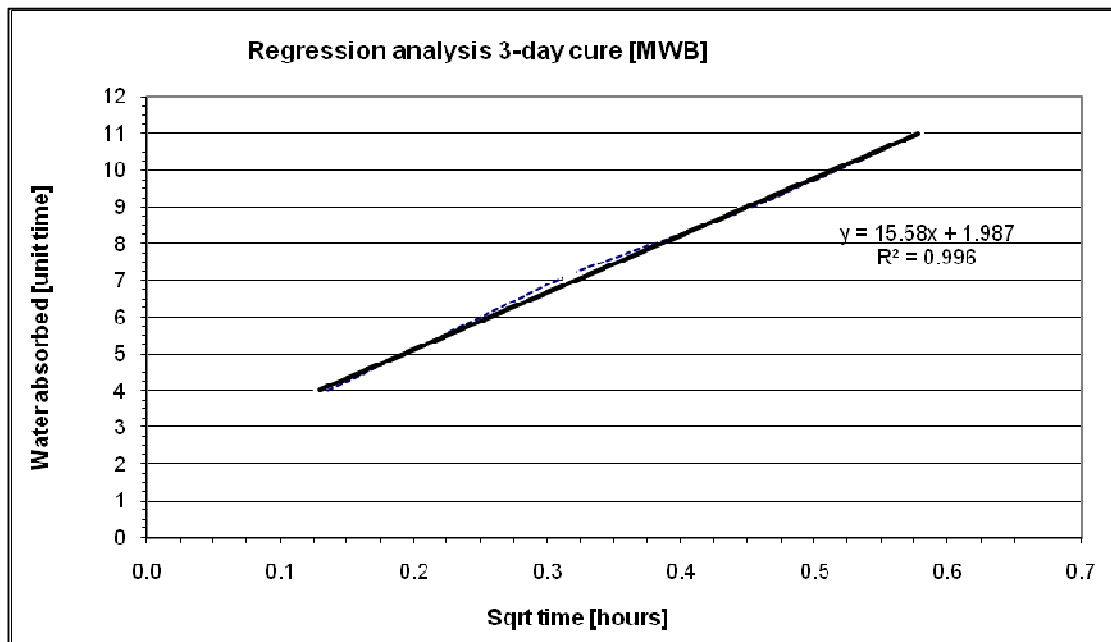
Water - Sorptivity calculations on concrete cured for 3 days

Preparation	Mechanical Wire Brush				
Test date	12.04.99				
Sample ID	3.3.6				
Sample thickness [mm] d =	25.1				
	25.0				
	25.3				
	25.2				
Average thickness [mm] d =	25.2				
Oven dry mass [g] Mo =	501.09				
Sat. wet mass [g] Msv =	527.98				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	501.16				
1	505.04	0.1	3.88	0.1	3.88
6	508.32	0.3	7.16	0.3	7.16
12	510.04	0.4	8.88	0.4	8.88
20	512.10	0.6	10.94		
Slope [g/ $\sqrt{\text{hrs}}$] F =		15.59		15.84	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		14.62		14.86	
Correlation coefficient R ² =		0.996		0.994	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



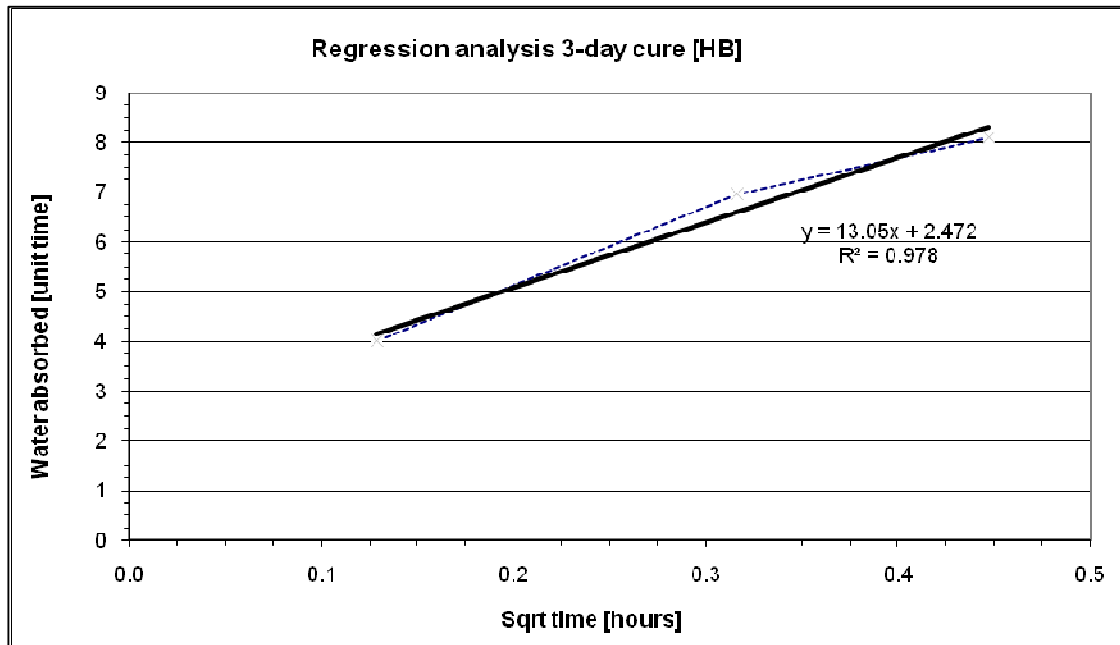
Water - Sorptivity calculations on concrete cured for 3 days

Preparation	Hand (Manual) Wire Brush				
Test date	13.04.99				
Sample ID	3.4.3				
Sample thickness [mm] d =	25.4				
	25.1				
	25.1				
	25.3				
Average thickness [mm] d =	25.2				
Oven dry mass [g] Mo =	496.64				
Sat. wet mass [g] Msv =	521.21				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	496.74				
1	500.75	0.1	4.01	0.1	4.01
6	503.70	0.3	6.96	0.3	6.96
12	504.84	0.4	8.10	0.4	8.10
20	505.06	0.6	8.32		
Slope [g/ $\sqrt{\text{hrs}}$] F =		9.83		13.06	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		10.13		13.46	
Correlation coefficient R ² =		0.899		0.978	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



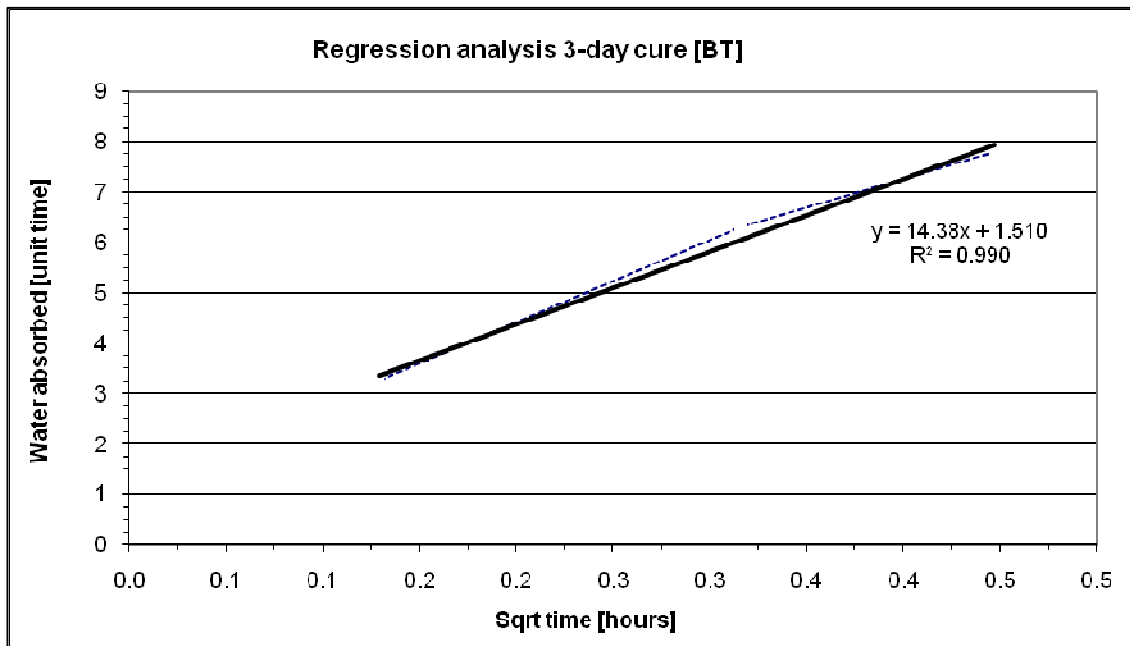
Water - Sorptivity calculations on concrete cured for 3 days

Preparation	Bushing Tool				
Test date	13.04.99				
Sample ID	3.4.6				
Sample thickness [mm] d =	25.6				
	25.7				
	25.2				
	25.4				
Average thickness [mm] d =	25.5				
Oven dry mass [g] Mo =	488.61				
Sat. wet mass [g] Msv =	516.56				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	488.68				
1	491.94	0.1	3.26	0.1	3.26
6	495.00	0.3	6.32	0.3	6.32
12	496.47	0.4	7.79	0.4	7.79
20	497.25	0.6	8.57		
Slope [g/ $\sqrt{\text{hrs}}$] F =		12.01		14.38	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		10.97		13.14	
Correlation coefficient R ² =		0.961		0.990	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



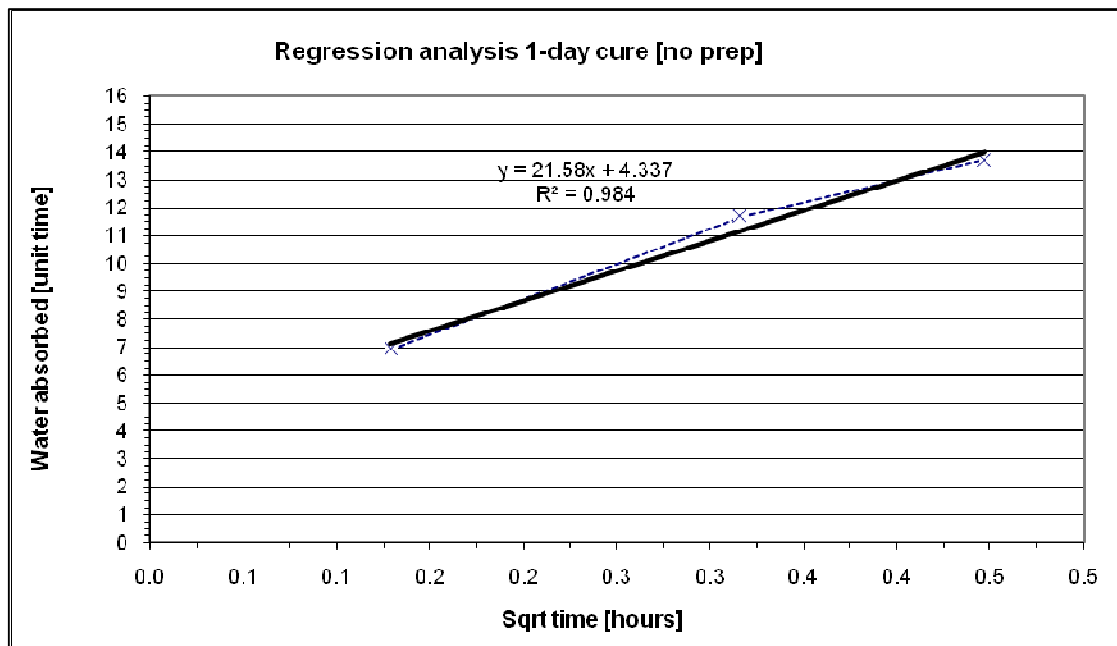
Water - Sorptivity calculations on concrete cured for 1 days

Preparation	none				
Test date	12.04.99				
Sample ID	4.2.3				
Sample thickness [mm] d =	24.6				
	24.5				
	24.3				
	24.2				
Average thickness [mm] d =	24.4				
Oven dry mass [g] Mo =	462.66				
Sat. wet mass [g] Msv =	494.98				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	462.81				
1	469.73	0.1	6.92	0.1	6.92
6	474.47	0.3	11.66	0.3	11.66
12	476.51	0.4	13.70	0.4	13.70
20	477.77	0.6	14.96		
Slope [g/ $\sqrt{\text{hrs}}$] F =		18.07		21.59	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		13.71		16.37	
Correlation coefficient R ² =		0.958		0.984	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



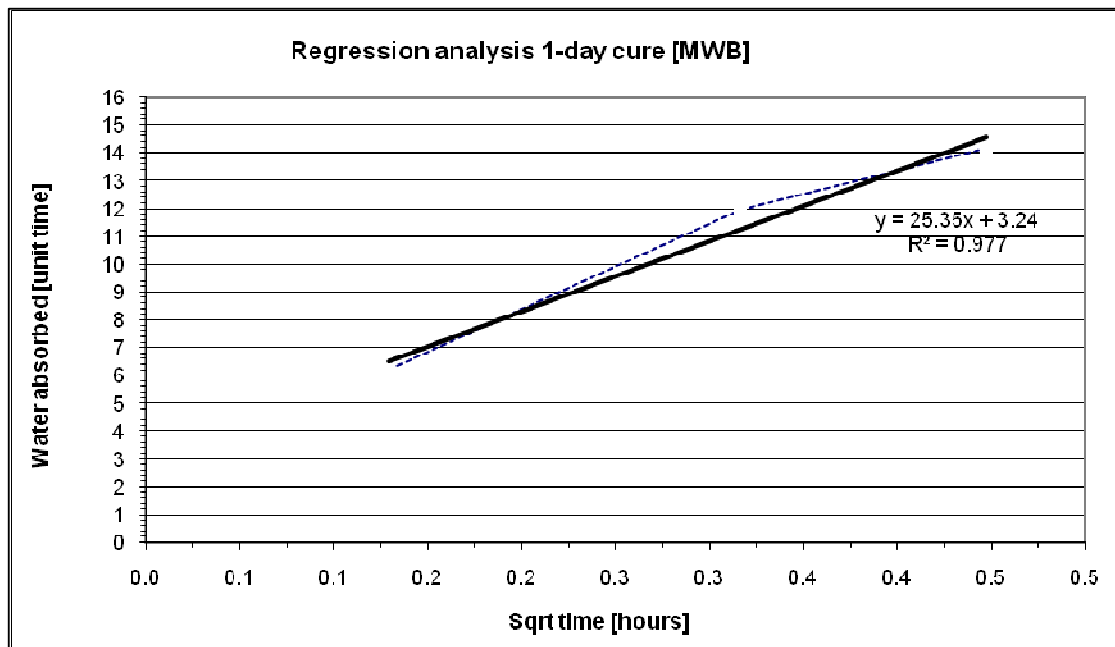
Water - Sorptivity calculations on concrete cured for 1 days

Preparation	Mechanical Wire Brush					
Test date	12.04.99					
Sample ID	4.2.5					
Sample thickness [mm] d =	25.8					
	25.6					
	24.3					
	24.3					
Average thickness [mm] d =	25.0					
Oven dry mass [g] Mo =	641.24					
Sat. wet mass [g] Msv =	678.59					
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]	
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =	
0	641.34					
1	647.56	0.1	6.22	0.1	6.22	
6	653.31	0.3	11.97	0.3	11.97	
12	655.50	0.4	14.16	0.4	14.16	
20	656.31	0.6	14.97			
Slope [g/ $\sqrt{\text{hrs}}$] F =		19.80		25.35		
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		13.29		17.02		
Correlation coefficient R ² =		0.921		0.977		

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



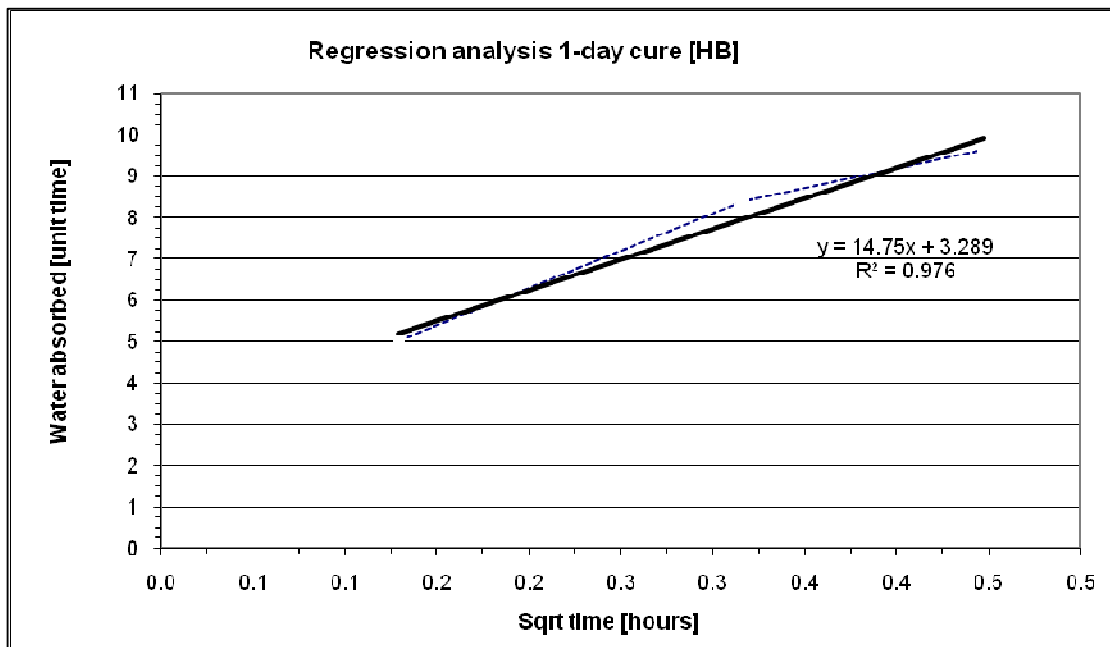
Water - Sorptivity calculations on concrete cured for 1 days

Preparation	Hand (Manual)					
	Wire Brush					
Test date	13.04.99					
Sample ID	4.6.3					
Sample thickness [mm] d =	25.3					
	25.2					
	25.4					
	24.7					
Average thickness [mm] d =	25.2					
Oven dry mass [g] Mo =	485.08					
Sat. wet mass [g] Msv =	513.25					
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]	
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =	
0	485.19					
1	490.21	0.1	5.02	0.1	5.02	
6	493.57	0.3	8.38	0.3	8.38	
12	494.83	0.4	9.64	0.4	9.64	
20	495.56	0.6	10.37			
Slope [g/ $\sqrt{\text{hrs}}$] F =		12.01		14.76		
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		10.76		13.23		
Correlation coefficient R ² =		0.941		0.976		

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



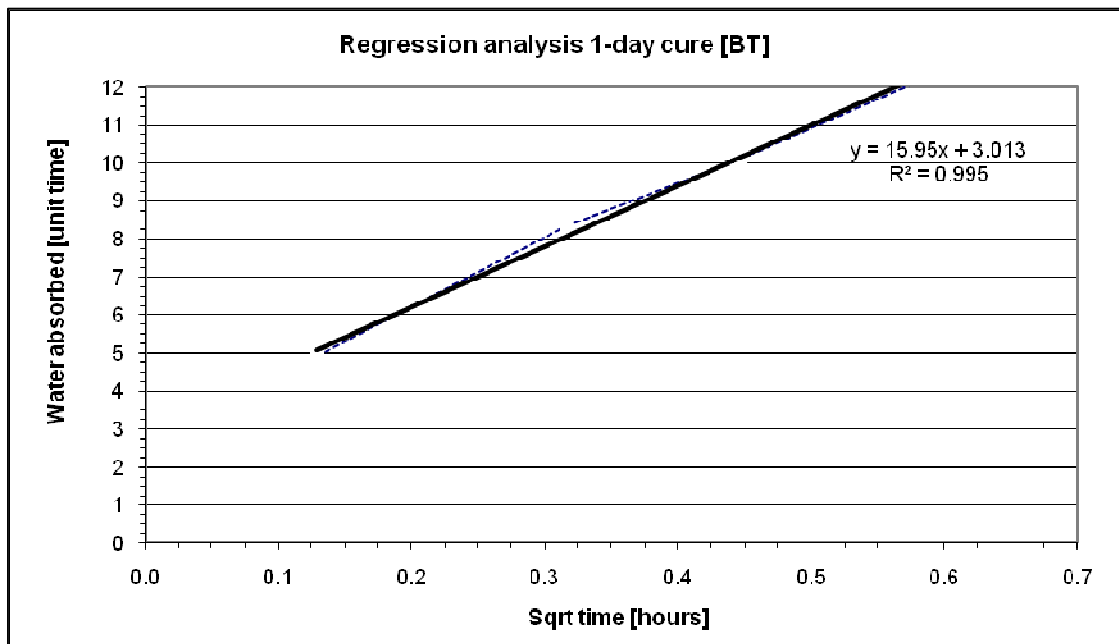
Water - Sorptivity calculations on concrete cured for 1 days

Preparation	Bushing Tool				
Test date	13.04.99				
Sample ID	4.6.6				
Sample thickness [mm] d =	25.9				
	25.8				
	25.7				
	25.7				
Average thickness [mm] d =	25.8				
Oven dry mass [g] Mo =	501.80				
Sat. wet mass [g] Msv =	530.01				
Time [min]	Mass [g]	Time [hrs]	Mass [g]	Time [hrs]	Mass [g]
t =	Mst =	$\sqrt{t}$ =	Mwt =	$\sqrt{t}$ =	Mwt =
0	501.88				
1	506.79	0.1	4.91	0.1	4.91
6	510.23	0.3	8.35	0.3	8.35
12	512.00	0.4	10.12	0.4	10.12
20	514.00	0.6	12.12		
Slope [g/ $\sqrt{\text{hrs}}$] F =		15.95		16.52	
Sorptivity [mm/ $\sqrt{\text{hrs}}$] S =		14.62		15.13	
Correlation coefficient R ² =		0.995		0.993	

where Mwt = Mst - Mso

where F = Mwt/ $\sqrt{t}$

where S = (F.d)/(Msv - Mso)



E. Adhesion Test Results

The individual test results expressed in N/mm^2 are detailed in the tables below. The results for the mode of failure are summarised in Tables 12 and 13 of the report with the adhesion strengths illustrated graphically in Figures 32 to 37.

TABLE E1: Bond strength and mode of failure for the elastomeric coating

Time from application to adhesion test	4-weeks			16-weeks		
	Bond strength	Average strength	Type of failure	Bond strength	Average strength	Type of failure
	N/mm ²			N/mm ²		
Concrete curing time	No preparation					
1-day	1.1; 1.2	1.15	I; I	1.2; 1.1; 1.5	1.27	I; S; S
3-day	1.1; 1.1	1.10	I; I	1.3; 1.5; 1.5	1.43	I; I; I
7-day	1.5; 1.8	1.65	I; I	1.6; 1.8; 1.8	1.73	I; I; I
28-day	1.5; 1.5	1.50	I; I	1.9; 1.2; 1.7	1.60	I; I; I
	Bushing tool					
1-day	1.0; 1.0	1.00	I; I	1.0; 1.2; 1.2	1.13	S; S; S
3-day	1.1; 1.1	1.10	I; I	1.3; 1.2; 1.3	1.27	I; I; I
7-day	1.2; 1.2	1.20	I; I	1.9; 1.5; 1.5	1.63	I; I; I
28-day	1.5; 1.3	1.40	I; I	1.5; 2.0; 1.7	1.73	I; I; S
	Mechanical wire brush					
1-day	1.1; 1.1	1.10	I; I	2.1; 2.2; 2.3	2.20	I; I; S
3-day	1.2; 1.4	1.30	I; I	2.5; 2.0; 2.0	2.17	I; I; I
7-day	1.6; 1.6	1.60	I; I	1.9; 2.0; 2.0	1.97	I; I; I
28-day	2.1; 1.9	2.00	I; I	2.5; 2.0; 2.0	2.17	I; I; I
	Hand wire brush					
1-day	1.1; 1.3	1.20	I; I	1.9; 1.5; 2.0	1.80	I; S; S
3-day	1.4; 1.6	1.50	I; I	2.3; 2.0; 2.2	2.17	I; I; I
7-day	1.4; 1.6	1.50	I; I	2.1; 2.1; 2.1	2.10	I; I; I
28-day	2.0; 1.6	1.80	I; I	2.0; 2.0; 2.1	2.03	I; I; I

TABLE E2: Bond strength and mode of failure for the aliphatic coating

Time from application to adhesion test	4-weeks			16-weeks		
	Bond strength	Average strength	Type of failure	Bond strength	Average strength	Type of failure
	N/mm ²			N/mm ²		
Concrete curing time	No preparation					
1-day	1.2; 1.4	1.30	S; S	1.8; 2.0; 2.0	1.93	S; S; S
3-day	1.5; 1.7	1.60	I; I	1.6; 1.7; 1.7	1.67	I; I; I
7-day	1.9; 2.5	2.20	I; I	2.0; 2.1; 2.4	2.17	I; I; I
28-day	2.0; 2.0	2.00	I; I	2.1; 1.9; 1.9	1.95	I; I; I
	Bushing tool					
1-day	1.1; 1.0	1.05	S; S	1.2; 1.2; 1.1	1.17	S; S; S
3-day	1.5; 1.5	1.50	I; I	2.5; 2.0; 1.9	2.13	I; I; S
7-day	1.7; 1.7	1.70	I; I	1.8; 1.7; 1.9	1.80	I; I; I
28-day	1.6; 1.9	1.75	I; I	2.0; 2.1; 2.1	2.07	I; S; S
	Mechanical wire brush					
1-day	1.9; 1.5	1.70	S; S	1.9; 2.0; 2.2	2.03	S; S; S
3-day	1.9; 1.7	1.80	S; S	1.9; 1.8; 2.1	1.93	S; S; S
7-day	1.9; 2.0	1.95	I; I	2.2; 2.2; 2.0	2.13	S; S; S
28-day	2.0; 1.8	1.90	I; I	2.0; 1.9; 1.9	1.93	I; S; S
	Hand wire brush					
1-day	2.0; 1.8	19.0	S; S	1.8; 1.9; 2.0	1.90	S; S; S
3-day	1.8; 2.0	19.0	S; S	2.1; 2.0; 1.9	2.00	S; S; S
7-day	2.0; 1.8	19.0	I; I	1.9; 1.7; 2.4	2.00	S; S; S
28-day	1.9; 1.7	18.0	I; I	2.2; 2.1; 2.5	2.27	S; S; S

TABLE E3: Bond strength and mode of failure for the epoxy resin based coating

Time from application to adhesion test	4-weeks			16-weeks		
	Bond strength	Average strength	Type of failure	Bond strength	Average strength	Type of failure
	N/mm ²			N/mm ²		
Concrete curing time	No preparation					
1-day	1.1; 1.2	1.15	S; S	1.9; 1.7;1.5	1.70	I; I S
3-day	1.3; 1.5	1.40	S; S	2.0; 2.0; 1.7	1.90	I; S; S
7-day	1.4; 1.4	1.40	I; I	2.0; 2.1; 2.0	2.03	I; I; I
28-day	1.3; 1.3	1.30	I; I	1.6; 1.4; 1.5	1.50	I; I; I
	Bushing tool					
1-day	2.0; 1.1	1.55	I; I	1.7; 1.8; 1.5	1.67	S; S; S
3-day	1.1; 2.0	1.55	I; I	1.7; 2.0; 1.8	1.83	I; S; S
7-day	1.5; 1.3	1.40	I; I	2.0; 2.0; 2.0	2.00	I; I; I
28-day	1.4; 1.9	1.65	I; I	2.4; 2.0; 1.9	2.10	S; S; S
	Mechanical wire brush					
1-day	1.5; 1.9	1.70	I; I	1.7; 1.8; 1.7	1.73	S; S; S
3-day	1.8; 1.9	1.70	I; I	2.0; 2.1; 2.0	2.03	S; S; S
7-day	1.4; 1.4	1.40	I; I	1.7; 2.2; 1.9	1.93	I; I; I
28-day	1.7; 1.9	1.80	I; I	2.4; 2.0; 2.2	2.20	I; I; I
	Hand wire brush					
1-day	2.2; 2.0	2.10	S; S	2.0; 1.6; 1.8	1.80	S; S; S
3-day	2.0; 1.5	1.75	S; S	1.9; 2.0; 1.8	1.90	I; I; S
7-day	1.5; 1.5	1.50	I; I	2.8; 2.7; 2.9	2.80	I; I; I
28-day	2.0; 1.8	1.90	I; I	2.1; 2.0; 2.0	2.03	I; I; I

TABLE E4: Bond strength and mode of failure for the cementitious based coating

Time from application to adhesion test	4-weeks			16-weeks		
	Bond strength	Average strength	Type of failure	Bond strength	Average strength	Type of failure
	N/mm ²			N/mm ²		
Concrete curing time	No preparation					
1-day	1.6; 1.5	1.55	C; C	1.7; 1.9; 1.5	1.70	I; I; I
3-day	1.5; 1.7	1.60	C; C	1.6; 2.5 2.1	2.07	I; I; I
7-day	1.8; 1.8	1.80	C; C	2.1; 1.7; 2.1	1.97	I; I; I
28-day	1.7; 1.7	1.70	C; C	2.1; 1.9; 2.1	2.03	I; S; S
	Bushing tool					
1-day	1.9; 1.7	1.80	C; C	1.7; 1.8; 2.0	1.87	I; I; I
3-day	2.0; 1.4	1.70	C; C	1.4; 1.5; 1.4	1.43	I; I; I
7-day	1.4; 2.0	1.70	C; C	1.4; 1.7; 1.5	1.53	I; I; S
28-day	1.9; 1.8	1.85	C; C	1.4; 1.6; 1.5	1.50	I; I; S
	Mechanical wire brush					
1-day	1.3; 1.5	1.40	C; C	2.1; 2.0; 2.0	2.03	I; I; I
3-day	1.5; 1.7	1.60	C; C	2.2; 1.9; 2.0	2.03	I; I; I
7-day	1.5; 1.6	1.55	C; C	2.0; 2.4; 2.0	2.13	I; I; I
28-day	1.8; 1.9	1.85	C; C	2.0; 2.0; 2.0	2.00	I; I; I
	Hand wire brush					
1-day	1.8; 1.2	1.50	C; C	2.0; 2.5; 2.3	2.27	I; I; I
3-day	1.2; 2.0	1.60	C; C	2.3; 2.3; 2.1	2.23	I; I; I
7-day	1.2; 1.9	1.55	C; C	1.8; 2.6 2.2	1.87	I; I; I
28-day	1.2; 1.5	1.35	C; C	2.0; 2.1; 2.7	2.27	I; I; I

TABLE E5: Bond strength and mode of failure for the masonry paint

Time from application to adhesion test	4-weeks			16-weeks		
	Bond strength	Average strength	Type of failure	Bond strength	Average strength	Type of failure
	N/mm ²			N/mm ²		
Concrete curing time	No preparation					
1-day	1.1; 1.2	1.15	S; S	1.7; 1.6; 1.9	1.73	I; I; I
3-day	1.1; 1.1	1.10	I; I	1.9; 1.8; 1.4	1.70	I; I; I
7-day	1.5; 1.2	1.35	I; I	1.9; 1.8; 1.9	1.87	I; I; I
28-day	1.1; 1.1	1.10	I; I	1.9; 1.9; 1.4	1.73	I; I; S
	Bushing tool					
1-day	1.0; 1.0	1.00	S; S	1.0; 1.1; 1.1	1.07	S; S; S
3-day	1.0; 1.0	1.00	I; I	1.5; 1.5; 1.6	1.53	I; I; I
7-day	1.0; 1.0	1.00	I; I	1.5; 1.4; 2.0	1.63	I; I; I
28-day	1.5; 1.2	1.35	I; I	1.5; 1.5; 1.5	1.50	I; I; S
	Mechanical wire brush					
1-day	1.4; 1.4	1.40	S; S	1.6; 1.5; 1.2	1.43	S; S; S
3-day	1.6; 1.5	1.55	I; I	2.0; 1.9; 1.9	1.93	S; S; S
7-day	1.6; 2.0	1.80	I; I	2.1; 2.0; 2.5	2.20	I; S; S
28-day	1.9; 2.0	1.95	I; I	1.9; 1.9; 1.9	1.90	I; I; I
	Hand wire brush					
1-day	1.2; 1.4	1.30	S; S	1.7; 1.4; 1.4	1.50	I; S; S
3-day	2.0; 1.9	1.95	I; I	2.0; 1.8; 2.4	2.07	I; I; S
7-day	2.1; 1.8	1.95	I; I	1.9; 2.2; 2.0	2.03	I; S; S
28-day	1.9; 1.8	1.85	I; I	2.0; 1.9; 1.7	1.87	I; I; I