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Minor Dissertation

Concrete surface coatings and the influence of substrate moisture condition on bond strength

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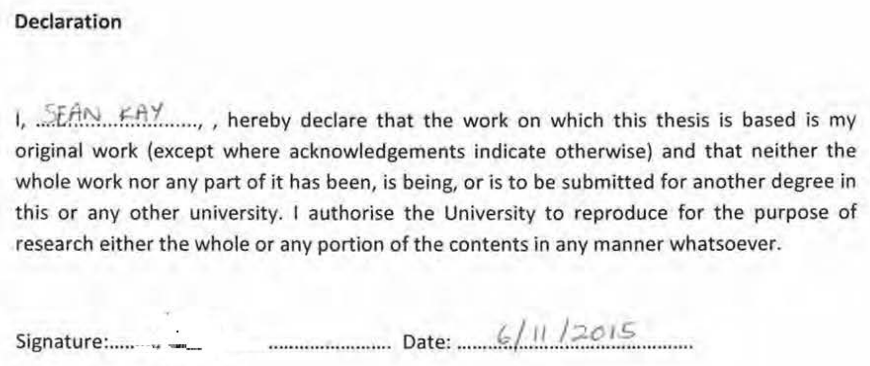
Contents

Plagiarism declaration



Declaration

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Abstract

Concrete structures, in particular reinforced concrete structures, have been designed and built for many years. Many previously built structures are now being compromised with regard to their condition and structural integrity. There has developed a need to maintain these structures and protect them in order to protect the users and minimise the expenses associated with repair and maintenance. Instead of resorting to demolishing and rebuilding, engineers are becoming increasingly capable of restoring and enhancing existing structures in order to maximise the original structures lifespan. One of the ways in which this is achieved is through the implementation of various repair and maintenance strategies. These strategies can range from cathodic protection of the steel reinforcement to increasing concrete cover of the section. The easiest and often most commonly used method, although often not effective when used on its own, is to coat the concrete surface with a protective coating. There are many coatings available, ranging from simple to complex formulations of inorganic and organic materials. These coatings each perform a unique function and will often be designed to combat a specific problem with which the structure is to be exposed. The formulation of the coatings are almost always designed correctly when they are manufactured, however, premature bond failure due to poor substrate surface preparation and various substrate moisture conditions still seem to occur after coating application.

This investigation will give insight into the effects a sound, clean and profiled concrete substrate that is subjected to different moisture conditions will have on the bond strength achieved when using cementitious based coatings. The reason for differing the moisture conditions of the substrate is that often on site the moisture condition of an existing substrate is not known prior to application of the coating. This investigation shows that epoxy modified cementitious coatings provide acceptable bond strength. In some cases, failure within the coating instead of the acceptable failure within the substrate has resulted, due only to the level of dryness of the substrate. A thorough investigation on the theory behind surface coatings, their properties and performance requirements was done and subsequently followed by a detailed experimental programme that was performed and analysed to provide insight to the said coating behaviour.

Inorganic coatings behave more predictably when applied to moist substrates as this is the ideal condition for the coating to adequately hydrate. In almost all the specimens with fully dried substrates, the resulting bond strength of the coating was less than that observed with the saturated surface dry substrate condition. It is therefore advised that the moisture condition stated by the coating manufacturer be adhered to as this will give acceptable results with failure taking place within the concrete substrate and not within the coating as a failure of the latter is completely unacceptable when referenced to the European and American set of standards. The European standard BS EN 1504: Products and systems for the protection and repair of concrete structures provide a more complete and reliable framework for the concrete repair industry and hence is preferred over any South African national standard currently available. Further research into the viability of a South African based standard will need to be investigated before being considered for use in this research paper.

List of symbols and acronyms

m/c: moisture condition
SSD: Saturated surface dry
*xyz: x indicates coating number, y indicates substrate moisture condition and z indicates substrate strength.
A: Tensile (cohesion) failure in the concrete substrate
A/B: Bond (adhesion) failure at the interface between the substrate and the repair material (product)
B: Tensile (cohesion) failure in the repair material (product)
B/Y: Bond (adhesion) failure at the interface between the repair material (product) and the adhesive layer.
Y: Tensile (cohesion) failure in the adhesive layer
Y/Z: Bond (adhesion) failure between the adhesive layer and the test dolly.
Z: Failure of the test dolly or apparatus
SS: Sum of squares
MS: Mean squares

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1. Introduction and Problem Statement

1.1. Background

Concrete elements, if designed and constructed correctly can last for their entire lifespan without the need for additional protection against the environment within which they are to be exposed. However, due to many unforeseen circumstances the elements may need this protection in order to maintain their structural integrity and overall appeal. Unforeseen circumstances can be a result of a lack of supervision during the construction phase of the element, inadequate element design size (resulting in low cover depth to reinforcement) due to a more aggressive environment, accidental damage, changes in the ambient conditions surrounding the element, inferior material quality used, as well as increased loads imposed onto the element during and after its construction, to name a few. Surface coatings can be and are in some cases the easiest and usually cheapest option for protecting these concrete elements from the environment they are exposed to, in addition to protective coatings they may be decorative. This being said implies that if the coating is compatible with the concrete surface and is sufficiently resilient to the environment it is to be exposed to, it will effectively allow the element to remain intact (provided the coating has been carefully designed to combat that specific the environment, for example the coating may need to protect the reinforced concrete element from a particular chemical attack). The structural integrity can also be maintained using various surface coatings that involve reinforced membranes but this is out of the scope of this research and as such will not be considered. The function or intended function of the surface coating will also not be a focal point for this research as the intent is not to provide verification of the coatings ability to function but rather on its ability to adhere to the concrete substrate to which it is applied. The preparation of the concrete substrate and its condition prior to the application of various surface coatings is the key to this investigation as well as to evaluate the effect (if any) of obtaining a substrate that is saturated but surface dry prior to coating application. Similar research has been done before, but the immediate coating of a prepared substrate (after 28 day moist curing) has, to the knowledge of the author, not been evaluated. Benn (2008) used specimens that had been cured at various levels and had been left exposed to the Johannesburg Highveld climate for a year prior to any testing, this investigation resulted in an increase in coating adhesion as the quality (achieved through good quality curing) of the host concrete surfaces increased. Previous investigations with regard to bonded overlays have also been done at the University of Cape Town by Talotti (2014). He investigated the influence of substrate moisture preparation on concrete overlay bond strength and found that saturated surface dry concrete, which is typically specified for bonded overlay application, had no beneficial influence on bond strength. In some instances the effect had a negative influence on the bond strength when compared to the drier substrate specimens.

1.2. Research Focus

The overall focus of this research is to establish a specification for each of the chosen coatings with regard to ideal concrete substrate surface preparation as well as to investigate the effect of pre-wetting the concrete substrate in order to achieve a saturated surface dry condition prior to application of the chosen coatings. The coatings were both the inorganic and organic types (where possible) and are specified further into the proposal.

Available methods for surface profiling and preparation were used for the experimental part of this research and were in line with common construction practices in order to improve the practicality of the results. The notion that the concrete substrate should have a minimum compressive strength of 25 MPa and a minimum substrate cohesive strength of 1.5 MPa (Sika, 2004) in order to be successfully coated will also be assessed in this investigation with preference given to the compressive strength. The main focus of the research was the effective bond strength created by each of the chosen coating systems and the corresponding influences of the concrete substrates to which they were applied.

1.3. Research Aim

The aim of this research is to investigate the effects different concrete substrate preparation methods (done according to a standard such as EN 1504), different concrete substrate qualities, and the effect of pre-wetting the concrete substrate on the bond strength achieved. The results were documented and analysed in order to link the findings to relevant theory and provide a guideline for achievable maintenance goals.

1.4. Hypothesis

The research was based on the hypothesis that surface preparation techniques such as wire brushing and sandblasting will indeed affect the bond strength achieved by the coating, provided the concrete substrate had been made sound (acceptable concrete cohesive strength achieved through proper material selection, concrete manufacture and curing methods) in all cases prior to the profiling methods used. The condition for pre-wetting the substrate in order to achieve a saturated surface dry condition needs further investigation as it is said to be a minimum requirement (Williams, 2012). Due to the curing conditions of many cementitious coating formulations (moisture cured), moisture related problems such as coating bubbling and peeling is likely to have a negative effect on majority of the coating systems and hence needs further evaluation.

1.5. Research Methodology

Since experimental work was carried out under controlled laboratory conditions there were certain assumptions and limitations to the work undertaken. This is important when relating experimental results to theory and ultimately to practice. The experimental work involved the following aspects:

- Obtaining concrete mix design for concrete of medium strength (30 MPa) and high strength (40 MPa). This was then be followed by the selection of available and appropriate concrete constituent materials.
- Establishing the concrete substrate specimen size needed to accurately use the pull-off tester. This was dependent on the available disc sizes. Specimens were hexagonal having a surface area of approximately 0.11 m^2 which enabled enough space for three pull-off test discs (diameter 50 mm) to be used on each specimen.
- The concrete specimens were prepared according to SABS methods described by Addis (2008) as follows:

1. The consistency and workability of the fresh concrete mix was assessed and recorded by doing the slump test.
2. The plastic cube moulds to be used were clean and lightly smeared with release oil on the inside. They were then filled with the well mixed concrete in 50 mm layers. Each layer was then tamped at least 45 times with the round end of the tamping rod. After tamping the last layer a steel float was used to remove the excess concrete.
3. The cube/mould was then covered by a sheet of plastic and stored in the laboratory. It was allowed to sit for 24 hours.
4. Once 24 hours passed, the mould was gently loosened in order to free the concrete specimen. The specimen was then placed into the water curing tank (water was 22 degrees Celsius) and the concrete specimen left to hydrate and cure in it for 28 days before removed for testing.

- Each of the chosen coatings was applied to oven dry, ambient dry and saturated surface dry specimens that were profiled using a light wet abrasive blasting method. This was done for both medium and high strength concrete substrates.

In order to achieve the dry conditions, the specimens were oven dried and dried under ambient conditions, and for the saturated surface dry (SSD) condition the specimen was removed from the water curing tank and allowed to dry under ambient conditions until no standing water can be seen. Once the 28 day strength was verified then the various coatings were applied.

- Six cubes were cast for each set of specimens in order to verify their 7 and 28 day compressive strengths. Cubes were in a saturated condition when tested.
- The coatings to be used were of Company A brand. Company A coatings of both the inorganic and organic categories were used (consultation on the best possible

coatings relevant to this research was sort). Corresponding Company A products to be considered for this investigation included but were not limited to the following:

  - Inorganic types: Sikalastic 150 and SikaTop Seal-107
  - Organic types: Sikagard 540W, (no available Alkyd and drying oil types), SikaBlackSeal-lastic, Sikagard 63N and Sikalastic 601BC (both have corresponding Primers (SikaFloor 161 and Sika concrete primer respectively)).

- Once all the coating systems were mixed (if necessary), applied and cured according to their respective datasheets then the specimens were prepared according to the requirements of the pull-off tester.
- Proceq DY-216 pull-off tester conforms to many standards including (but not limited to) EN 1542, BS 1881 Part 207, ASTM D4541 and ASTM D7234. The tester is automated and therefore reduces the risk of human error when conducting the experiment. Further details will be described at a later stage of the investigation when interpreting the results obtained.

1.6. Research Protocol

Preliminary time and work schedules were constructed and updated as laboratory equipment, construction materials, available workspace and products were acquired. Once mix design was done then material quantities were checked and any moulds made. This then allowed for the manufacturing of the concrete specimens and once this was done then a definite time frame of one day is needed for the specimens to harden before being removed from the moulds and placed in water to cure for the next 28 days. Following this a day was required for the cube crushing tests to verify strength. Once this was complete then coating preparation could commence. Each type of coating cured differently and therefore the datasheets were reviewed and consulted to ensure that the drying times and conditions were adhered to.

All procedures were visually recorded, notes taken and any concerns immediately dealt with (when found to be applicable).

1.7. Conclusion

Three modified cementitious based (inorganic) concrete surface coatings were used due to the rigid nature and applicability to bond strength testing. These coatings were applied to concrete specimens having compressive strengths of 30 MPa and 40 MPa (common strengths used in practice). Both of these strength types were lightly wet sandblasted to obtain sound concrete along all of the specimen’s surfaces and were then subjected to three differing moisture conditions prior to coating application. Therefore a total of 9 substrate specimens were cast for each strength type. Cubes were cast for strength verification.

The experimental work done is of vital importance as it will either conform or not to the theory and manufacturer specifications. Although it is stated that the substrate must be dry it is not the case for all coating options. Theory specifically states (Bassi and Roy, 2002) that in order for coatings to adequately adhere to the concrete substrate the substrate must be clean, dry and sound. The assumption that any method for profiling can be used as long as the substrate produces a sound and relatively rough surface will also be verified or not once the experimental results have been analysed and interpreted. Due to the previous work done by Talotti (2014) it would also be likely to suggest that the organic or cement based coatings will not benefit from the saturated surface dry condition of the substrate. The literature reviewed will also be cross referenced before any further assumptions are made with regard to any experimental work and the analysis of any uncertain results obtained.

2. Literature Review

The aim of this literature review is to establish the fundamentals of surface coatings and establish whether or not similar work has been carried out within this research topic. These fundamentals include the various formulations, main usage or function of concrete surface coatings, concrete substrate quality, surface preparation methods including surface cleaning of contaminants and methods for abrading concrete to remove laitance as well as other contaminants, surface profiles, coating application methods, various South African coating supplier/manufacturer products and similar research done on the topic of concrete surface coatings with regard to the adhesion effects surface preparation might have. Coatings are important for the protection of our structures (be it steel, concrete or reinforced concrete structures) and as such they must be understood before they can be expected to perform according to specification. There needs to be an adequately investigated method of surface preparation (with an associated surface profile) for individual groups of surface coatings which will provide the user with an achievable level of adhesion. The adhesion being affected by the bond between the coating and the concrete substrate entails that controlling the substrate surface and substrate quality will give rise to more predictable bond strength. Adequate bond relates to an enhanced possibility of improved long term coating performance. The gap between theory and practice must be narrowed in order to provide a substrate with a surface coating that will not prematurely fail due to poor bond between the coating and the substrate. Failure within the cementitious coating as a result of substrate moisture condition (such as inadequate strength gain, cracking and blistering) should also be investigated.

2.1. Introduction

Concrete structures (in particular reinforced concrete structures) have been viewed in the past as solid, impenetrable structures that show very little deterioration throughout its lifespan and therefore early deterioration of reinforced concrete structures over the past two decades have spurred a need for more durable concrete design innovations in order to understand the mechanisms and processes of reinforced concrete deterioration (Ballim et.al. 2009). Recent studies and observations have proven that many factors including environmental, construction material enhancements, improved building practice, increased structural load changes and advancements in many technologies within the engineering field have affected many of these older structures negatively. Old structures were previously not designed or built to combat these changes, which has subsequently led to advances within the fields of structural strengthening and reinforced concrete repair methods. Deterioration of structural elements can be a result of physical, mechanical, chemical as well as external environmental factors. If accounted for within the design phase and adequately followed throughout the construction and maintenance phases, the concrete structure will continue to function to its specifications throughout its entire intended lifespan.

There are many repair options available and the final choices are usually dependant on the requirements that need to be fulfilled (usually within client or environmental constraints (Bassi and Roy, 2002)). It is therefore extremely important to first identify the source of the deterioration before commencing with any repair work. The most common type of repair and protection solution used for concrete elements is that of surface coatings. O'Brien (2007) states that even 50 years ago when coatings were less complicated in formulation, premature failure had often occurred. This review will therefore be focused on the durability and effectiveness of concrete surface coatings and will pay particular attention to instatement preparation and adhesion properties. It will also be aimed at new concrete structures as this will aid in the use of laboratory testing conditions for both concrete test specimen preparation and laboratory testing methods to verify manufacturer and theoretical specifications.

The contents of this review will not be focused on the identification of the deterioration mechanisms nor the function of various other available repair methods but rather on the effectiveness of the usage of concrete surface coatings. This includes common concrete surface coating options, instatement procedures (particular attention to surface preparation), commercially available coating material and systems, testing methods for adhesion (focusing on the pull-off test) as well as future maintenance needs (if available).

The documents used as guidelines include the *American Concrete Institute (ACI) International, BRE International, the concrete society and International concrete repair institute (ICRI) – Concrete Repair manual (ACI and BRE, 2003),* various sections of the European Standard (*EN 1504:2008)* as well as Bassi and Roy's *Handbook of coatings for concrete (2002),* amongst various research articles and reports.

2.2. Concrete Surface Coatings

2.2.1. Definitions

The following definitions are taken from the Australian Vicroads Standards, section 686 – coatings for concrete (VicRoads, 2009), as these best describe the terms found within the context of this research.

Coating(s): An interchangeable term, meaning either the actual process of covering the concrete surface with a layer(s) of paint, or representing a protective or decorative coating as defined in this clause.

Decorative coating system(s): These can either be film-forming coatings, surface treatments or combinations of these which can improve the aesthetic appearance of a concrete surface.

Film-forming coating(s): Viscous materials which form a pin-hole free film on the concrete surface to improve its aesthetic appearance or provide protection by acting as a *barrier to the ingress of aggressive agents. Coatings are generally applied in 2 or more layers. Thin coats have a dry film thickness of 100-300 micron, high build coatings generally exceed 1mm, whereas cementitious coatings are generally thick applications ranging from 1 to 20mm thick.*

Pore-lining penetrant(s) (Hydrophobic Impregnation(s)): These are low viscosity fluids (ie. Silane, silane/siloxane, siloxane, solid silane or silane creams) which react with the available hydroxyl group of the silicate structure of the concrete substrate in the presence of moisture, thus depositing water-repellent silicone resins chemically bonded to the walls of the concrete pore structure. These hydrophobic products can penetrate the concrete by several millimetres and work by repelling water and waterborne chloride ions.

Protective coating system(s): These can either be film-forming coatings, surface treatments or combinations of these which can impart protective qualities to the concrete surface against the ingress of aggressive agents.

Sealer(s): These are viscous fluids which are intermediate between pore-lining penetrants and film-forming coatings. They can penetrate and block pores of the concrete substrate and also form a thin film on its surface.

Surface treatment(s): These are viscous materials such as pore-lining penetrants (hydrophobic impregnations) and sealers which can penetrate the concrete or block the pores of the concrete to improve its aesthetic or protective qualities.

Concrete surface coatings can be used for many reasons, such as for aesthetic or protective functions. The requirements for the coating will therefore affect and influence the type of coating used on the concrete surface as well as the associated costs involved. Bassi and Roy (2002) state that concrete coatings can provide a surface capable of the following characteristics: decorative enhancements, improved cleanability, reduced dust adhesion, enhanced slip and abrasion resistance, reinforcement corrosion protection, and chemical resistance to name a few. Bassi and Roy (2002) further state that in order to achieve adequate surface coating performance, the concrete (substrate) characteristics must be carefully considered prior to application of the coating. Improper and inadequate substrate surface preparation is the leading cause of concrete surface coating failure and this has brought about the importance of investigating the surface for contaminants, defects, internal contaminants, bond breakers, and potential moisture vapour transmission problems prior to any application (Bennet, 2015). It is therefore critical to the performance of the coating that the substrate be sound, clean, free from any surface defects and dry in order to establish an adequate mechanical bond (Basham, 1998). The coating manufacturer will also have a well set out and established guide on surface preparation requirements and any additional needs prior to application of their product which will be discussed for common commercially available products.

2.3. Basic components of Coatings/Paints

Surface coatings (essentially paint formulations) are considered to be made up of fine particulate pigmentary materials (pigments) that are dispersed in a polymeric binder (resin) and normally dissolved or dispersed in a liquid carrier phase (Bassi and Roy, 2002). Minor additives are also added by the manufacturer to modify and control the required properties of the coating.

2.3.1. Paint formulation

Bassi and Roy (2002) describe each major component of the paint formulation as follows:

- Polymeric or resin binder: This is essentially the film-forming component of the paint formulation which can be divided into two broad categories, those being of convertible and non-convertible types. Convertible types have materials that are in an unpolymerized or partially polymerized state and undergo reaction to form a solid film following application. Non-convertible types have polymerized binders that are dispersed or dissolved in a medium which leaves a coherent film on the surface after evaporation of the medium has occurred following application.

  Convertible types include: Alkyd, amino, epoxy, phenolic, polyurethane and silicone resins.

  Non-convertible types include: Chlorinated rubber, acrylic and vinyl resins.

Note: Bitumen and inorganic silicates are also binder types used in paint formulation but are not classified as polymers.

- Pigments: These are particulate solids that are dispersed in paints in order to produce a paint of a certain colour, opacity, durability and strength. Inorganic and organic substances are used differently as they have differing characteristics. Organic pigments tend to be used more for decorative paint formulations. Pigments should be insoluble in the medium used, free of soluble salts and should essentially be chemically inert.

- Solvents: These are volatile liquids that are added to the paints in order to dissolve the resin component of the binder and modify the viscosity of the paint formulation. For non-convertible types the solvent determines the drying time and final properties of the final film as well as the coating application characteristics prior to setting. For emulsion paints (non-convertible type) the solvent is simply water whereas a variety of organic compounds are available for resin-based paints.

  It is therefore clear that surface coatings are paint formulations consisting of a binder (provides bond to surface as well as film-forming component), pigments (provides colour, opacity and resistance) and solvents (to enable the paint to spread and be evenly dispersed).

2.3.2. Coating options

Coatings can generally be divided into two generic categories, those either being of an organic or of an inorganic type. According to Bassi and Roy (2002), inorganic coatings can be subdivided into cement based masonry paints (decorative) or polymer-modified cementitious coatings (protective); and organic coatings can be subdivided into four categories: thermoplastics and synthetic rubbers, alkyds and drying oils, bituminous materials, and thermosetting polymers. This is supported in the Concrete Repair manual (ACI and BRE, 2003) as well.

- Inorganic coatings:

  - Decorative: Cement based paints usually of the masonry type. These paints are relatively low cost and are available in a limited range of colours.

  - Protective: Usually of a polymer-modified cementitious type coating. Applied at a greater thickness than the above decorative type and is usually between 2 mm and 3 mm thick. The polymers (commonly acrylic polymers or fibre-reinforced polymers) impart specifically designed for properties such as an increase in coating flexibility, improved abrasion resistance and lowered porosity (without any significant loss of coating compressive strength when compared to unmodified cementitious coatings or mortars).

All these cement type coatings rely on the hydration process to convert from a fluid state to a solid state. Application temperatures and humidity are therefore key factors that should be controlled as far as possible. Curing guidelines (supplied by manufacturer) must be followed as well in order to enable maximum hydration to take place and therefore adequate layer/film-formation.

- Organic coatings:

  - Thermoplastic and synthetic rubber: For this type, the polymer is either dissolved in an organic solvent (possibly a blend of solvents) or is dispersed as small solid particles in water (waterborne). A physical drying process occurs (not by a chemical reaction) and a coherent dry film results. The drying process does progress with depth (thickness of coating) and it is therefore very important to ensure that very slow or very rapid drying at the surface is avoided as well as excessively thick coating applications. If it is not avoided then solvent entrapment can result in the lower part of the film and therefore lead to inadequate coating performance.

    Important factors that influence the drying process most significantly include: ambient conditions such as temperature, humidity and wind speed; the absorptivity of the concrete surface to be coated; and time laps between any successive coating applications.

These types of coatings are however the most widely used systems because of their ease of application and because they are almost certainly one-pack products that are easy to use. These coatings are usually based upon acrylic polymers.

- Alkyds and drying oils: Alkyd coating systems consist of many variations. These are traditionally founded on oil-based and oleo-resinous paints. Solvent evaporation followed by an oxygen-induced cure reaction result in drying and hardening respectively.

  Some coatings of this type may become excessively brittle with age.

- Bituminous materials: Bitumen can be obtained either from the distillation residue of crude petroleum (or from natural mineral deposits) or pitch from the destructive distillation of coal tar. These materials have been mainly used as damp-proofing or waterproofing coating systems for concrete surfaces.

  Bituminous materials can be of the following forms as a direct result of its application processes:

- Thermosetting polymers: A cross-linked network structure is produced as a result of in-situ reactions, which make up the dry film. Solvented or waterborne systems are followed by a drying process.

The more common coatings of this type are based on epoxy and polyurethane resins. Thermosetting systems are however more difficult to use as they are generally two-pack products that must be adequately mixed and applied (by a skilled and adequately trained individual). There are one-pack products that are based upon moisture curing polyurethanes but controlled application conditions must exist in order to prevent any water ingress during curing as this will inevitably lead to excessive carbon dioxide evolution and negatively affect the cured films properties.

2.3.3. Usage of coatings

According to the European standard (EN 1504), as made available through a publication through sika (2004), coatings can be used for the following reasons:

- Protection against ingress: this is essentially reducing or preventing altogether the ingress of adverse agents such as water, harmful liquids, chemicals, gases, vapours and biological agents.

- Moisture control: coatings can be used here in order to control and maintain the moisture content in concrete by keeping it within a specific range of values.

- Physical resistance: coatings enable an increased substrate resistance to both physical and mechanical attack.

- Resistance to chemicals: these coatings are specifically designed to combat and reduce the effects of adverse chemicals which would normally deteriorate the concrete.
- Increasing resistivity by limiting moisture content: these coatings increase the electrical resistivity of the concrete substrate.

The main elements that are controlled by the coating is still that of moisture and oxygen, particularly for reinforced concrete structures, as these elements are the main reasons for the potential for steel reinforcement corrosion to occur within the concrete provided conditions for the reaction are achieved. The process of reinforcement corrosion is activated when the passivating layer of gamma ferric oxide found around the reinforcing steel within the concrete breaks down. Once passivation is lost, the steel will rust under ideal conditions of moisture and oxygen. Therefore if the coating was intended to prevent the conditions for the steel passivating layer break down then it would be concerned with maintaining the pH or preventing chloride penetration (as an example) but this is more complex and hence if the coating can either prevent moisture or oxygen further penetrating the reinforced concrete area then rust will not be able to form regardless of the conditions found at the level of the steel (Addis, 2008).

2.4. Surface Preparation requirements

Before commencing with any surface coating system application, the surface of the deteriorated (or new) concrete must be prepared to varying specifications (as per product requirements). It is therefore important that concrete removal and concrete surface preparation be done precisely and thoroughly checked before any material is applied. The Engineer must conduct inspections before any repair material or surface coating system is applied. High pressure water jetting with some sand introduced is an adequate method to achieve most surface bonding requirements but many other methods can be used to achieve the desired surface profile under various site conditions or constraints. Bond strength is majorly influenced by surface cleanliness, the presence of a laitance layer on the substrate, micro-cracking in surface region of substrate, compaction of patch repairs as well as curing methods used. Surface defects and surface preparation methods will therefore be discussed prior to the various application methods found. American Standards for concrete surface cleaning and for the practice of abrading concrete include ASTM D 4258 and ASTM D 4259 respectively. These standards were chosen over the European standards (found in EN1504) as they provide details on the methods to be applied during the experimental work. The first standard (ASTM D 4258, 1999) provides methods for surface cleaning of concrete in order to remove grease, dirt, and loose material prior to coating application. The methods include broom cleaning, vacuum cleaning, air blast cleaning, water cleaning, detergent water cleaning, and steam cleaning. The second standard (ASTM D 4259, 1999) provides a practice that is intended to alter the surface profile of the concrete as well as to remove foreign materials and weak surface laitance. The practice includes abrasive blasting (wet or dry), mechanical abrading, water blasting, as well as similar procedures that will change the concrete surface profile.

2.5. Common surface defects to be treated

The major cause of premature coating failure (failure for the coating to adhere to the surface, failure to adequately form a film, failure to be decorative or protective and hence render it unable to function on the concrete substrate as intended) has been investigated by Bennett (2015). He states that one must thoroughly investigate the surface to be coated in order to identify any of the contaminants (surface or internal), surface defects, potential bond breakers and any potential moisture vapour transmission interferences prior to application of the coating system. These can be identified through signs of dusting, cracking, efflorescence, water, oils, curing compounds, formwork release agents as well as laitance. His investigation also discovered that premature delamination will occur if moisture vapour pressure is allowed to build beneath the coating in the case of non-breathable coating systems.

2.5.1. Laitance

Laitance is essentially fine cement powder layer which can be found on all poured concrete and has a very poor bond to the body of the concrete (Bassi and Roy, 2002). Laitance must be removed by acid etching or blasting methods prior to any coating application in order to achieve adequate bonding to the concrete substrate.

2.5.2. Moisture

According to Cement Concrete & Aggregates (CCA) (2007) it is important to understand the function of the moisture present within the concrete itself as well as any moisture surrounding the concrete to be coated prior to any application. Moisture within the concrete can be found in the capillary pores and the gel pores of the concrete matrix; the moisture can also exist in the form of a liquid phase where the pores are saturated or as a vapour phase which then establishes a level of relative humidity within the concrete (CCA, 2007). The relative humidity therefore changes over time due to the nature of the movement of the water vapour within the concrete which is due to changing ambient conditions. The moisture and movement of moisture can affect the coating negatively if it is not dealt with beforehand. Some of the consequences include: poor coating curing (as some coatings may cure and hydrate in the presence of moisture, leaving excess moisture available in the substrate, thus developing poor bond strength); providing a moisture barrier which prevents adequate contact between the uncured coating and the substrate; osmotic blistering can also result as the *"moisture will flow from areas where water contains low levels of dissolved salts to areas of higher concentrations in order to establish equilibrium"* conditions (there are several factors which allow this process to occur and one of these factors is an impermeable surface coating). However, bond strengths of 1.5 MPa are generally enough to resist water pressure from hydrostatic as well as capillary sources of moisture.

Munger (2015) goes further by stating that in addition to adhesional strength most blistering can be identified by studying the moisture-vapour transmission rate of the coating which is the *“rate at which molecular water passes through the inter-molecular spaces within the coating”*. This rate is however unique to each coating formulation. Areas of poor adhesion along the interface between the coating and the substrate will cause blistering due to a steady build-up of moisture and hence moisture related pressure at those areas.

An online entry found in the journal of architectural coatings magazine (Durability + Design, 2011) elaborates on the loss of adhesion and blistering of concrete surface coatings by stating that concrete is invariably a porous substance which allows for the movement of water vapour and gases within its matrix structure. Therefore breathable coatings (coatings which allow for water vapour to mitigate up through the concrete and eventually evaporate to the atmosphere whilst still preventing liquids from penetrating into the concrete) are important in situations where blistering is highly likely to occur. These coatings can be useful where the substrate must be protected from the ingress of moisture in order to avoid any unwanted reactions from taking place within the concrete matrix structure itself, such as alkali silica reaction (ASR).

Moisture can therefore play a vital role in the effectiveness of the surface coating being used which means that testing the moisture content of the substrate prior to application of a coating system is important. Sika (2004) states that moisture content above 4% by volume or visible rising moisture (condensation) on the bottom of the plastic sheet method (confirmed by test ASTM D4263 which is essentially a polyethylene sheet approximately 1 m^2 taped to the concrete surface and left in place for 24 hours) indicates the need to dry the substrate further in order to achieve lower moisture content for acceptable coating application. There are some coating formulations that allow for wet substrate application (wet substrate may be due to freshly laid concrete or concrete with high moisture content (above 10%)) but these are usually of the inorganic type and will therefore need to be investigated further. Inorganic coatings that are of the latex-modified cementitious type are characterised by having the ability to set and bond to the concrete substrate in the presence of moisture (CCA, 2007). CCA (2007) also state that most water based products result in moisture being drawn into the concrete substrates surface when applied but that the drying of this moisture is not the concern. The major concern is that as the moisture penetrates the concrete there is resulting dissolved alkalis which may affect the pH levels of the concrete and this may then negatively affect the applied coating. This may then be highlighted when the concrete has excess moisture added to it. Water added to the substrate in order to obtain a saturated surface dry condition needs to be investigated in order to obtain an idea as to whether or not the moisture will indeed influence the bond between the coating and the substrate by either influencing the mechanical or chemical interactions at this interface. Cementitious modified coatings all require damp curing due to the hydration required by the Portland cement in order to form the strength characteristics needed by the coating, thus indicating that moisture within the coating is essential to the cohesive and adhesive bonds to be created.

2.6. Surface preparation methods

Before the type of surface preparation method is decided upon, the concrete surface that is to be coating must first be investigated. This also includes how the surface was finished and cured. According to Bassi and Roy (2002) a steel trowel finish will give a smooth surface, a broom finish will give a rough finish and a poured-in-place concrete surface is likely to have a higher percentage of air pockets. Therefore for new concrete structures or elements it is important that all standards be followed during the design, production, placement, compaction, and curing and it is also important that form release methods and products be according to manufacturer specifications in order to achieve the compatibility with the coating system.

2.6.1. Surface preparation

Surface preparation can be done according to the following process as provided by Basham (1998):

I. Conduct a preliminary survey

This is the first step and is one of the most important as it identifies (or gives the investigator an idea of) the major causes or potential causes of deterioration the concrete substrate will be subjected to. This step involves the following:

- Examining the concrete surface to identify the presence of debris, dust, oil, grease, laitance, mortar splatter, efflorescence, curing agents, and any other contaminants.
- Test for laitance can be done with a knife. If a powdery material can be scraped from the concrete surface then excessive laitance is present.
- Conduct a moisture test to get baseline floor moisture content in conditions where water will be used to clean the concrete surface.

II. Known surface condition requirements

This is fundamentally an understanding of what is required by the surface in terms of surface preparation and roughness requirements. A field strength test may be required if a minimum surface strength has been specified. Usually pull-off test results of between 175 and 300 psi (between 1.2 and 2.1 MPa) are required.

III. Repair surface defects

This is essentially the same procedure as used for conventional concrete repair methods. Patch repairs, filling of voids, repairing of cracks (that cannot be covered by the coating), repairing any corroded reinforcement, mitigating potential reinforcement corrosion problems such as installing cathodic protection systems, bonded overlays if required, excessive material may need to be removed in order to achieve a desired profile, honeycombing repair, grinding or filling. This is essential prior to surface coating as these defects will directly affect the bond and therefore affect the coatings ability to protect the underlying concrete substrate.

IV. Clean and roughen the surface

This involves the process of removing loose debris and dirt by sweeping, vacuuming as well as air or water blasting. Scraping off heavier deposits of oil, grease or other loosely attached contaminants. This is then followed by the use of detergent or non-solvent emulsifier and a stiff-bristled brush to remove any contaminants that may still be present.

Mechanical abrading techniques and acid etching should be used as a final resort.

V. Inspect and test the surface before coating

Final inspection before application of coating system, involves the following:

- Use of a dark cloth to test the surface for dust. When cloth is wiped across the surface and a powdery layer is left on the cloth then the surface is too dusty for coating application.
- Water can be sprinkled onto the dried surface. If the water forms droplets on the surface without immediately spreading out then the surface may be oily or dusty.
- Simple pH paper can be used to obtain the surface acidity. This is important if chemical solutions were used in the cleaning process.
- Measure the concrete surface temperature in order to compare results to manufacturer specifications (if required).
- Lastly test for moisture in one or more of the following ways:

1. Test found in ASTM D 4263-83 (2012). Tape tightly to the concrete surface an 18 inch x 18 inch (0.457 m x 0.457 m) clear polyurethane sheet (approximately 4 mils (0.1 mm) thick) and leave it for a minimum of 16 hours. If moisture collects on the underside of the sheet then the moisture content of the concrete is likely to be too high (mainly for organic type coatings). This test is indicative of capillary moisture.
2. The rate of moisture vapour emission can be measured by placing a fixed amount of calcium chloride in a dish placed inside a transparent plastic cover which is sealed to the surface. After 60 to 72 hours, the calcium chloride is weighed and the amount of water absorbed determined.
3. Obtain and use a surface moisture meter to measure and compare values (if available).

Testing for moisture is important as moisture affects the hydration and strength gain of both the concrete substrate and the cementitious type coating. Too much moisture will result in weak matix formation as well as excessive bleeding and too little moisture will also result in weak matrix formation as well as the potential for moisture to be absorbed from surrounding moisture sources. Blistering, pinholes as a result of vapour transmission will be promoted in conditions such as those obtained when a moist cementitious coating is bonded to a dry concrete substrate (and vice versa).

2.6.2. Cleaning methods

Bassi and Roy (2002) go further by stating that several cleaning methods are available but no one is specific to a particular type of coating and rather to what method will be most suited (more convenient to carry out) to the project.

The concrete must be clean, dry and sound before any coating is applied.

The cleaning methods available are:
- Mechanical wire brushing for small areas.
- High-pressure water jetting provided there is adequate drainage. Detergents are commonly used in conjunction with this cleaning method.
- Fungicidal wash.
- Wet, dry or vacuum abrasive blasting.
- Mechanical impact techniques (such as needle gunning or bush hammering).
- Mechanical abrasion techniques.
- Acid etching.

2.6.3. Surface preparation methods

The following surface preparation methods are provided in the concrete repair manual (ACI and BRE, 2003) and are specific for the removal or cutting of sound concrete (cleaning methods for loose material such as debris and dust are not considered here) in order to alter the surface profile of the concrete substrate.

These include:

- Erosion

I. Abrasive forces are applied to the surface of the concrete being prepared in order to wear away the top layer of cement paste as well as the fine and coarse aggregate all at a relatively uniform rate. This is achieved by grinding action using stones, abrasive discs, or blocks with embedded diamonds. A flat surface having little to no profile is produced.

II. High and ultra high pressure water jetting is another form of erosion (water erosion). Pressurised water is projected onto the surface of the concrete and both cavitation and frictional forces are generated to wear away the cement paste. The profile achieved is not as smooth as the previous abrasive method as the water jetting will only wear away the cement paste and fine aggregate leaving protrusions of coarse aggregate behind (prolonged exposure to the water jet will eventually result in the undercutting of the coarse aggregate).

- Impact

Momentary mechanical loads (impact or dynamic loads) are applied at fixed rates in order to produce loads that are greater than the concretes compressive and tensile strength. This is achieved by striking the surface repeatedly with hardened points which in turn fractures the cement paste and coarse aggregates. Some of the cracks and loosened aggregates are left behind leaving a bruised concrete surface. Methods of this type include: scarifying, scabbling, milling and needle scaling.

- Pulverization

  This is the action produced by small particles at high velocity colliding with the concrete surface. Bruising of the surface does not occur under this action as the mass of the particles are considered small compared to that of the concrete. The cement paste is once again worn away by the hard, sharp-edged media being projected onto it. As with water jetting this method also undercuts the coarse aggregate and with time a highly profiled surface is obtained. Abrasive blasting and steel shot blasting are types of this method.

- Expansive pressure

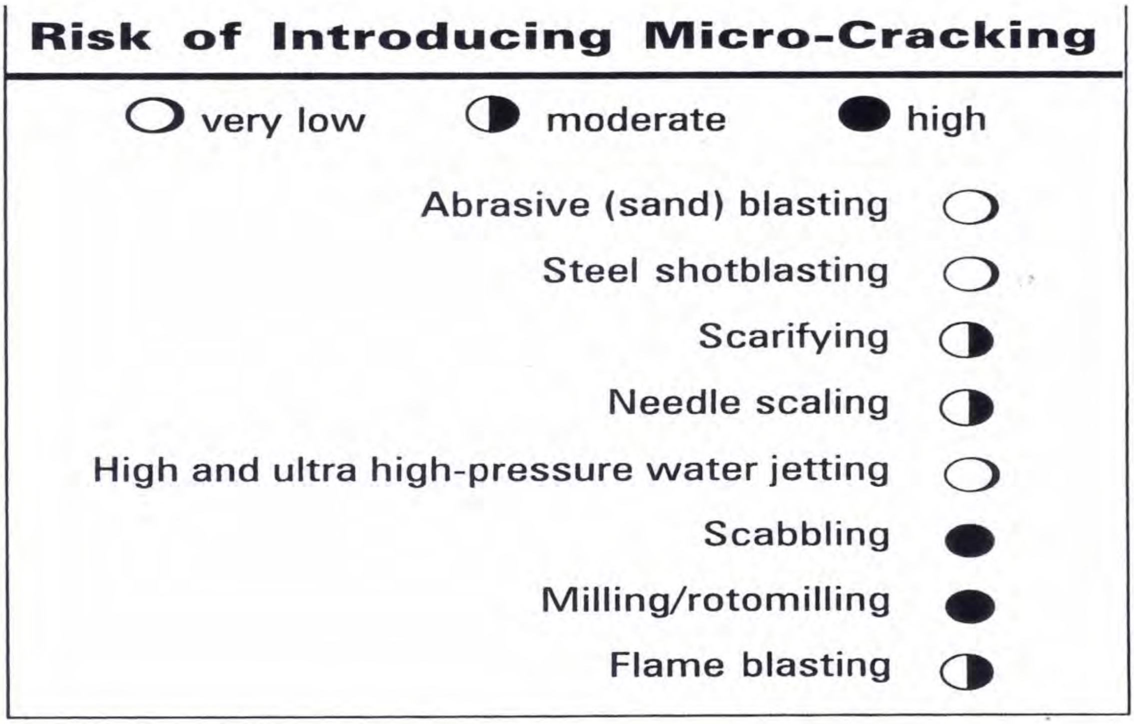
Steam and water are two forms of this method.

I. Steam: the capillary and absorbed water available in the cement paste is rapidly heated and converted to steam using a high temperature heat source. The sudden increase in vapour pressure due to the steam generation produces tensile forces near the surface of the concrete. If these tensile stresses are greater than the strength of the concrete then both the matrix and aggregate with fracture. This type of fracture causes thin layers of concrete to scale or pop off the surface. Flame blasting (flame scaling) is the method available.

II. High and ultra high pressure water jetting at pressures between 15000 and 45000 psi (103 and 310 MPa) can produce a cutting effect which is similar to that of the steam method. Milling or scarifying equipment is usually used initially in order to remove around 10 mm of the original surface. This is to introduce cracks and micro-cracks within the surface of the concrete. The cracks are subsequently penetrated by the high expansive pressurized water. This results in tensile failure along any planes of weakness within the surface layer.

- Bruising

Several of the above methods have been shown to reduce the tensile strength of the concrete and hence lower its effective bond strength particularly when using impact preparation methods. Bruising is essentially a weakened layer containing interconnecting micro-cracks approximately 3 to 10 mm deep. Figure 2.1 indicates the relative risk of introducing surface bruising for each of the aforementioned methods and can be seen below.



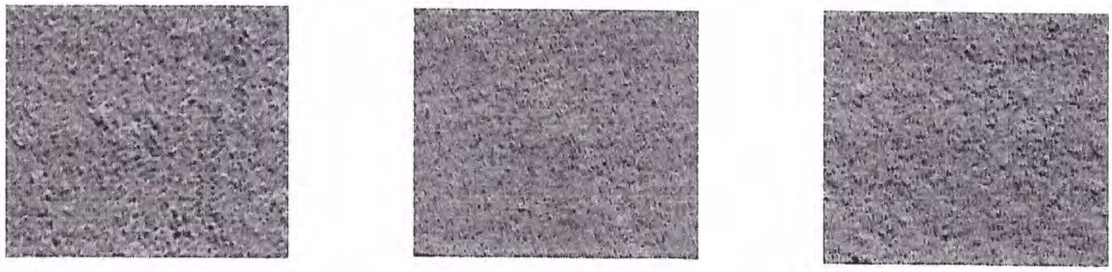
Risk of Introducing Micro-Cracking

○ very low ◑ moderate ● high

Abrasive (sand) blasting	○
Steel shotblasting	○
Scarifying	◑
Needle scaling	◑
High and ultra high-pressure water jetting	○
Scabbling	●
Milling/rotomilling	●
Flame blasting	◑

Figure 2.1: risk of micro-cracking (ACI and BRE, 2003)

Figure 2.2 represents the various profiles that are produced from each of the previously described surface preparation methods.



CSP 1 (acid etched)

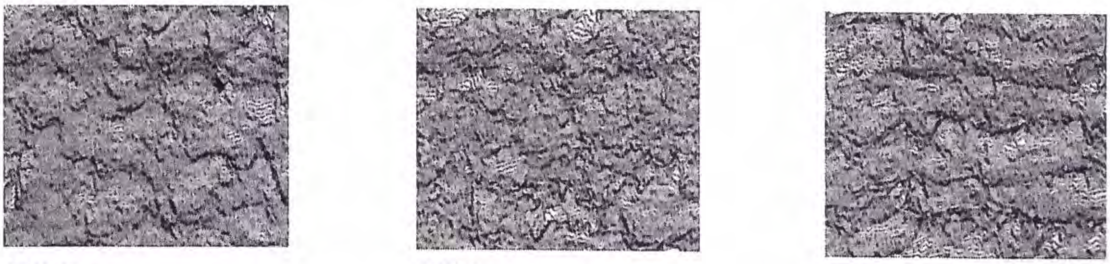
CSP 2 (grinding)

CSP 3 (light shotblast)

CSP 4 (light scarification)

CSP 5 (medium shotblast)

CSP 6 (medium scarification)



CSP 7 (heavy abrasive blast)

CSP 8 (scabbled)

CSP 9 (heavy scarification)

Figure 2.2: profile examples (ACI and BRE, 2003)

Using the above figure as a visual guideline helps to determine the type of coating to be applied. This can be seen in Figure 2.3.

From Figure 2.3 below it can be seen that multiple preparation methods have the ability to produce more than one profile if desired. The different profiles are obtained by varying the time the surface is exposed to the method being applied.

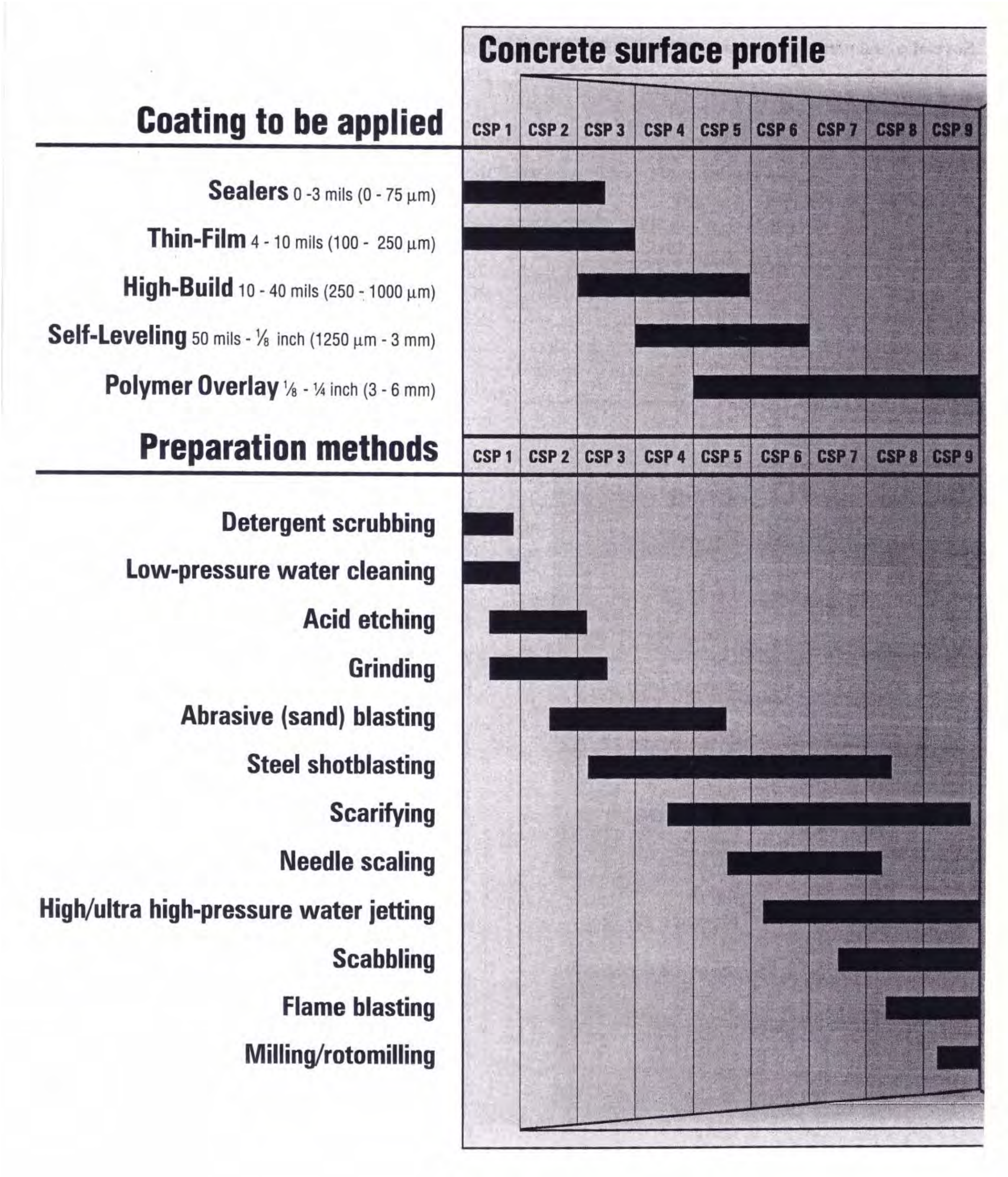


Figure 2.3: achievable profiles (ACI and BRE, 2003)

2.6.4. According to Bassi and Roy (2002) even if the concrete surface has been prepared correctly there is still a possibility of the following surface conditions occurring:

- Friable surfaces: Direct application to friable or dusty surfaces will result in a weak interfacial layer being formed between the coating and the substrate surface. Adhesion will therefore be negatively influenced and subsequently lowered. Excessive vapour pressure/drive or osmotic pressure conditions can lead to blistering and in some cases delamination of the coating (prevalent in polyurethane coatings).

In order to minimise the effect of this, a sealer that is compatible with the topcoat can be used. Sealers such as solution acrylics, epoxy emulsions and relatively dilute moisture cure urethanes will penetrate the friable layer and aid in its consolidation.

- Porous concrete: as the solvent or water is absorbed into the substrate, some gases are emitted and can result in severe pinholing. With solvent based systems, the solvent and the polyurethane polymer can be absorbed into the substrate which will cause a problem if insufficient coats are available for enabling a multi-coat application.
- Efflorescence/laitance: concrete often contains high levels of water soluble salts which may diffuse to the surface of the concrete. If the substrate is saturated but the surface is dry for application of the coating, the water and associated salts will move toward the surface of the concrete. The water (vapour) will generally be able to escape through the pores of the coating but the salts will be left behind the coating to build up. If the build up is large enough then delamination can occur. A penetrating sealer is often the solution to the problem in this case.
- Dampness: the general requirement is for a dry substrate but this is often not possible due to certain prevailing conditions. A wood moisture equivalent (WME) of below 28% WME is usually ideal but not possible. Specially formulated epoxies or polyurethanes containing hydrophilic solvents (which absorb moisture) are recommended for substrates with high moisture content.

2.7. Application requirements

As stated by Bassi and Roy (2002), no matter the choice of coating there are only three main types of application methods. These methods include brush, roller or spray application.

In order to decide between the three types, the following must be considered:

- Environmental considerations
- Surface area size and accessibility
- Required surface finish
- Project constraints

These factors contribute to the overall selection of the coating application method chosen. Spray application may be suited for larger surface areas but environmental conditions may not allow for its usage safely. Brush application may give the best coverage quality but the surface area may be too large and hence be too labour intensive to be used economically. Structural and elemental constraints will also affect the choice of application method to be used. A combination of two or all of the methods can be done economically provided it is foreseen in the design and construction phases (especially in new constructions).

2.8. Supplier/Manufacturer products and recommendations

The following supplier/manufacturer websites were visited and relevant product datasheets consulted in order to tabulate similar product types and their respective surface and adhesion specifications. Product manufacturers/suppliers were sourced on their relevance to the South African coating industry. Many paint manufacturing companies are available but the following were chosen due to their products relevance to the concrete surface coating requirements of this research.

The suppliers/manufacturers being: Company A (Sika), Company B (3M South Africa), Company C (Carboline) and Company D (Stoncor).

1. **Company A Products:**

   Company A has structured their choice of coating systems according to the respective functions of the coating. Common products were chosen according to these functions and can be seen in the table 2.1 found in the appendix.

2. **Company B Products:**

   Company B has structured their coating products according to the function and location of the coatings and can be seen in table 2.2 found in the appendix.

3. **Company C Products:**

   Their products have been conveniently categorised based on their function as well as the primary components of the coatings. See table 2.3 in the appendix.

4. **Company D Products:**

   The individual formulations of epoxies, acrylics, cementitious and waterproofing products have been separately structured. These products can be seen in table 2.4 of the appendix.

Note that for almost all the products, provided by each supplier, it is stated that the concrete substrate must be above dew point temperature (3-5 °C) and the relative humidity should not exceed 85% upon application of the new coating in order to prevent subsequent coating delamination from occurring.

The various potential products were tabulated (found in the appendix- tables 1 to 4) and are summarised as follows highlighting important features:

- Company A:

  Coatings for concrete protection, chemical resistance and waterproofing were viewed and the following coatings were found to be potentially relevant and useful:

  Sikagard 540W – acrylic emulsion based coating,
  SikaTop seal-107 – polymer modified cementitious mortar slurry,
  Sikagard 63N – epoxy protective coating,

Sikagard-720 Epochem – epoxy modified cementitious fine textured mortar.

The acrylic and epoxy coatings were found to behave more as a paint and hence results obtained using the pull-off testing method proposed would not be a true interpretation of the failure that would normally occur. These coatings would fail due to peeling and shearing actions instead of due to a normal applied load. Therefore this research will be focused on cementitious type coatings. The SikaTop seal-107 and Sikagard-720 Epochem are potentially ideal candidate coatings for this research and upon further investigation it is clear that the intended surface preparation needs and pull-off testing needs of these two inorganic type coatings are within the requirements intended for this research.

- Company B:

  Coatings are available for wall application and corrosion protection:

  XF 129 – Urethane coating,
  Polynox 136 – water based acrylic coating,
  162 CR – Epoxy coating,

  The information available for these products are limited in that there is no reference made to substrate moisture condition requirements, limited information on expected adhesion failure values and no definitive information on the consequences of not using a primer where it is stated as - if needed. The nature of the coatings are also not of the inorganic type (the information on composition is not clear).

- Company C:

  The coatings are available in categories of composition and are as follows:

  Industrial Alkyds, water-borne acrylics, epoxy primers and finishes, and aliphatic polyurethanes. The relevant products available for each category is found in table 3 but once again no inorganic coatings are clearly identified. The adhesional properties of all the coatings are also unavailable. Substrate preparation requirements are made clear and will be useful if this manufacturer is chosen.

- Company D:

  The coatings viewed from this supplier/manufacturer are categorised on composition and function. These include epoxies, acrylics, cementitious and waterproofing coatings. The relevant coatings to be considered are:

  Pro-struct 6231 – high build epoxy coating,
  Pro-struct 684/4 – high build protective barrier acrylic coating,
  Pro-struct 506 flexicoat – polymer modified cementitious coating,
  Vandex BB75 – cementitious water proofer,

Sufficient details are given on surface preparation requirements as well as application methods. However, limited information is made available on expected adhesion values and failure modes.

It is important to note that although the methods of surface preparation have been specified in most of the above four suppliers/manufacturers, no one particular method has been sufficiently detailed or recommended for a particular product. It is also clear that the datasheets do not provide adequate information to the customer on the bond strength to be achieved by many of the above products. The formulations of the coatings are also vaguely provided in the product datasheets but are not fully described due to manufacturer confidentiality when it comes to trade secrets. The tables found in the appendix are only inclusive of random products from each of the categories provided by the supplier's website.

Further investigation must therefore be done on each of the products to be used for the purpose of this research and will be discussed at a later stage once the products have been finalised. Due to availability as well as detailed and accurate information, Company A products will be investigated first.

2.9. Tests and Standards

Performance assessment is important to ensure satisfactory performance properties of the coating and its application as well as for the establishment of long-term product confidence. Tests relevant to the intended use of the product or coating system must be done and evaluated in order to verify this confidence. The intended use being the principles found in EN1504 (European standard, 2008), namely: ingress protection, moisture control, physical resistance, resistance to chemicals, and increasing resistivity which has been discussed previously (section 2.3.3). However, the focus here is on the bond strength (adhesion and/or cohesion) between the coating (regardless of the type of coating) and the prepared concrete surface. The test to be discussed will therefore be the pull-off test as stated in the concrete repair manual (ACI and BRE, 2003).

2.9.1. Pull-off test

The pull-off test (ACI and BRE, 2003) is a very practical test as it can be carried out under site or laboratory conditions. The test is also found in the American standards ASTM D4541 which is the standard test method for pull-off strength of coatings using portable adhesion testers and ASTM D7234-12 which describes the standard test method for pull-off adhesion strength of coatings on concrete using portable pull-off adhesion testers. The test and equipment used will be discussed in more detail under section 3.7.

- The following is a summary of the test (ACI and BRE, 2003):

  The pull-off test makes use of a steel or aluminium dolly that is fixed to an isolated area (usually partially cored area) of the coating with an adhesive (usually epoxy glue). The dolly has a diameter of 50 mm and once fixed in place is subjected to a tensile force. Once failure occurs the maximum force is recorded and converted to a stress.

The quality of the concrete and that of the coating is important when analysing the results. According to this repair manual (ACI and BRE, 2003) and the pre-standard prEN 1542, it is specified that minimum values for adhesion of greater than 1 N/mm^2 for a test on vertical surfaces and greater than 1.5 N/mm^2 on horizontal top surfaces should be achieved. Values that are less than 1 N/mm^2 should however not be rejected if the failure had occurred within the body of the concrete given the concrete is of an acceptable quality upon further investigation.

Failure between the concrete and coating or failure between successive layers of the coating (generally results in a clear separation) is under no circumstances acceptable. Failure between the concrete and coating is generally an indication of inadequate surface preparation and the exposed surface must be further investigated. Certain elastomeric coatings that have been applied to good quality concrete may be allowed to fail within the coating itself (coating cohesive failure).

- Notes on test standard ASTM D 4541 – 02:

  The test is essentially the same as the above description in that a loading fixture is secured perpendicular to the surface of the coating area to be tested, using a suitable adhesive. A testing apparatus is then attached to the fixture in a manner that will allow for tension to be applied normal to the test surface. A gradually increasing load is then applied until either a plug of test material is detached or a specified value has been reached. The maximum failure loads as well as the percentage of adhesive and cohesive failure are then recorded.

  It should be noted that pull-off strength results may differ when using different testing devices as the results obtained depend on certain instrument parameters.

  O'Brien (2012) states that three distinct failure types can be seen when using this test method to analyse pull-off strength. These include "*cohesion failure (failure within one distinct layer), adhesion failure (failure between two distinct layers), and a glue failure*". He also states that the three general types of test equipment mentioned in the standard are based on the mechanism the equipment uses to generate the tensile force which is mechanical, hydraulic or pneumatic. He goes further to state that results can differ significantly if the incorrect equipment was specified. Other influencing factors include "*the degree to which the surface was prepared prior to attaching the dolly, the method by which the dolly is prepared prior to affixing it to the surface, the adhesive selected, including the temperature during cure of the adhesive and the time interval between attaching the adhesive and performing the pull*". It is therefore clear that equipment and test material to be used must be checked and any accompanying instructions followed thoroughly when doing the test. Three tests are required per test surface in order to statistically characterise that test surfaces behaviour.

- Typical illustration of the modes of failure to be expected during the test:

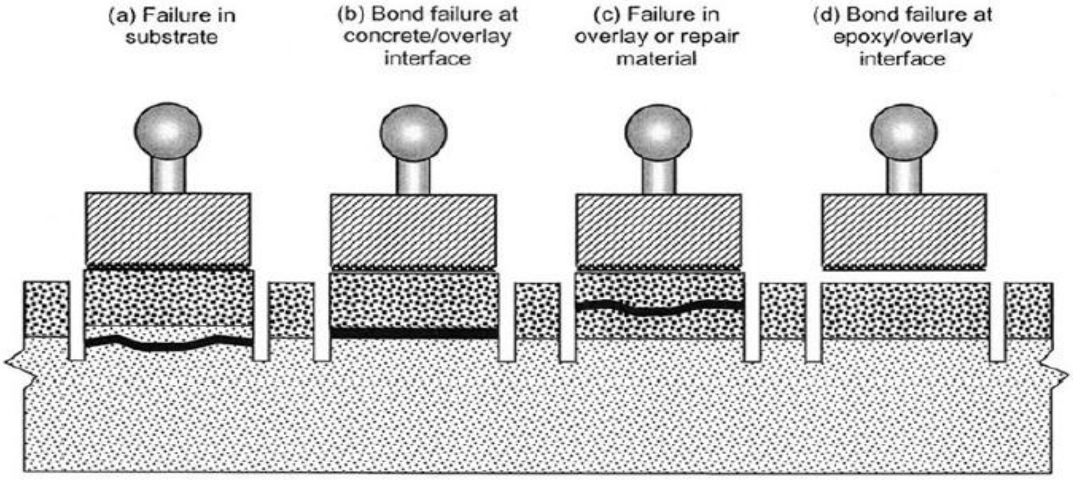


Figure 2.4: typical failure (A.C.Tech, n.d.)

2.10. Previous findings

Research on the moisture related affects on surface coating adhesion has been done by Benn (2008). He investigated the influence of curing and surface preparation on the adhesion of protective coatings on concrete. He subjected four sets of concrete beams to differing controlled curing conditions in order to produce differing near-surface concrete quality and also exposed the elements for one year to the Johannesburg Highveld climatic conditions before doing any preparation or coating on the elements. The elements were prepared using three different methods as well as leaving a specimen as is. The specimens were coated using five different coatings, these coatings were of the following types: elastomeric, aliphatic, epoxy resin based, cementitious based and masonry paint.

A criterion for failure based on the pull off test results was established and in order for the system to remain intact the following two conditions had to be met: 1) Adhesive strength must be greater than shrinkage stresses, and 2) Cohesive strength must be greater than shrinkage stresses.

The main findings were as follows:

- No preferred method of surface preparation is provided in literature.
- Having prepared the surface before application of coating, the adhesion had improved. Four methods of surface preparation were used, being: hand/wire brushing, mechanical brushing, brushing tool (similar results to that of jack hammering) and no preparation.
- The wire brushing technique was the easiest to carry out and also gave the best results for adhesion.

- Aliphatic coatings (Aliphatic acrylic polyurethane compound which can be used as coating) showed the best adhesion properties. Epoxy resin and cementitious-based coatings gave only satisfactory results for adhesion.
- Compaction and curing had influenced the porosity and permeability of the near-surface concrete. Adhesion strength improved with improved quality of concrete surface which is achieved through good quality curing.

As the last statement is potentially influential to this research it needs to be incestigated. Addis (2008) states that curing makes it possible for cementitious reactions of Portland cement to continue and hence improve the concrete strength, permeability and durability. It is also stated that "*curing has the greatest effect on the surface and near surface zone of the concrete*". This confirms that the concrete surface does indeed improve with increasing quality of curing. The same can be said for compacting as this is essentially the removal of entrapped air found in the fresh concrete. The removal of 1% of air voids will reduce the strength by approximately 6% (Addis, 2008) thus confirming the above conclusion made by Benn (2008).

2.11. Conclusion

It is clear from the product datasheets acquired that surface preparation, substrate quality and application methods are important influences for the effectiveness of the coating being applied. It is also clear that a general substrate requirement is for it to be sound, clean and free from contaminants which happen to coincide with the theory previously discussed. It is evident in a few product datasheets that the required concrete surface profile before coating application is vaguely stated and has been made with reference to sandpaper grit (in both instances). This is of a concern because a surface profile will determine the preferred method of surface preparation to be used in order to achieve that particular profile. From the tables, surface preparation methods almost always involve mechanical methods and are focused at establishing a sound substrate surface layer prior to product application. There is however no reference to what they (the manufacturers) deem to be a sound substrate. There is an occasional requirement for a certain compressive and tensile strength of the substrate for a particular coating but this is not consistent or stated as a requirement for many of the other coating products provided in the tables. Adhesion requirements or final adhesion strength of the products are not made available in many of the datasheets which does not help in establishing a reference to the theoretical requirements of >1N/mm^2 for vertical surfaces and >1.5 N/mm^2 for horizontal top surfaces, however, values less then these must not be rejected if the failure had occurred within the concrete substrate.

The pull-off test has been found as a good method for determining the bond strength of the coating on the surface as well as a method for visually assessing where the failure had occurred (within the concrete, between the concrete and the coating, within the coating layer itself, or due to adhesive failure) and this aids the investigator.

There are many theoretical requirements that have been left out of the manufacturer requirements in relation to the substrate condition prior to application of a surface coating. The suppliers/manufacturers do not state whether the product will perform differently if the surface profile differs due to incorrect use of surface preparation methods but simply state that provided the substrate is sound, clean and free from contaminants then the product can be applied. It is also important to note that in all cases there is no particular surface preparation requirement for any individual type of surface coating (inorganic or organic types) and therefore bond strength for all types of coatings can be compared to those two values of 1 and 1.5 N/mm^2. There is thus a need to further investigate the effects of these profiles and different preparation methods on the adhesion of the coatings to those controlled surfaces.

It is also evident that moisture within and surrounding the concrete substrate is an important aspect when considering the longevity of the coating to be applied. In most cases where a cementitious type coating is to be used, a saturated but surface dry substrate condition is the minimum acceptable criteria prior to coating application. The concrete substrate must however have cured sufficiently long (minimum 28 days) in order to achieve its maximum hydration and strength characteristics. In a controlled environment the effects of pre-wetting the sufficiently cured concrete substrate prior to coating application needs to be investigated in order to confirm whether or not this condition does indeed positively influence the adhesion of the coating to the substrate. This condition may very well be detrimental to the uncured coating and hence directly affect its ability to gain sufficient bond strength. This pre-wetting condition may also affect the results obtained by the pull-off test and thus needs to be investigated. Previous studies involved specimens with differing near surface strengths as a result of curing and has not provided focus on the aforementioned condition.

Inadequate surface preparation and excess moisture within the substrate prior to coating application has been found to be a leading cause of failure for many organic type coatings. These coatings are generally impermeable and blister due to vapour pressure build up at the interface between the coating and the substrate, this phenomenon is less likely to affect inorganic or cementitious type coatings as they are more permeable and can use the water to aid in their hydration reaction. Adequate surface profiling has also been shown to improve the mechanical bond achieved by effectively increasing the total substrate surface area to be coated.

The need to investigate the effect of substrate moisture on the surface coating bond strength is evident as literature has mainly focused on moisture related studies involving organic coating as well as repair overlays.

3. Experimental details

3.1. Aim of experimental work

The aim of this experimental work was to establish if there is a relationship between substrate moisture condition and the effective bond strength created by modified cementitious based (inorganic) concrete coatings, provided the concrete substrate was sound and free from contamination prior to coating application. Secondly, the effect on bond strength of medium and good quality concrete substrates which is primarily based on the substrates compressive strength was also to be evaluated. In order for coatings to fulfil their design functions they needed to adhere adequately to the surface they were being applied to. Cementitious based coatings are ideal for concrete protection as they provide similar characteristics to the concrete substrate surface itself. The rigidity of the coatings also allowed for adequate and reliable interpretation of the pull-off test results to be obtained. Any trends when interpreting the results were noted and related to theoretical results where applicable.

3.2. Scope and limitations of experimental work

Due to restrictions and requirements for a minor dissertation the following was achieved through the laboratory work:

- Substrate strengths of 30 MPa and 40 MPa were produced and verified using standard cube compression tests at 7 and 28 days.
- 13 mm Greywacke coarse aggregate and Philippi dune sand were used as these are common materials found within the Cape Town region. Cement was of ordinary Portland cement type, to be verified at a later stage when dealing with the respective concrete mix designs.
- Three different moisture conditions were chosen and subsequently implemented on each of the two chosen substrate strengths.
- Specimen moulds included 100 mm plastic cube moulds and custom hexagon wooden moulds. Details to follow.
- To complete hydration processes all the specimens were moisture cured for the full 28 days before any moisture conditions were imposed.
- Laboratory equipment were utilised where possible and any obscurities or obstacles duly noted.
- Coating specifications and requirements were as thoroughly followed as possible.
- Light wet sandblasting was done on the concrete substrate, as close as possible to that achieved in practice, and hence theory was only used as a guide with regard to actual surface profiles achieved.

3.3. Materials and equipment

3.3.1. Coarse and fine aggregates

According to Addis (2008), aggregates are inert mineral particles that make up about 70% of the volume of the concrete as a whole. Fine aggregate consists of particles that will pass through a sieve with 4.75 mm^2 openings and coarse aggregate are particles that are unable to pass through.

Common coarse aggregate and fine aggregate used within the Western Cape region is that of Greywacke and Philippi dune sand origin and hence will be utilised in this research.

13 mm Greywacke coarse aggregate was used due to its availability in the laboratory. The same can be said for the Philippi dune sand which was used as the fine aggregate component. The nature of the particles of the greywacke is that of an angular decent and can be seen in the image below (Figure 3.1, not to scale).

Figure 3.1: 13mm greywacke

Philippi dune sand was the chosen fine aggregate. The procedure for preparing the fine aggregate included oven drying it for 24 hours (and then allowing it to cool) in order to reduce any additional moisture absorbed by the particles left exposed to the Cape Town environment. The particles can be seen in Figure 3.2. The sieve analysis for the batch used can be found in the appendix and indicates a fineness modulus of 2.1. This represents a sand between that of a fine and medium sand (Addis, 2008).

Figure 3.2: Philippi dune sand

3.3.2. Cement

The cement chosen for use in the mix design was that of PPC CEM II/A-L 52.5 N. According to PPC (2015), their ordinary Portland cement conforms to the 52.5 N strength class of SANS 50197-1 for common cements and is ideal for a wide range of applications within the construction industry. This particular cement product includes the addition of between 6 and 20% lime extender. The relative density is 3.14 and the approximate volume of a 50 kg bag is +-33 litres.

3.3.3. Laboratory equipment

The following are the main equipment used throughout the laboratory work and is visually shown below. Their use will be described in further sections when applicable.

- Slump testing apparatus:
  The slump test equipment comprises a mould, base plate and tamping rod.

Figure 3.3: slump test apparatus

- Scale:
  The scale is vital in establishing the correct material quantities to be used in the production of the respective concrete strengths.

Figure 3.4: scale

- Concrete mixer:
  The concrete mixer enables consistent mixing of aggregate, cement and water which make up the concrete.

Figure 3.5: mixer

- Specimen Moulds:
  Due to availability of these moulds as well as ideal pull-off test surface area requirements, these wooden moulds were used.

Figure 3.6: specimen moulds

- Curing tanks:
  The concrete curing tanks consist of water that is kept at a temperature of 22-24 degrees Celsius which is used for 28 day curing of all specimens.

Figure 3.7: curing tank

- Drying oven:
  Used initially to dry the fine aggregate and later used to dry the concrete specimens that required oven drying as their moisture condition. Temperature set at 50 degrees Celsius.

Figure 3.8: drying oven

- Compression testing machine (Amsler machine):
  The Amsler machine was used for all cube strength testing.

Figure 3.9: Amsler machine

- Coring machine:
  Used for the partial coring requirements recommended for the pull-off testing in EN1542 (1999).

Figure 3.10: coring machine

3.4. Concrete Specimen details

3.4.1. Dimensions

Cube specimens were all made using the 100 mm plastic moulds and hence the dimensions were 100 mm x 100 mm x 100 mm. The plastic moulds enabled consistency amongst all cube specimens as well as enabled ease of removing cubes from moulds once partially hardened (after 24 hours).

Average Hexagon mould dimensions are as follows:

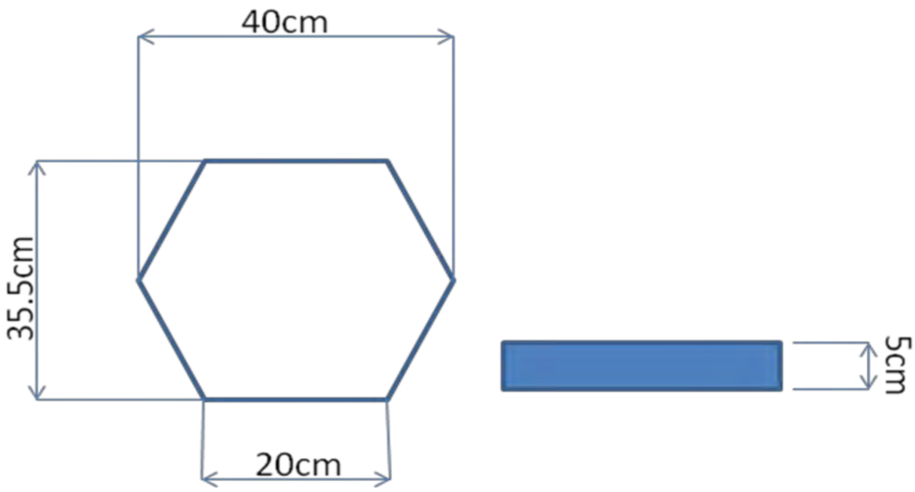


Figure 3.11: hexagon mould dimensions

3.4.2. Mix designs used

The following trial mixes were obtained for both the 30 MPa and 40 MPa concrete mix designs:

- 30 MPa: using a water to binder ratio of 0.7

		For 1m^3	
	Density (kg/m^3)	Mass (kg)	Volume (m^3)
water	1000	185	0.185
CEMII/A-L 52.5N	3140	264	0.084
13mm greywacke	2700	1050	0.389
Philippi dune sand	2650	906	0.342

Table 3.1: 30 MPa mix design

- 40 MPa: using a water to binder ratio of 0.55

		For 1m^3	
	Density (kg/m^3)	Mass (kg)	Volume (m^3)
water	1000	185	0.185
CEMII/A-L 52.5N	3140	336	0.107
13mm greywacke	2700	1050	0.389
Philippi dune sand	2650	845	0.319

Table 3.2: 40 MPa mix design

3.4.3. Casting and curing

For each of the above two strength mixes, 9 x concrete hexagon specimens and 6 x concrete 100 mm cubes were cast. The total concrete volumes for each were calculated to be approximately 0.055 m^3 and the mix designs subsequently altered.

The raw materials were then prepared and thoroughly measured to ensure minimal obscurities and material losses. Once preparation was complete, the components were thoroughly mixed using the concrete mixer. The slump test apparatus was then prepared and the test done according to the method described in Addis (2008) with results being recorded as per the test requirements. Addis (2008) states that the slump test is done in accordance with SABS Method 862-1:1994 and is a measure of concrete consistency. This test is standard and was done for both concrete mixes. After the test the concrete used is placed back into the mixer and subsequently mixed back into the original concrete contents.

The plastic cube moulds and wooden hexagon moulds were thoroughly cleaned and all internal faces coated with a release agent in anticipation of being filled with the concrete mix. The concrete was then placed in the moulds and then vibrated in order to achieve suitable compaction. The cube specimens were levelled using a steel float where necessary, this was not done for the hexagon specimens as using a float hardens the surface and also the surface was to be sandblasted. All specimens were then covered with polythene sheeting for 24 hours.

Figure 3.12: prepared mould and concrete filled moulds to be vibrated

Figure 3.13: specimens prior to placement of sheeting

After the 24 hour period which allows for initial hydration and hardening, the specimens were all de-moulded, labelled and placed in the concrete curing tanks for the next 28 days to ensure complete hydration is achieved and majority of strength is developed.

Figure 3.14: de-moulded specimens

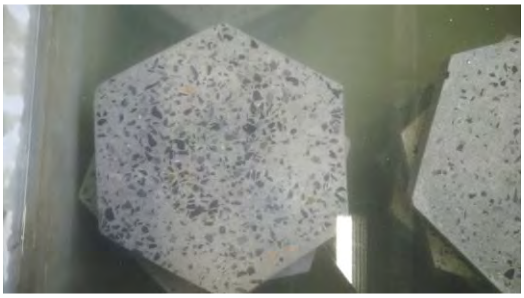


Figure 3.15: specimens curing

3.4.4. Compressive strength testing procedure

The Amsler machine was used to do compressive strength testing on all cubes. Three cubes from each mix were tested at 7 days after underwater curing and then another three of each mix at 28 days after underwater curing. Load testing was done after cubes were weighed and the machine was loaded with the cubes still in a saturated condition. Load was applied to side faces as cast (Addis, 2008).

3.5. Substrate preparation

3.5.1. Surface profile details

The surfaces of all specimens were to be prepared identically. The surface to be achieved was to be sound, free from any contaminants and profiled to a roughness suitable for application of a coating. The chosen method was wet sandblasting as this method provides the most reliable and uniform surface profile development to be achieved over all specimens, this method is also suitable as the specimens will be saturated after they have been suitably profiled thus providing no need to prevent moisture from entering the specimens. Concrete repair manual (ACI and BRE, 2003) describes the effective profile achieved through the use of abrasive blasting techniques. The achievable profiles are between CSP2 and CSP5, with CSP3 being the most commonly achieved profile. The CSP 3 profile as indicated in the literature review section (Figure 2.2) was therefore aimed at, with aggregate exposure at the surface, as this profile is suitable for most types of coatings. Aggregate exposure is achieved due to the cement being eroded by the action of the high pressure water and sand mixture being projected onto it and the typical surface profile achieved can be seen in Figure 3.20 below showing the aggregate. It is also important to note that some of the specimens showed outcrops of aggregates on the surface that had set close together, these outcrops are due to the dry concrete mixture but showed no signs of honeycombing. These outcrops could have been due to the low workability and consistency of the mix but will be discussed later. The aim of the wet sandblasting was simply to remove any potential layers of laitance that may have formed at the surface of the substrates to be coated. The wet sandblasting also minimises any potential bruising or micro-cracking of the substrate surface and also aids in cleaning the surface. The grading analysis for the sand used for sandblasting can be found in the appendix below the dune sand sieve analysis. The below images show the apparatus used as well as the before and after specimen surfaces.

Figure 3.16: wet sandblasting

Figure 3.17: motor and pump

Figure 3.18: sandblasting sand with feed hose

Figure 3.19: substrate surface prior to sandblasting

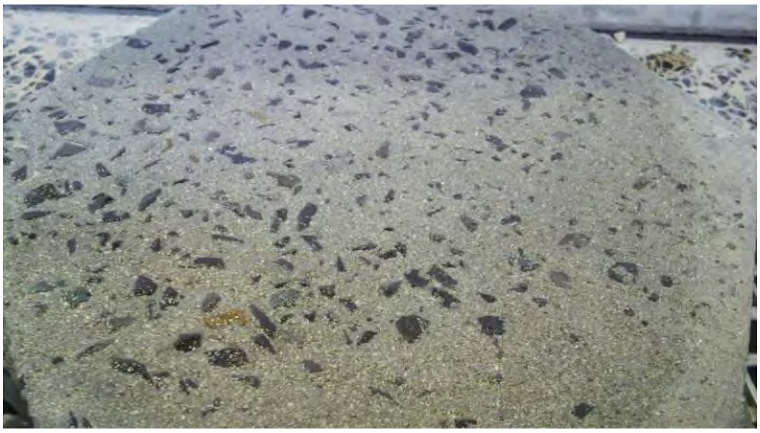


Figure 3.20: substrate surface after sandblasting

The specimens were removed from the curing tanks only after 28 days and allowed to dry for 24 hours prior to wet sandblasting. Once the surfaces were prepared sufficiently using this method of sandblasting they were once again placed in the curing tanks to allow for saturation.

Although in South Africa formed faces are usually the exposed faces requiring protection from external forces, the practical nature of the pull-off test requires it to be preferably done on horizontal element surfaces. The enhancements in the pull-off equipment technology now enables more accurate readings along any face (be it vertical or horizontal). Baring this in mind, the choice of using the unformed face (as is the case for cast in-situ slabs) was done to ensure a level specimen (as provided by the bottom formed face) with the unformed face requiring minimal attention as it is to be wet sandblasted and profiled accordingly. This implied that the surface finish was only important after it was profiled. Had the need been to use a more basic method of surface profiling (such as wire brushing) then the use of the formed face would have been considered due to the fact that a minimal amount of surface material would effectively be profiled. Since a uniform surface layer is to be removed by wet sandblasting (up until a level of sound concrete) the use of the unformed compared to the bottom formed surface will have a minimal effect on the pull-off test results for the coatings as they are mechanically and chemically bonded to the new enhanced surface profile.

3.5.2. Preparation and Cleaning methods prior to coating

The chosen coatings were applied to concrete substrates that had three differing moisture conditions. Each coating was applied to 3 x 30 MPa specimens and 3 x 40 MPa specimens. These 3 (3 x 30 MPa and 3 x 40 MPa) were each subjected to different moisture conditions.

The substrate moisture conditions were as follows:

- Moisture condition 1: Oven dried.

For this condition the specimens were oven dried for 36 hours at 50 degrees Celsius and then left to cool for a further 24 hours in the oven room of the main laboratory prior to any coating application. The temperature of the room was 23 degrees Celsius with a relative humidity of 50%

Figure 3.21: specimens oven dried

- Moisture condition 2: Dried under ambient conditions.

Specimens were removed from the curing tanks and left to dry under ambient conditions (within the laboratory at 23 degrees Celsius with a relative humidity of 50%) for 24 hours prior to any coating application.

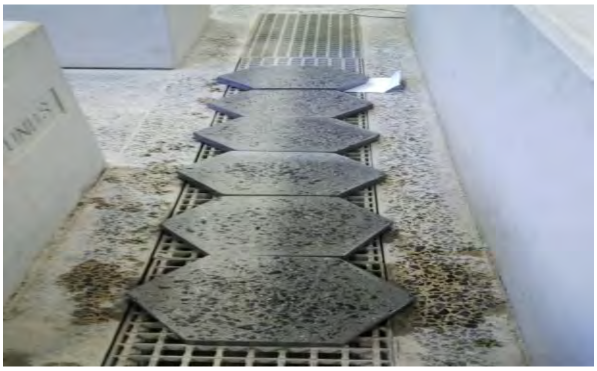


Figure 3.22: ambient drying

- Moisture condition 3: Prepared according to coating requirements.

Each of the three product datasheets (found in the appendix) were used to prepare the respective specimens prior to application. These requirements are discussed in the section to follow (3.6.3. below). The substrates moisture conditions are stated by the supplier as being damp, pre-wetted and saturated surface dry prior to coating.

3.6. Coating details

3.6.1. Selected products

The following inorganic (cementitious based) coating types were chosen:

1. Coating 1: Sikagard-720 Epochem.

   Three-part, epoxy modified cementitious, thixotropic, fine textured mortar for levelling and finishing of concrete, mortar or stone surfaces (product datasheet 1, 2012). Layer thickness to be between 0.5 mm and 3 mm.

   Components consist of: Part A – resin (white liquid), Part B – hardener (transparent yellow liquid), Part C – filler (aggregate powder).

Figure 3.23: Sikagard-720 Epocem

2. Coating 2: SikaTop Armatec-110 Epochem.

Cementitious, epoxy resin compensated three-component coating material with corrosion inhibitor, used as bonding primer and reinforcement corrosion protection. Meets the requirements of EN 1504-7. (product datasheet 2, 2012). Layer thickness to be 1 mm.

Components consist of: Part A – white liquid, Part B – colourless liquid, Part C – light grey powder.

Figure 3.24: SikaTop- Armatec 110

3. Coating 3: SikaTop Seal-107 ZA.

Two-part polymer modified cementitious waterproof mortar slurry comprising of a liquid polymer and a cement based mix incorporating special admixtures. Complies with the requirements of EN 1504-2 as a protective coating. (product datasheet 3, 2012). Layer thickness to be between 0.75 mm and 1.5 mm

Components consist of: Part A – liquid polymer and additive (white liquid), Part B – Portland cement selected aggregate and admixtures (grey or white powder).

Figure 3.25: SikaTop Seal-107

3.6.2. Product preparation

The following preparation methods and requirements were followed according to the prescribed methods in each of the 3 product datasheets (product datasheet 1/2/3, 2012).

Coating 1: Prior to mixing, shake part A briefly, then pour into the container of part B and shake vigorously for at least 30 seconds. The mixed binder (A+B) can now be poured into a suitable mixing container (30l) and then part C is gradually added whilst stirring with a power mixer. Mix thoroughly for 3 minutes until a uniform mix is achieved.

Coating 2: Shake A and B thoroughly before opening. Pour liquid contents A+B into a mixing container and mix for 30 seconds. While mixing components A+B slowly add component C. mix the three components together for 3 minutes, minimising the addition of air. Leave contents to stand for 5-10 minutes until coating exhibits a brush-able, weakly dripping consistency. A low speed (<250 rpm) electric drill mixer may be used.

Coating 3: Shake part A. Pour approximately half of part A into the mixing container and add part B whilst slowly mixing. Add the remainder of part A and continue mixing until a uniform lump free consistency has been achieved.

Please note that due to laboratory restrictions all mixing was done manually but consistency and uniformity for all coatings were monitored and thoroughly inspected prior to use. No high speed mixing was identified in the coating requirements and hence manual mixing was deemed sufficient, provided all components were mixed together to form a homogeneous coating.

3.6.3. Application and curing (product datasheet 1/2/3, 2012)

Coating 1: The substrate must be damp but free of standing water and free of all contaminants. The concrete substrate must also be sound and of sufficient compressive strength (minimum of 25 N/mm^2) with a minimum pull off strength of 1.5 N/mm^2. The substrate must be prepared mechanically using abrasive blast cleaning or high pressure water jetting equipment to remove cement laitance, especially oil or wax containing layers and achieve an open textured surface. All dust, loose and friable material must be completely removed from the surface prior to coating application preferably by brush or vacuum.

The coating can then be applied onto the matt-damp substrate and spread evenly using a trowel or spatula. Assuming matt-damp conditions as being free of standing water with no lightening of the concrete surface (due to surface drying). A layer thickness of between 0.5 mm and 3.0 mm should be achieved.

Figure 3.26: Applied Coating 1

The curing details are as follows: 14 days @ +10°C, 7 days @ +20°C and 4 days @ +30°C. Hence due to laboratory conditions a full cure at 7 days was expected.

Coating 2:

The substrate surface shall be thoroughly pre-wetted and not be allowed to dry before application of the concrete coating. The concrete shall be free from dust, loose material, surface contamination and any materials which may reduce the bond or prevent suction or wetting by repair materials.

First layer should be applied approximately 1.0 mm thick. Application can be done using medium hard brush or spray gun. To achieve good bond the coating must be applied well into the substrate, filling all pores.

Figure 3.27: Applied Coating 2

According to the datasheet, the details for the curing treatment include protecting the fresh mortar from rain while it is setting. They specify a waiting time of 12 hours @ +20°C before application of a patching mortar or concrete. Therefore curing for a minimum of 3 to 5 days will be sufficient for this experiment.

Coating 3:	The substrate must be prepared by suitable mechanical preparation techniques such as high pressure water jetting, needle guns, blastcleaning, scabblers etc. and properly pre-wetting to a saturated surface dry (SSD) condition. Once again achieving a SSD condition is to be assumed (due to a lack of provided instructions and literature) as being free from standing water and with no surface colour changes. The substrate must also be structurally sound and free from all traces of contaminants.

Apply the coating either mechanically, by spray or by hand using a stiff brush. Coating is generally applied in the same direction. Layer thickness between 0.75 mm and 1.5 mm thick.

Figure 3.28: Applied Coating 3

The coating must be cured immediately after application for a duration of 3 to 5 days in order to achieve full cement hydration and minimise cracking. Polythene sheeting or similar approved methods may be used to achieve this. Curing will be done for a minimum of 5 days using a polythene sheet.

All three coatings will therefore be cured under a polythene sheet for 7 days at a laboratory temperature of 23°C to ensure full cement hydration prior to any pull-off testing. This 7 day period is above the recommended for full cure according to the datasheets provided. Once the product has fully cured then it can be put in use. This notion is tested and therefore a 28 day cure would be insignificant for this investigation in light of the curing details provided by the manufacturer for each of the three identified coatings.

3.7. Pull-off test details

3.7.1. Requirements

Vicroads (2013), which makes reference to AS 1580, AS 1580.408.5, and EN 1542:1999 to describe the test method used to determine the tensile bond strength of concrete repairs which use mortars, grouts, concretes and other products, was consulted to further investigate the pull-off test requirements for the concrete coating systems. This literature was therefore applicable to the requirements of this investigation.

The following was described and summarised within the document (Vicroads, 2013):

- Circular cross-section steel test dollies to be used having a diameter of 50 mm +-0.5 mm and a thickness of at least 20 mm. These dollies should ensure that tensile load can be applied normal to the identified test surface so as to minimise the risk of any shear force being generated.

  A high strength solventless adhesive, usually a two-pack epoxy, shall be used to secure the dolly to the test surface. The following adhesive was made available by the laboratory.


Figure 3.29: Two-pack adhesive


Figure 3.30: Glued test dollies

The available adhesive is manufactured by HBM and is a two-component fast curing adhesive (mainly used to secure strain gauges) that is composed of an acrylopolymer based on methyl methacrylate with inorganic extender. The usage as an adhesive under strain measurements makes it suitable for use in tension under relatively low loads.

At least 3 test sites will be chosen to do the bond test per specimen.

- Core drilling will be done using a diamond coring barrel with an axis at 90 degrees +-1 degree to the surface. The core will be drilled through the coating to a depth of at least 15 mm beyond the coating and into the concrete substrate.

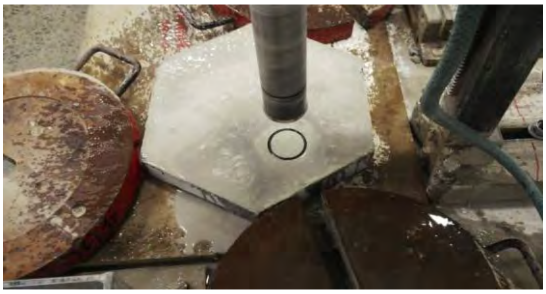


Figure 3.31: partial coring

Figure 3.32: partial core

- Before applying the test dolly, the surface to be tested must be cleaned in order to remove any loose materials on the surface. Grinding equipment can be used to clean the dolly itself, followed by degreasing and drying to remove any moisture along the side where the adhesive is to be applied. A thin layer of adhesive can now be applied to the surface of the specimen so that the adhesive will form a uniform layer between the dolly and the outer surface of the core. The dolly is now placed on the core face so that the centre of the dolly coincides with the centre of the core itself. Pressure should then be applied to the top of the dolly in order to expel any entrapped air and carefully remove extruded adhesive once done. The adhesive should then be allowed to harden as per manufacturer's specifications.

- Once the adhesive sets, the load can be applied. The load is to be applied continuously and at an even rate. The rate of load application should not exceed 10 N/sec until failure. The load at failure is then recorded.

- The type of failure is then determined from a visual assessment. The types of failure will be recorded and described under the results and interpretation of results section that is to follow.

3.7.2. Proceq DY-216

The apparatus made available for the pull-off test is that of the Proceq DY-216. Proceq (2014) states that the Proceq DY-2 family of automated pull-off testers covers the complete range of pull-off applications with unmatched ease of operation. The Proceq DY-216 has a working range of 1.6 to 16 kN tensile force and 0.81 to 8.1 MPa stress range using a test disc diameter of 50 mm which covers most applications. The standards that are conformed to are: EN 1542, EN 1015-12, EN 1348, ISO 4642, BS 1881 Part 207, ASTM D4541, ASTM C1583, ASTM D7234-05, ASTM D7522, ZTV-SIB 90, JGJ126-2000, JGJ144-2004, JGJ110-2008.

One of the advantages of using this device is that a constant load rate is achieved using integrated, feedback controlled motors. The device also allows the selection of the standard the operator wishes to use as a reference and therefore the standard chosen was EN 1542 for all the pull-off tests that were performed. Automatic calculation of bond strength (given in units of MPa) was also a benefit of this device.

The test discs were thoroughly cleaned of adhesive traces by first heating the dried adhesive found on the end of the disc to a temperature that allowed it to be safely removed using a steel scraper. The process was repeated until all adhesive was removed from the face of the disc. The scraper was always parallel to the surface of the disc so that no damage to the surface of the disc could occur. The disc was then left to cool before being reused, thus no deformation could occur. The discs were prepared identically for all specimen testing and hence partial or whole adhesive failure will not be due to this preparation method.

Figure 3.33: Proceq DY-216

Following the recommendation found in standard EN 1504-2 for the use of standard EN 1542 for adhesion testing, it is clear that the above method and equipment was suitable for the pull-off test requirements. The substrates to be tested include a wet sandblasted finish to sound concrete at the surface of the substrate as well as known strength characteristics of the substrate through compressive cube strength testing, thus there was no need to test the cohesive strength of the substrate surface prior to coating application. The standard does recommend the substrate surface be tested but for the purposes of this experiment along with insight into the known characteristics of the substrates it was deemed unnecessary. The surface preparation was done according to methods described in the concrete repair manual (ACI and BRE, 2003) and the substrate surface moisture was found to be sufficiently dry when checked using the polythene sheet method (described in section 2.6.1.V).

4. Results and Interpretation of results

4.1. Introduction

The results to follow are a true representative of actual work done within the laboratory and will be interpreted as accurately as possible taking into account any anomalies. The methods used to obtain the following results were shown in the previous section.

4.2. Slump tests

The slump test for each mix:

30 MPa mix gave a measured slump of 1 mm (which is interpreted as a zero slump) and the 40 MPa mix gave a slump of 20 mm. The workability of the 30 MPa mix was very low as the mix was very dry. Plasticizer is a simple means of adjusting the slump without affecting the strength, but for this experimental work it was not deemed necessary as strength was the only influencing factor to be considered. The same can be said for the 40 MPa mix but the 20 mm slump indicates a better consistency than that of the 30 MPa.

The visual results can be seen below:

Figure 4.34: 30 MPa slump test

Figure 4.35: 40 MPa slump test

4.3. Cube strength tests

100 mm Cube strength tests were done for each of the strength mixes at both 7 and 28 days wet curing. The saturated cubes were weighed before each of the tests in order to establish the respective densities. The cube crushing tests were also done using saturated cubes as previously described.

The average results of three tested specimens are as follows (Individual results can be found in the appendix):

- Average 7 and 28 day values:

Table 4.1: average 7 day and 28 day cube strengths

		Weight (kg)	Density (kg/m^3)	Crushing strength (kN)	Compressive strength (MPa)
7 day	30 MPa	2.27	2270	231	23.1
	40 MPa	2.268	2268	335.5	33.6
28 day	30 Mpa	2.328	2328	301.96	30.2
	40 Mpa	2.326	2362	402	40.2

4.4. Pull-off tests

Once the specimens and coatings were prepared in-line with the details and requirements previously discussed, the following pull-off test results were obtained. The bond strengths as well as the visual failures were recorded and will now be discussed. Three pull-off tests were done per specimen and the average will then be taken.

Tester used: Proceq DY-216

The tests were only done once each of the applied coatings had sufficiently cured according to their respective datasheets (curing for 7 days was done). Adequate curing was ensured in order to allow each of the coatings to obtain the best possible bonding criteria to the substrate surface to be achieved. This is important as the coatings are cementitious in nature and therefore require time to cure in order to hydrate. Specimens were all exposed to laboratory conditions and therefore no preference in favour of a particular coating was established.

Failure types with regard to the substrate, interface between the substrate and the coating, the coating, the interface between the coating and the adhesive, and the adhesive will be discussed and visual evidence obtained will be shown in order to validate the failure and any potential anomalies found within the results.

The results are as follows:

- Pull-off test bond strength results:

	Coating 1: Sikagard 720		**Coating 2: Armatec 110**		**Coating 3: SikaTop Seal 107**	
	30 MPa	**40 MPa**	**30 MPa**	**40 MPa**	**30 MPa**	**40 MPa**
moisture condition 1	111* (MPa)	112* (MPa)	211* (MPa)	212* (MPa)	311* (MPa)	312* (MPa)
	1.22	2.99	0.79	1.2	0.21	0.27
	1.68	1.82	1.05	1.55	0.2	0.13
	1.26	2.72	1.39	1.32	0.13	0.14
average:	**1.39**	**2.51**	**1.08**	**1.36**	**0.18**	**0.18**
standard deviation	**0.25**	**0.61**	**0.30**	**0.18**	**0.04**	**0.08**
moisture condition 2	121* (MPa)	122* (MPa)	221* (MPa)	222* (MPa)	321* (MPa)	322* (MPa)
	2.44	3.08	0.73	2.5	0.13	0.5
	2.28	2.43	2.36	1.72	0.13	0.39
	2.46	3.14	2.17	1.84	0.2	0.44
average:	**2.39**	**2.88**	**1.75**	**2.02**	**0.15**	**0.44**
standard deviation	**0.10**	**0.39**	**0.89**	**0.42**	**0.04**	**0.06**
moisture condition 3	131* (MPa)	132* (MPa)	231* (MPa)	232* (MPa)	331* (MPa)	332* (MPa)
	2.32	2.1	2.82	2.09	0.42	0.74
	2.77	2.82	2.78	2.37	0.6	0.69
	2.68	2.36	1.47	1.94	0.26	0.8
average:	**2.59**	**2.43**	**2.36**	**2.13**	**0.43**	**0.74**
standard deviation	**0.24**	**0.36**	**0.77**	**0.22**	**0.17**	**0.06**

Table 4.3: Pull-off test results

The *xyz in the above table indicates the coding system used. The three digits indicate coating number, substrate moisture condition and substrate strength respectively.

The following graphs represent the above results and are given in order to establish any trends and hence make the comparison and reasoning behind differences easier to obtain and visualise.

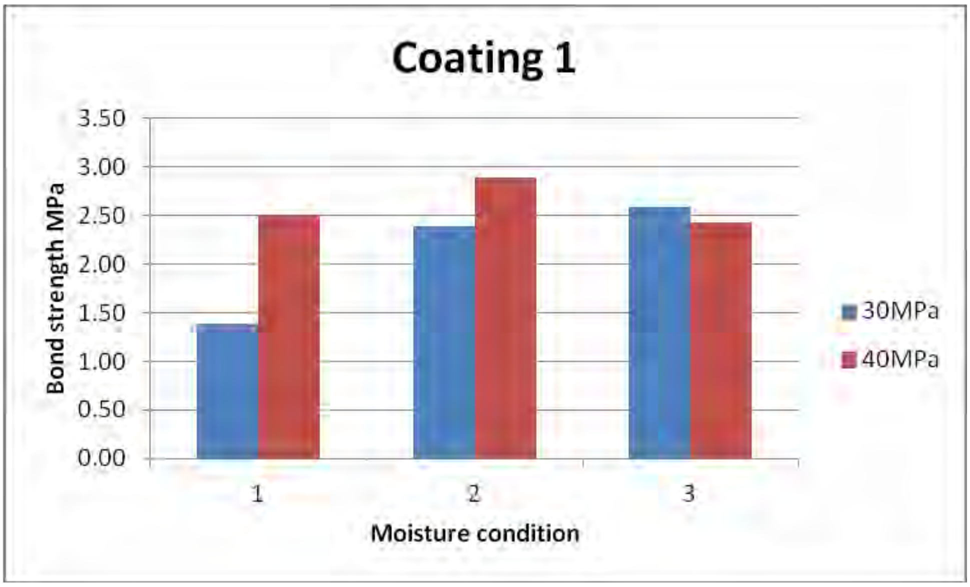


Figure 4.36: coating 1 average bond strengths

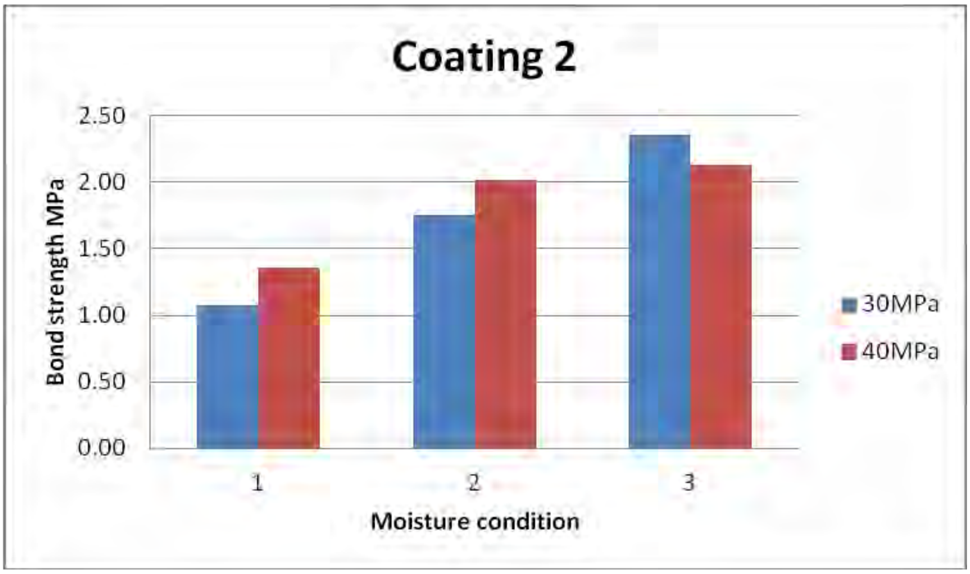


Figure 4.37: coating 2 average bond strengths

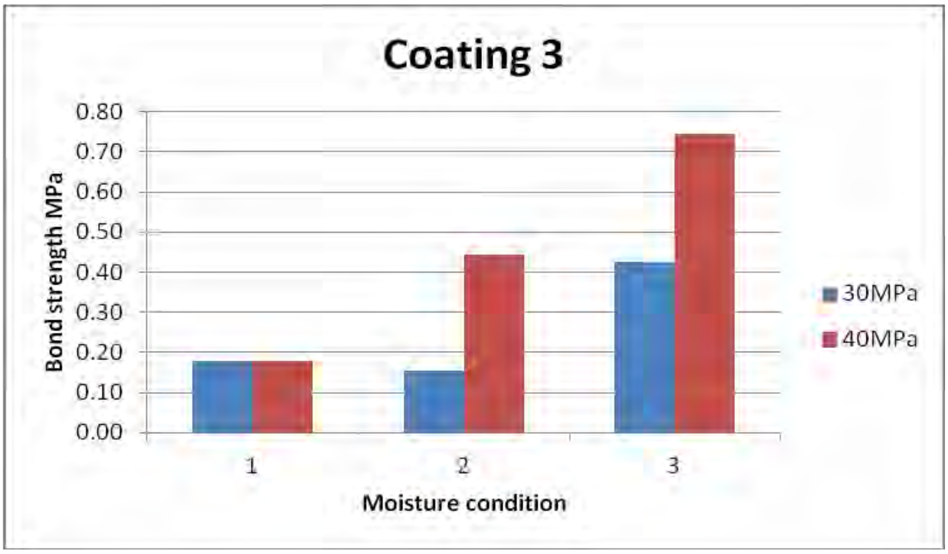


Figure 4.38: coating 3 average bond strengths

4.4.1. Statistical analysis of Pull-off results

Statistical Analysis of the data is required in order to compare the mean values obtained during the pull-off tests. The statistical methods to be used for the analysis include the Student t-test as well as the ANOVA (analysis of variance) test.

The two tests are briefly described:

I. Two-sided two-sample t-Test assuming equal variance

"This function performs a two-sample Student's t-test to test the null hypothesis that the population means of two groups are equal, or "not different". This version of the test assumes that the variance of the two data sets are equal" (Morgan and Deming, 2006). This test is therefore useful when comparing the average bond strengths of the 30 MPa and 40 MPa substrates for each of the 3 coatings.

The analysis involves the following set of equations (Morgan and Demming, 2006) with the aim of obtaining a t statistic to allow comparison and conclusion on the outcome of the stated null hypothesis:

- Firstly calculate the mean of each group $\bar{X}_i$, where i is the population group and is 2 for this type of test.
- Then state the number of test samples per group, n_i.
- Once that has been done then the below equation (1) can be used to calculate the sum of squares (SS) for each of the two groups.

$$SS = \sum x^2 - \frac{(\sum x)^2}{n} \text{.....1}$$

- Once you have obtained the means ($\bar{X}1$ and $\bar{X}2$), the number of samples (n1 and n2) per group, and the sum of squares (SS1 and SS2) for each group, you can use the below equation (2) to calculate a t value ($t_{calculated}$).

$$t = \frac{\overline{X1} - \overline{X2}}{\sqrt{\left[\frac{SS1 - SS2}{n1 + n2 - 2}\right]\left[\frac{1}{n1} + \frac{1}{n2}\right]}} = \frac{\overline{X1} - \overline{X2}}{\sqrt{\left[\frac{SS1 + SS2}{2n - 2}\right]\left[\frac{2}{n}\right]}} = \frac{\overline{X1} - \overline{X2}}{\sqrt{\frac{2(SS1 + SS2)}{2n^2 - 2n}}}$$
$$= \frac{\overline{X1} - \overline{X2}}{\sqrt{\frac{2(SS1 + SS2)}{2(n^2 - n)}}} = \frac{\overline{X1} - \overline{X2}}{\sqrt{\frac{SS1 + SS2}{n^2 - n}}} \text{......2}$$

- For an independent t-test the degree of freedom is calculated as follows using equation 3.

$$df = n1 + n2 - 2 \text{......3}$$

- The degree of freedom (df) along with the specified significance level (alpha α) is now used to identify the critical t value. The two-tailed t-Test includes a reference t table (found in the appendix) which is now used to obtain the $t_{critical}$ value.

- A comparisson is made between the absolute value for the calculated t and the critical t (found in the table).

  If the $t_{calculated}$ is less than $t_{critical}$ then the results are not significant at the alpha level (for a 95% confidence interval, alpha is taken as 0.05 probability level). This implies that the differences in means between the two groups cannot be statistically significant or meaningful at the 0.05 probablility level.

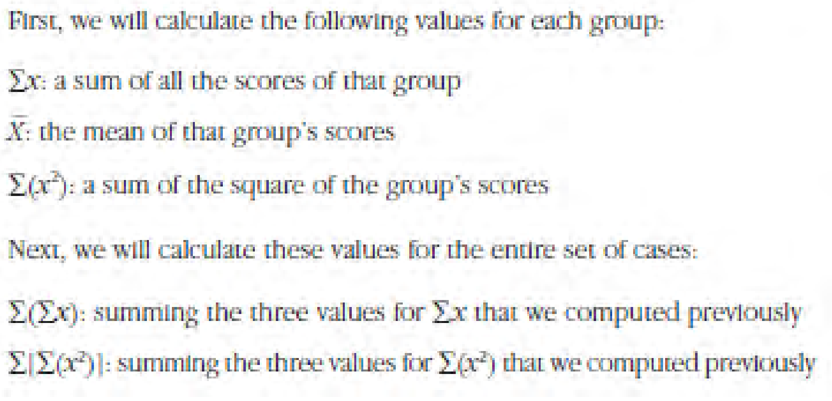
II. One-way analysis of variance (ANOVA)

"This tool performs a "one-way analysis of variance" to test for the significance of differences among the means of more than just two groups. Specifically, one-way analysis of variance (ANOVA) tests the null hypothesis that the different groups all have the same popultation mean ($H_0 = \mu_1 = \mu_2 = \mu_3$) versus the alternative hypothesis (H_a) that at least one group mean is different from the others" (Morgan and Deming, 2006).

The steps for performing this analysis is given by Morgan and Deming (2006) as follows:

- The test is fundamentally based on the previous t-test except using a greater amount of samples to be compared. The first step is to sum the data found in each group, and then once again calculate the averages of each of the groups. The inividual scores (group data) must then be squared and then summed.

- Once these are obtained then the more complex summations can be done for the entire dataset (including all individual groups). Shown in the last two steps of the below equations (4).



First, we will calculate the following values for each group:

$\sum x$: a sum of all the scores of that group

$\bar{X}$: the mean of that group's scores

$\sum(x^2)$: a sum of the square of the group's scores

Next, we will calculate these values for the entire set of cases:

$\sum(\sum x)$: summing the three values for $\sum x$ that we computed previously

$\sum[\sum(x^2)]$: summing the three values for $\sum(x^2)$ that we computed previously

......4

- The following three equations are used to calculate the sum of squares required for this analysis.

$$SS\ total = \sum(\sum(x^2)) - \frac{[\sum(\sum x)]^2}{N} \text{......5}$$

$$SS\ between = \sum\frac{(\sum x)^2}{n} - \frac{[\sum(\sum x)]^2}{N} \text{......6}$$

$$SS\ within = SS\ total - SS\ between \text{......7}$$

- The mean squares (MS) for the between groups and within groups is now calculated using equations 8 and 9.

$$MS\ between = \frac{SS\ between}{df\ between} \text{......8}$$

$$MS\ within = \frac{SS\ within}{df\ within} \text{......9}$$

- The F statistic (similar in theory to the t statistic) can now be calculated using the MS values above.

$$F = \frac{MS\ between}{MS\ within} \text{......10}$$

The steps can be combined to form the below equation, but care must be taken so that correct placement of values is done.

$$F = \frac{MS\ between}{MS\ within} = \frac{\frac{SS\ between}{df\ between}}{\frac{SS\ within}{df\ within}} = \frac{\frac{SS\ between}{df\ between}}{\frac{SS\ total - SS\ between}{df\ within}}$$

$$= \frac{\left(\frac{\sum\frac{(\sum x)^2}{n} - \frac{[\sum(\sum x)]^2}{N}}{n(groups) - 1}\right)}{\left(\frac{\left[\sum(\sum(x^2)) - \frac{[\sum(\sum x)]^2}{N}\right] - \left[\sum\frac{(\sum x)^2}{n} - \frac{[\sum(\sum x)]^2}{N}\right]}{N - n(groups)}\right)} \text{......11}$$

- As with the previous test, a table must now be consulted to obtain a critical value. The F table (found in appendix) can now be used to obtain $F_{critical}$. The degrees of freedom for both MS between and MS within must be used along with the alpha probability level to identify the F critical value.

- Compare $F_{calculated}$ to $F_{critical}$, if $F_{calculated}$ is higher then this implies that there is a statistically significant differenece between the means of the groups. The test does however not state which group is causing the difference (or the number of groups (example groups A B C)) and a further test can then be done by comparing the means of, say, AB AC and BC. A suitable t-test can be done to achieve a more suitable result regarding the difference and which two groups are significantly different.

III. Results using the above tests

- For the Two-sided two-sample t-Test, it made sense to compare the pull-off strength results for each of the concrete substrate strengths (30 MPa and 40 MPa). This will be done for each specific moisture condition. Therefore a total of 9 t-tests (labelled test 1 through 9 below) will be performed. The tests will be done using the t-test formulation function obtainable through Excel. The results were manually verified using the aforementioned steps and equations prior to executing all 9 tests. The individual analyses can be found in the appendix.

  The below table (Table 4.3) highlights the important factors found within the results of the Excel analysis of the two-tailed t-tests having assumed equal variance and an alpha of 0.05 (95% confidence):

Table 4.3 t-test summary

	Coating 1: Sikagard 720			Coating 2: Armatec 110			Coating 3: SikaTop Seal 107		
	m/c 1	m/c 2	m/c 3	m/c 1	m/c 2	m/c 3	m/c 1	m/c 2	m/c 3
Test number	1	2	3	4	5	6	7	8	9
t calculated	-2.93	-2.09	0.65	-1.39	-0.47	0.48	0	-5.11	-3.07
t critical	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78
P(T<=t)	0.04	0.104	0.55	0.23	0.66	0.65	1	0.007	0.04

It is important to remember that the null hypothesis is that there is no difference between the means of the two samples. Therefore an alternative hypothesis would be that there is a statistically significant difference between the means. Results will be analysed in the section that follows this.

- For the ANOVA test, the three datasets to be compared were chosen to be the moisture conditions (m/c 1,2 and 3) for each coating on a particular substrate strength. Therefore a total of 6 tests were performed. The Excel results can once again be found in the appendix.

Excel ANOVA summary:

Table 4.4 ANOVA test summary

	Coating 1		Coating 2		Coating 3	
	30 MPa	40 MPa	30 MPa	40 MPa	30 MPa	40 MPa
test number	1	2	3	4	5	6
F calculated	28.55	0.8	2.5	6.2	5.46	58.77
F critical	5.14	5.14	5.14	5.14	5.14	5.14
P-value	0.00089	0.49	0.16	0.035	0.045	0.00012

Once again it is important to remember the null hypothesis in order to correctly evaluate whether or not the mean values for each moisture conditions are statistically different or not. In this case the null hypothesis is also that there is no difference between the means of each group or that the means of each group are equal.

The results will be interpreted in the section to follow.

4.4.2. Pull-off failure modes

In order to fully understand the extent of the results obtained the following failure criteria must first be discussed. After the failure modes have been described, visual inspection images will follow. This will aid in the interpretation of the above graphs obtained. Hence reference to these graphs will only be made once the failure of each individual test has been provided.

Vicroads (2013) states the following Failure modes:

- A: Tensile (cohesion) failure in the concrete substrate
- A/B: Bond (adhesion) failure at the interface between the substrate and the repair material (product)
- B: Tensile (cohesion) failure in the repair material (product)
- B/Y: Bond (adhesion) failure at the interface between the repair material (product) and the adhesive layer. (Not stated in the document by Vicroads (2013) but deemed relevant nonetheless).
- Y: Tensile (cohesion) failure in the adhesive layer
- Y/Z: Bond (adhesion) failure between the adhesive layer and the test dolly.
- Z: Failure of the test dolly or apparatus

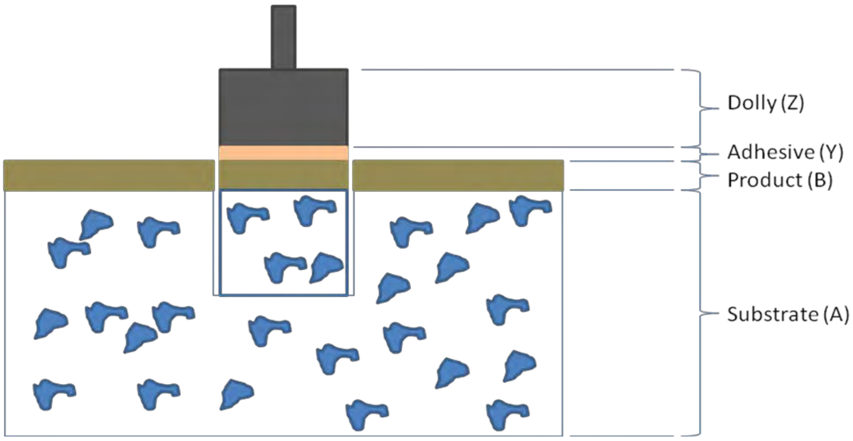


Figure 4.39: test components

Vicroads (2013) goes further to state that if there is a combination of these types of failure, a visual inspection shall be made of the failure face to assess and report the percentage of each type of failure which will be based on the surface area. The percentage will be rounded to the nearest 10%. The accuracy is therefore not extremely important but merely acts as a guide in the interpretation of the said results.

The obtained failure modes can be seen in the following table (Table 4.4):

Table 4.5: failure modes

	Actual Failure modes					
	Coating 1: Sikagard 720		**Coating 2: Armatec 110**		**Coating 3: SikaTop Seal 107**	
	30 MPa	**40 MPa**	**30 MPa**	**40 MPa**	**30 MPa**	**40 MPa**
moisture condition 1	111*	112*	211*	212*	311*	312*
Failure modes	B	A	B	B	B (90%) + B/Y (10%)	B (80%) +B/ Y (20%)
	A	A	B	B	B	B
	B (60%) + Y (10%) + B/Y (30%)	B	B	B	B (90%) +B/ Y (10%)	B
moisture condition 2	121*	122*	221*	222*	321*	322*
Failure modes	A	A	A (10%) + B (30%) + B/Y (60%)	B	B	B (90%) +B/ Y (10%)
	A (90%) + B (10%)	A	A (10%) + B (90%)	B	B	B (60%) +B/ Y (40%)
	A	A	B	B	B (70%) + A(20%) + B/Y (10%)	B
moisture condition 3	131*	132*	231*	232*	331*	332*
Failure modes	A	A	A	A	B	B
	A	A	A	A	B	B
	A (70%) + B (30%)	A	A	A (50%) + B (40%) + B/Y (10%)	B	B (90%) + B/Y (10%)

*note that no actual bond failure between the coatings and the substrate was found.

4.4.3. Visual inspection of Pull-off test

The visual inspection can be summarised as follows:

Table 4.6: visual inspection coating 1

<table>
<tr><td rowspan="2"></td><td colspan="2">Coating 1: Sikagard 720</td></tr>
<tr><td>30 MPa</td><td>40 MPa</td></tr>
<tr><td>Moisture condition 1</td><td></td><td></td></tr>
<tr><td>Moisture condition 2</td><td></td><td></td></tr>
<tr><td>Moisture condition 3</td><td></td><td></td></tr>
</table>

Table 4.7: visual inspection coating 2

<table>
<tr><td rowspan="2"></td><td colspan="2">Coating 2: Armatec 110</td></tr>
<tr><td>30 MPa</td><td>40 MPa</td></tr>
<tr><td>Moisture condition 1</td><td></td><td></td></tr>
</table>

Moisture condition 2		
Moisture condition 3		

Table 4.8: visual inspection coating 3

	Coating 3: SikaTop Seal 107	
	30 MPa	40 MPa
Moisture condition 1		
Moisture condition 2		
Moisture condition 3		

The following anomalies were noted during the inspection and were therefore deemed as influencing factors on the registered loads during the tests:

- Post sandblasting: exposed aggregate patches were noticed on the following specimens – 121*, 211*, 311* and 321*. These patches were avoided where possible when choosing the partial core locations.
- Actual coating layer thicknesses that were achieved were as follows:

Coating 1 – 3.0 mm to 4.0 mm (epoxy modified cementitious micro mortar)
Coating 2 – 1.0 mm to 1.5 mm (epoxy resin modified bonding primer)
Coating 3 – 1.0 mm to 1.5 mm (polymer modified cementitious slurry)

These are all on the maximum thicknesses or slightly over due to the difficulty in measuring the coating thickness whilst it is being applied. The coverage areas expected from the three coatings was used as a base for estimating the amount of material required to cover each of the six specimens (for each coating). This is also believed to be a better representation of the quantity and thicknesses being achieved on site given the common application equipment used by most construction companies. An attempt to measure the wet film thickness was not used as the expected coating coverage area was found to be a defining factor for many on-site applications. The direct dry film thickness was measured using a vernier calliper along the edges of the cored profile to give an average coating thickness per specimen which was deemed sufficient to represent the overall coating thickness for the purposes of this investigation. Further experimental work can be done in the future when investigating the effects of coating thickness on bond strength. This investigation however is only concerned with the application of one coat of the coating and as such the actual dry film thickness of the coats was within range of that expected. Time constraints regarding the saturation condition of the moisture condition 3 specimens as well as the setting time of the coatings to be applied hindered the process of being able to precisely measure the wet film thickness so that option would have been hurried resulting in unreliable results.

4.5. Interpretation of results:

Considering all the above results the following can be said with regard to the pull-off tests.

4.5.1. Statistical analysis results can be interpreted as follows:

I. t-Test analysis

The results from the t-test can be interpreted as follows in order to establish whether or not the mean values achieved on both the 30 MPa substrate and 40 MPa substrates are statistically different from each other for each of the applied coats and at a specific moisture condition. This therefore relates the pull-off strengths to the substrate strength differences only. Note that t calculated value is taken as an absolute value for comparison to t critical value.

For Coating 1 (Sikagard-720 EpoCem)

- Moisture condition 1:

t calculated (= 2.93) > t critical (= 2.78)

This indicates that there is a statistically significant difference between the mean bond strengths of coating 1 applied to 30 MPa and 40 MPa substates exposed to moisture condition 1.

- Moisture condition 2:

t calculated (= 2.09) < t critical (= 2.78)

The above indicates that there isn't a statistically significant difference between the mean bond strengths of the two substrates.

- Moisture condition 3:

t calculated (= 0.65) < t critical (= 2.78)

This results in the same as above in that there is not a statistically significant difference between the two means.

For Coating 2 (SikaTop Armatec-110 EpoCem)

- Moisture condition 1:

t calculated (= 1.39) < t critical (= 2.78)

Once again this comparison is indicating no statistically significant difference between the mean values.

- Moisture condition 2:

t calculated (= 0.47) < t critical (= 2.78)

This results in the same conclusion as above.

- Moisture condition 3:

t calculated (= 0.48) < t critical (= 2.78)

Again indicating no statistically significant difference in mean values is obtained.

For Coating 3 (SikaTop Seal-107 ZA)

- Moisture condition 1:

t calculated (= 0) < t critical (= 2.78)

For this coating at moisture condition 1 we again see no significant difference between the means.

- Moisture condition 2:

t calculated (= 5.11) > t critical (= 2.78)

This indicates a statistically significant difference in mean bond strengths, which would indicate that a sample set is larger than the other.

- Moisture condition 3:

t calculated (= 3.07) > t critical (= 2.78)

This results in a statistically significant difference between the mean bond strength values and thus will need further investigating.

II. ANOVA analysis

The following is an interpretation of the results obtained through the ANOVA analysis. The null hypothesis is to be employed here as well.

For Coating 1 (Sikagard-720 EpoCem)

- 30 MPa substrate strength:

  F calculated (= 28.55) > F critical (= 5.14)

  This indicates that there is a statistically significant difference between the mean coating bond strengths having various moisture conditions applied to the 30 MPa substrates.

- 40 MPa substrate strength:

  F calculated (= 0.8) < F critical (= 5.14)

  The above indicates that there isn't a statistically significant difference between the mean bond strengths of the moisture conditions.

For Coating 2 (SikaTop Armatec-110 EpoCem)

- 30 MPa substrate strength:

F calculated (= 2.5) < F critical (= 5.14)

This indicates that there isn't a statistically significant difference between the mean coating bond strengths having various moisture conditions applied to the 30 MPa substrates.

- 40 MPa substrate strength:

F calculated (= 6.2) > F critical (= 5.14)

The above indicates that there is a statistically significant difference between the mean bond strengths of the moisture conditions.

For Coating 3 (SikaTop Seal-107 ZA)

- 30 MPa substrate strength:

F calculated (= 5.46) > F critical (= 5.14)

This indicates that there is a statistically significant difference between the mean coating bond strengths having various moisture conditions applied to the 30 MPa substrates.

- 40 MPa substrate strength:

F calculated (= 58.77) > F critical (= 5.14)

This indicates that there is a statistically significant difference between the mean coating bond strengths having various moisture conditions applied to the 40 MPa substrates.

III. Summary of important factors:

The statistically significant differences in bond strength noted above are as follows:

- Substrate strength influences on bond strength.

For the case of substrate strengths the bond strength achieved by coating 1 having a moisture condition 1 indicated that the 40 MPa substrate had potentially shown a large increase in average bond strength when compared to the 30 MPa substrate average result, or the 30 MPa has potentially achieved a mean bond strength value less than the 40 MPa substrate.

Coating 3 when applied to substrates with a moisture condition of type 2 and 3 (ambient dried and SSD conditions respectively) has shown that the substrate strengths (30 MPa and 40 MPa) have shown statistical differences in mean value comparison. For moisture condition 2 t calculated was much higher than t critical therefore indicating the largest difference in mean values. This can be interpreted as the 40 MPa substrates mean bond strength being much higher than the 30 MPa substrates mean bond strength. The same interpretation can be given for the moisture condition 3 with the difference in mean being statistically less than that for moisture condition 2.

- Moisture condition influence on bond strength.

Interpreting the results of the ANOVA test results show the following tests having statistically significant differences when comparing the mean bond strengths obtained from various moisture conditions.

For coating 1 applied to a 30 MPa concrete substrate the F calculated was more than 5 times greater than the critical F. This indicates that there is a large difference between the mean bond strengths obtained from the 3 moisture condition tests. The analysis doesn’t provide sufficient details to identify which condition is providing the largest statistical difference but considering the mean results in Table 4.3 the largest difference can be seen between results from moisture condition 3 and moisture condition 1.

Coating 2 applied to the 40 MPa substrate has also shown a statistically significant difference in means, however, not as large a difference as in the above case. The largest difference being between that of the moisture condition 3 results and the moisture condition 1 results.

Results of coating 3 applied to both the 30 MPa and the 40 MPa have shown that the moisture conditions provide mean values that are statistically significant in their differences. For the application to the 30 MPa substrate, the difference in mean values is not as large, which can be interpreted as one of the moisture conditions allowing more favourable bond strength development than one of the others. The difference is likely to come from the comparison between moisture condition 3 and moisture condition 2 (from Table 4.3). The application onto the 40 MPa substrate has shown a F calculated value more than 10 times greater than the F critical value. This is a very large statistical difference and upon interpretation the difference in means could be due to the comparison between the means of moisture condition 3 and moisture condition 1. Although values are smaller than the 1.5 MPa provided in literature, the statistical difference is still large, thus conditions for bond strength are much more favourable on a 40 MPa substrate having a moisture condition of 3 (SSD) when compared to the coating being on a completely dry surface.

4.5.2. From the tables and graphs:

Coating 1: (Sikagard-720 EpoCem)

- Differences between the two strength categories (30 MPa and 40 MPa) for each moisture condition (m/c) is given below:

m/c 1	Failure modes were only the same for 1 out of the 3 tests done. Most common failure mode being that of failure in the concrete substrate. 40 MPa is more likely to favour a higher bond strength which has been shown in the statistical analysis above. Comparison of the means confirm this result.
m/c 2	Failure within substrate for both strengths.
m/c 3	The stronger concrete substrate gave poorer pull-off strength results in this instance. Failure within the substrate was dominant once again. The mean values are however statistically not significantly different.

- Difference between the moisture conditions of the 30 MPa strength class:

m/c 1 and m/c 2	Predominantly coating layer failure for m/c 1 and predominantly substrate failure for m/c 2, hence the high percentage difference.
m/c 2 and m/c 3	Indicating that there is a small difference between the ambient dried moisture condition and the product

	specific condition. This is due to the similar failure modes experienced. m/c 3 also failed predominantly in the substrate.
m/c 1 and m/c 3	High difference is once again due to the dominancy experienced by each moisture conditions failure mode. Similar failure to that experienced between m/c 1 and m/c 2 above.

- Difference between the moisture conditions of the 40 MPa strength class:

m/c 1 and m/c 2	Predominantly failure in the substrate layer for m/c 1 and only substrate failure for m/c 2.
m/c 2 and m/c 3	The results indicate that moisture condition 3 gave lowest results. Failure was due to substrate failure for m/c 3.
m/c 1 and m/c 3	Similar failure as for m/c 1 and m/c 2 above. m/c 3 is however still the lowest registered average strength.

All the above mean comparisons have been shown to be statistically insignificant and therefore no distinct conclusions can be made as there are potentially no major differences (within a 95% confidence).

Coating 2: (SikaTop Armatec-110 EpoCem)

- Difference between the two strength categories (30 MPa and 40 MPa) for each moisture condition (m/c) is given below:

m/c 1	Failure within the coating layer was experienced by both substrate strength classes.
m/c 2	Majority of failure was that of coating failure however the poorer substrate strength experienced two out of the three tests as failure within the coating and partly within the substrate.
m/c 3	Mean results Indicate that the 40 MPa substrate gave potentially lower pull-off strengths than the 30MPa substrate. This condition predominantly failed within the substrates for both strength classes.

Statistically the mean comparison of these moisture conditions had no significant influence and hence no influencing factors are noted.

- Difference between the moisture conditions of the 30 MPa strength class:

m/c 1 and m/c 2	majority of failure for m/c 2 was within the substrate, whereas m/c 1 only had failure in the Coating layer only.

m/c 2 and m/c 3	The lowest difference shows that the ambient dried moisture condition behaved similar to the saturated surface dry condition when considering the other two percentage differences. The failure mode for m/c 3 was in the substrate only and m/c 2 had a combination of failure modes (majority being coating failure).
m/c 1 and m/c 3	Significant difference (table 4.3) between completely dry and saturated surface dry conditions. It is important to note that m/c 1 failed in the Coating and m/c 3 failed in the substrate, hence the significant difference.

The statistical analysis has shown the comparison between these mean bond strengths to be insignificant and will be treated as such.

- Difference between the moisture conditions of the 40 MPa strength class:

m/c 1 and m/c 2	Failure within the substrate for both conditions.
m/c 2 and m/c 3	Once again indicating that the ambient dried condition behaved in a similar manner to the SSD condition. Percentage difference is much closer than the above result for the 30 MPa strength class. The test showed failure in the coating for m/c 2 and predominant substrate failure for m/c 3.
m/c 1 and m/c 3	Still the highest difference although not as much of a difference as for the 30 MPa substrate. The high difference is due to the fact that m/c 1 failed within the coating and m/c 3 failed predominantly within the substrate.

These comparisons were shown to have a statistically significant difference. As explained in early sections, the likely difference will be between moisture condition 3 and moisture condition 1.

Coating 3: (SikaTop Seal-107 ZA)

- The difference between the two strength categories (30 MPa and 40 MPa) for each moisture condition (m/c) is given below:

m/c 1	Failure was within the coating as well as at the interface between the coating and the adhesive.
m/c 2	The 30 MPa strength class had two out of the three tests fail within the coating only and hence had a greater impact on the results obtained.
m/c 3	Predominant failure was within the coating layers. Once again the poorer strength class failed within the coating only and the higher strength class had an

	instance where failure was partially at the interface between the coating and the adhesive layers.

Moisture conditions 2 and 3 have both been shown to have statistical differences in average bond strength when comparing the 30 MPa and 40 MPa substrate test results.

- Difference between the moisture conditions of the 30 MPa strength class:

m/c 1 and m/c 2	m/c 2 had a portion fail within the substrate and hence this has resulted in the results being lower than both the m/c 1 and m/c 3 results.
m/c 2 and m/c 3	Indicating that m/c 3 shows a significant improvement in pull-off strength obtained. Failure within the coating layer dominated the results.
m/c 1 and m/c 3	Once again indicating that that product specific substrate moisture conditions prior to application had a significant positive influence on the results obtained.

Statistically there is a significant difference in the means and this is most likely to occur between moisture condition 3 and moisture condition 2.

- Difference between the moisture conditions of the 40 MPa strength class:

m/c 1 and m/c 2	This indicates that the moisture present due to the ambient dried substrate preparation has positively influenced the pull-off strength results.
m/c 2 and m/c 3	The failure for m/c 2 indicates that failure at the interface between the coating and the adhesive has influenced the results obtained. m/c 3 failed within the coating predominantly.
m/c 1 and m/c 3	This is a significant increase in pull-off strength. Although failure modes were very similar in each case the moisture conditions has resulted in the product specific moisture condition being superior by more than 300%.

This substrate strength class has statistically been shown to have the largest difference in mean bond strength values achieved between the three moisture conditions. The difference is likely to be between moisture condition 3 and moisture condition 1.

4.5.3. Summary of the significant results:

- Coating 1:

The highest pull-off test bond strength (2.88 MPa) was achieved by the 40 MPa substrate strength exposed to moisture condition 2.

Under oven dry conditions the mean bond strength between the 30 MPa and 40 MPa substrates were shown to differ statistically. With the 40 MPa producing a significantly higher average bond strength than the 30 MPa.

The results for the 30 MPa substrates showed a general increase in achieved bond strength as moisture within the substrate increased.

Predominant failure within the substrate was achieved for majority of cases.

- Coating 2:

Highest bond strength of 2.36 MPa was obtained by the use of the 30 MPa substrate exposed to moisture condition 3. No significant difference between the means of any of the 30 MPa and 40 MPa substrates for any moisture condition.

A significant increase in bond strength from moisture condition 1 (oven dry) through to moisture condition 3 (pre-wetted substrate) was achieved for the 40 MPa strength class. This indicates that moisture had positively influenced the results.

Failure within the coating predominated for the drier substrates and failure within the concrete substrates predominated for the product specific moisture conditions. This can be due to the coating being unable to fully hydrate as the dry substrate (produced by m/c 1) might be drawing the moisture out of the coating. This would explain the coating cohesive failure as the cementitious material in the coating is unable to form a continuous film and strengthen. The bond strength has therefore shown the need for moisture within the pores of the substrate to prevent the substrate from drawing moisture from the coating, allowing it to cure and hydrate and increase the likelihood of preventing coating failure by coating cohesion failure.

- Coating 3:

A bond strength of 0.74 MPa was achieved by the 40 MPa substrate under moisture condition 3. This was the highest average strength. Improvement in bond strength was shown to improve by using the 40 MPa substrate for moisture conditions 2 and 3.

The 40 MPa results increase almost linearly as the moisture conditions go from dry to saturated surface dry. This is not as clear a case as for the 30 MPa as partial substrate failure has influenced the results for moisture condition 2 significantly. Unsound or fractured aggregate particle could have been cause of low result. Excluding this test result would result in a positive increase between moisture condition 1 and moisture condition 2. A statistical difference exists between all moisture conditions for both the 30 MPa and 40 MPa substrate bond strength developments.

Moisture condition 1 showed severe pin holing implying that the coating moisture was being absorbed by the underlying substrate, this absorption would have forced some gas to be expelled and hence a resulting pinhole effect was seen. Moisture condition 2 showed far less pin holing along the specimen surfaces. The hydration of these coatings is once again being compromised as coating cohesive failure was experienced. The mechanical and chemical bonds between the coating and the substrate could therefore not be fully tested as the coating was not able to hold itself together. The pin holing must not be mistaken for ‘bug holes’ as the latter is a result of voids as well as cracks in the substrate surface itself. This effect would have had similar results in the other specimen results as well due to the identical nature of the specimen preparation. The gentle nature of the wet sandblasting would also have ensured that no micro cracks would have resulted and due to the sufficient compaction effort and visual inspection of the specimen surfaces, no voids were identified or recorded. Hence the defect of ‘bug holes’ is unlikely to be the reason behind the many holes found along the surface of the two moisture conditions for this particular coating. Bug holes are also found along the surface of the concrete and would have been identified post surface profiling. The resultant holes found along the coating surface under the dry conditions is therefore a clear indication that the coating moisture is forcing air out of the concrete substrate as it is being drawn into the substrate. Prior to profiling, the surface of the concrete substrate does show signs of bug holes due to the dry concrete mix used, however, post profiling the surface is clearly free from the surface voids as sound concrete was found (Figures 3.19 and 3.20).

Moisture condition 3 (product specific conditions) provided the highest results for all test cases.

Failure was predominantly within the coating for both substrate strength classes over all moisture conditions. Considering the more flexible nature of this coating compared to coating 1 and 2 (epoxy based), the resulting failure within the coating when compared to the substrate failure found to predominate the other two coatings could indicate that the flexibility along with incomplete cohesive strength development of the polymer modified cementitious mortar slurry has negatively influenced its ability to perform as expected (or at least in line with the other coatings that were subjected to identical conditions). The effect of flexibility will need further investigation to establish whether or not this is a key factor in determining the expected failure mechanism or mode. Flexible coatings will need to be tested by other methods such as peeling or shear testing. This assumption that the polymer modified coating’s flexibility has directly or indirectly affected it’s mode of failure will therefore need further investigation to be verified.

4.6. Summary

In conclusion it is clear that moisture levels within the substrate had influenced all three of the chosen coatings. The product specific moisture condition gave the highest bond strength results for coating 2 and 3. It is also clear that the mode of failure for coating 2 significantly influenced the results obtained. Failure within the substrate had resulted in pull-off strengths above 2 MPa for all coatings (coating 1 and 2 experienced this failure only) with this type of failure. Coating 3 with the lowest results had only failed within the coating layer.

Product datasheets (Sika, 2012) indicate the following achievable bond strengths:

- Coating 1 = greater than 2 N/mm^2 for EN1542 test method (3 N/mm^2 ITT results)
- Coating 2 = greater than 1.5 N/mm^2
- Coating 3 = 2 to 3 N/mm^2 (failure in substrate)

Coating 1 specimens all had bond strengths greater than 2 MPa for all conditions except for the 30 MPa moisture condition 1 specimen. Coating 2 achieved bond strength greater than 1.5 MPa for moisture conditions 2 and 3 but not for the completely dry moisture condition 1. Coating 3 was the only coating to obtain a bond strength that was not within the above range. This is due to the fact that failure had not occurred in the substrate as stated but rather within the coating layer. Failure of less than 1 N/mm^2 was achieved in the experiment.

5. Conclusions

In conclusion the following important findings are noted regarding the experimental results obtained as well the investigation as a whole:

The substrate surfaces were all made sound and clean using light wet abrasive blasting and thoroughly air blasted prior to any coating application. This being said implies that failure due to inadequate substrate preparation is unlikely to be a major influencing factor on the bond strength results achieved in this research. The quality of concrete being that of both 30 MPa and 40 MPa is also not likely to influence the results as theory tends to agree that concrete substrate strength greater than 25 MPa will enable adequate bond strength development. Considering these factors the failure experienced by the coatings suggest the following: coating 1 with the highest bond strength had failed within the concrete substrate primarily over all moisture conditions which shows that the coating performed as designed for over all moisture conditions; coating 2 performed according to the manufacturers specification (failure in the substrate) only for moisture condition 3 (SSD) with the other two moisture conditions failing within the coating (which is unacceptable); and coating 3 gave the lowest bond strength of 0.74 MPa with a primary failure within the coating itself for all moisture conditions (which is an unacceptable failure condition assuming the coating is directly comparable to the performance of the other two epoxy modified coatings).

Therefore it is clear that the first two epoxy modified cementitious coatings performed much better than the polymer modified cementitious coating under the adhesion testing method chosen for this investigation. The layer thickness and coating flexibility may have also influenced these findings as the coating 3 layer thickness was less than the other two. The results indicate that, in general, the drier the substrate the weaker the resulting bond strength. SSD conditions for epoxy modified cementitious coatings are therefore encouraged as they satisfy the theoretical requirements and this implies that the manufacturer specifications are indeed correct and can be followed to meet the minimum requirements. The polymer modified coating has however failed with regard to the pull-off test in all moisture condition cases regardless of the trend shown and an alternative method for evaluating its bond strength will need to be investigated.

The failures within the coating as a result of the drier substrate therefore negatively influenced the results of the test. This could indicate that the substrate has indeed absorbed moisture from the coating and impeded its ability to hydrate sufficiently. This phenomenon is clear from the analysis of coating 2 and coating 3 where failure within the coating was recorded. In all cases where the substrate has failed during the test, the results for bond strength have been above 2 MPa. Considering the current research results it is clear that moisture plays a vital role in the achievable bond strength as well as the mode of failure experienced by the specimen under consideration. It is therefore recommended that in practice the manufacturer’s recommendations be followed when dealing with epoxy modified cementitious coatings and polymer modified coatings be avoided until the concern over its achievable bond strength has been investigated, the flexible nature as well as the polymerization of coatings of this type has been shown to be inadequate with regards to the pull-off test only and should be taken into consideration if this is the only test made available to use. Even though the conditions for the coating were adhered to according to manufacturer specifications, the coating did not perform as expected.

6. Further investigation recommendations

With respect to the current investigation, the exact same experiment can be done only this time isolating surface preparation as the influencing factor. Different profiles can be evaluated and compared to see if the surface profile has any influence at all on the bond strength and mode of failure achieved.

Climatic exposure conditions over time after application of coatings can also be evaluated to see if prolonged exposure to moisture and temperature influences the bond negatively.

A more detailed investigation into the differences between the epoxy modified and polymer modified cementitious coatings needs to be done in order to better understand the individual effects on bond strength.

Due to the nature of organic coatings and the fact that pull-off testing is not the best option to test bond strength due to the paint like nature of these coatings, it would be wise to investigate the bond strength achieved by these types of coatings under the same conditions as was done in this investigation using more suitable testing methods.

A more suitable test for evaluating the more flexible polymer modified cementitious coating needs to be done in order to verify the results obtained from this investigation. The effect of the polymer in relation to the cement structure can be a key factor when determining the most suitable test for these types of coatings.

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Appendix

Potential coating products:

Table 1.1: Company A: Sika products

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
concrete protection						
crack bridging coating	Sikagard 550W Elastic	One-part, plasto-elastic coating based on UV-curing acrylic dispersion with excellent crack-bridging properties.	Surface must be dry, sound and free from loose and friable particles. Steam cleaning, high pressure water jetting or blast cleaning is recommended. New concrete must be at least 28 days old to ensure adequate hydration.	brush, roller or airless spray	application of sikagard 550W elastic primer may be required prior to application of this coating	
flexible coating	Sikagard 540W	One-component, acrylic emulsion based, pigmented, high build, protective coating.	same as above	brush, roller or airless spray	sealobond primer may be used.	
	SikaTop seal-107	Two-part polymer modified cementitious waterproofing mortar slurry comprising of a liquid polymer and cement based mix inclusive of admixtures.	Substrate must be structurally sound and free from traces of contaminants, loose and friable particles, cement laitance, oils and grease, etc. This can be achieved by the use of suitable mechanical preparation techniques such as high pressure water jetting, needle guns, blast cleaning, scabblers etc. and properly pre-wetted to a saturated surface dry condition. The concrete must also have a "pull off"	stiff brush or spray (slurry), trowel (mortar)		2.0 to 3.0 N/mm^2 (failure in substrate)

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
			strength greater than 1.0 N/mm^2			
	Sikalastic 150	Two-pack elastic fibre-reinforced flexible waterproofing coating. It contains an acrylic emulsion liquid component and a cement/special aggregates fibres and additives as the powder component.	Concrete must be structurally sound, dry, free from laitance, clean and free from dirt, oil, grease, other contaminants as well as free from loose or friable particles. The concrete can be prepared using mechanical techniques such as high pressure water jetting, needle guns, grit blasting, hammers etc. the substrate must be dry or slightly wet before application of coating.	trowel, roller or spray		~0.5N/mm^2 (EN1542)
chemical resistant coating	Sikagard 63N	Two-part epoxy protective coating. It is a total solid, two-part epoxy resin coating.	The substrate must be sound and of a minimum of 25N/mm^2 compressive strength with a minimum pull off strength of 1.5N/mm^2. The substrate must be prepared using abrasive blast cleaning or scarifying equipment in order to remove laitance and achieve an open textured surface.	Stiff brush, roller or airless spray.	sikafloor 156 or sikafloor 161 may be used as primer	>1.5N/mm^2 (failure in concrete)
	Sikalastic 841ST	Two-part, elastic, 100% solids, very fast curing pure polyurea liquid applied membrane.	same as above	Can only be spray applied using special two-part hot	Concrete or screed substrate has to be primed or levelled in	

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
				spray equipment.	order to achieve an even surface.	
waterproofing	Sikalastic 841ST	previously described				
	Sikalastic 150	previously described				
	SikaTop seal-107	previously described				
	Sikagard 63N	previously described				
	Sikagard 720 Epochem	Three-part, epoxy modified cementitious, thixotropic, fine textured mortar for levelling and finishing concrete, mortar or stone surfaces. Suitable for moisture control, restoration work, physical resistance, preserving or restoring passivity and/or increasing resistivity.	The substrate must be sound and of a minimum of 25N/mm^2 compressive strength with a minimum pull off strength of 1.5N/mm^2. The substrate must be damp but free from standing water and free from all contaminants. The substrate must be prepared using abrasive blast cleaning or high pressure water jetting equipment in order to remove laitance, especially oil or wax containing layers and achieve an open textured surface.	Trowel, sponge or brush. Aliva hopper gun application as well.	Primer suitable for green, damp or damp aged concrete.	>=2.0N/mm^2

Table 2.2: Company B: 3M products

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
Coatings for walls						
	External wall coating FP812	Low maintenance, high build coating for cementitious and plaster wall surfaces.	All surfaces should be clean, dry and free from contamination. A proprietary fungicidal wash should be used to treat areas of moss or lichen growth. Any areas contaminated with dirt, oil or grease should be detergent pressure washed and left to dry. All dust and loose materials should then be swept away.	brush, roller or airless spray	not necessary	
	Urethane coating XF 129	Urethane coating with excellent adhesion to correctly prepared and primed surfaces.	Clean, dry and free from contaminants.	brush, roller, airless spray or conventional spray	if needed	4 MPa (failure in concrete) ASTM D4541
corrosion protection	Encapsulating coating polynox 136	water based acrylic anti-corrosive coating specifically formulated to provide long term protection and encapsulation of previously coated structures	Surface must be free from contaminants. Wire brushing, high pressure water jetting or mechanical grinding methods may be used.	brush, roller or spray		

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
	Epoxy coating 162 CR/ 162 EP	two-component, 100% solids lining for the internals of tanks, vessels and other equipment in contact with dirty water, oils and mild aqueous chemicals. Can be used on concrete surfaces with an appropriate primer.	Light abrasive blasting or mechanical scarifying should be done, taking care not to expose the aggregate. All dust and loose residue must be removed and the surface sealed using 3M Scotchkote epoxy sealer SP810.	brush or roller	3M Scotchkote epoxy sealer SP810	

Table 2.3: Company C: Carboline products

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
Industrial Alkyds	Carbocoat	primarily for steel application				
Water-borne Acrylics	Carbocrylic 3350 ZA	Water borne acrylic latex. Formulated from durable 100% acrylic resins to protect and beautify exterior surfaces.	Must be properly primed before application of coating.	brush, roller, conventional or airless spray	yes	
Epoxy primers and finishes	Carboguard 893 SG	Epoxy polyamide with corrosion inhibitor.	Concrete must be cured 28 days at 24 degrees Celsius and 50% relative humidity. Surface should be in accordance with ASTM D4258, surface cleaning according to ASTM D4259. Voids may also require the need to be surfaced.	brush, roller, conventional or airless spray		
	Carboguard 635	Cross-linked epoxy polymeric amine.	Same as above.	same as above		
Aliphatic polyurethanes	Carbothane 1345 ZA	Single package oil-free polyurethane. A hard, tough urethane coating.	Apply directly to properly prepared concrete or other cementitious surfaces. The surface should be at least as rough as medium grit sandpaper and free from laitance. Acid etching or mechanical abrasion can be used to achieve this.	brush or roller		

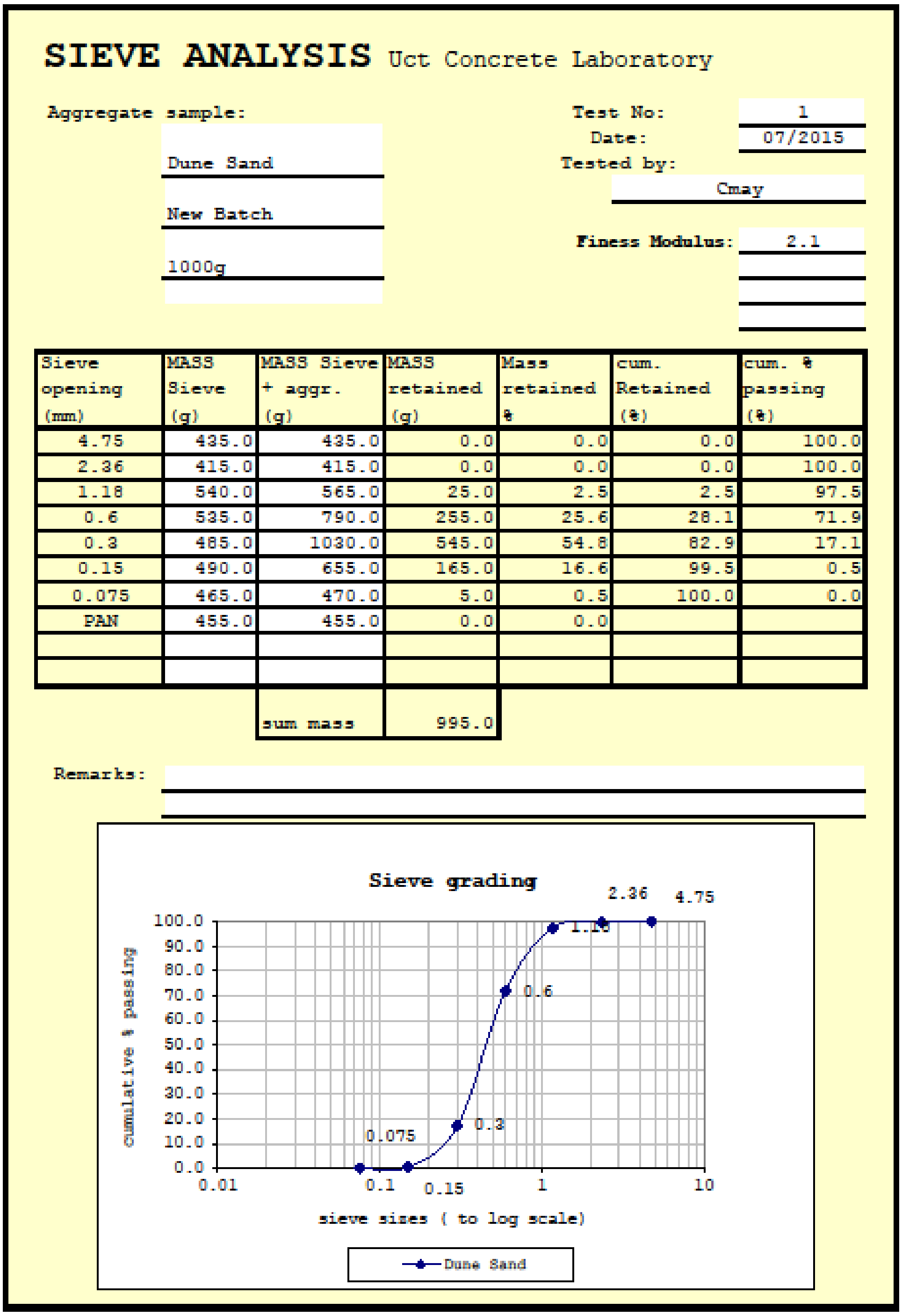
Table 2.4: Company D: Stoncor products

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
Stoncor						
coatings						
Epoxies	Pro-struct 6231	Textured high build epoxy coating.	Prepare surface and apply coating onto primed surfaces in accordance with manufacturer's detailed instructions.	trowel and textured roller	yes	
	Pro-struct 632, 632/22	High build coating, lining and grouting resin.	Proper preparation is critical to ensuring adequate bond. The substrate must be dry and free of wax, grease, oils, fats, soil, loose materials and laitance. Laitance and unbonded cement must be removed by mechanical means such as abrasive blasting or grinding. Heavy duty industrial detergents can be used to remove other contaminants. The surface must have open pores throughout with main aggregate in concrete exposed. The surface should have a sandpaper texture. The substrate's moisture content should be below 5% and the tensile strength above 2 MPa.	squeegee and medium nap roller		

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
Acrylics	Pro-struct 611	Non-yellowing curing and sealing compound.	Substrate surface must be clean and free from standing water. Any material that may affect the adhesion must also be removed.	roller or spray		
	Pro-struct 684/4	High build protective barrier.	Abrasive blasting or other methods must be done to remove laitance. Prime concrete with Pro-struct 689 and allow drying for approximately 4 hours before over coating.	brush, roller, conventional or airless spray	Pro-struct 689	
Cementitious	Pro-struct 506 flexicoat	Two-component polymer modified cementitious coating that forms an elastomeric waterproofing membrane.	Clean surface with a wire brush and thoroughly soak with water. Dampening should also be maintained immediately ahead of application in order to avoid ravelling.	block brush or spray		
waterproofing						
Acrylic, Bituminous and cementitious	Pro-struct 201	Bituminous sealer or primer for porous and non-porous surfaces.	Clean, dry and free from contaminants.	brush or roller		
	Pro-struct 203	Rubberised bituminous emulsion waterproofing.	For porous surface apply a primer coat using one-part Pro-struct 203 liquid with one-part clean water. A UV protection coating may be applied four days after application of Pro-struct 203 if required.	brush or roller	as described	

function	product	brief description	substrate quality and surface preparation requirements	application type	primer required	adhesion
crystaline and Barrier	Vandex BB75	cementitious, ready-mixed surface water proofer.	Substrate must be sound, even, open-pored, and roughened and the substrate surface must also be free from voids, large cracks or ridges. Suitable means must be used to remove any adhesion reducing substances. The substrate must be moistened and damp but not wet at the time of application.	brush, trowel or suitable spray		
self adhesive	Bituthene LM	Two-component elastomeric (asphalt-modified urethanes) liquid applied waterproofing membrane.	Surface shall be dry and free from dust, grease or other contaminants. Ambient temperature must also be greater than 5 degrees Celsius			880N/m (ASTM D-903)

Sieve analysis: dune sand



SIEVE ANALYSIS Uct Concrete Laboratory

Aggregate sample: Dune Sand

New Batch

1000g

Test No: 1

Date: 07/2015

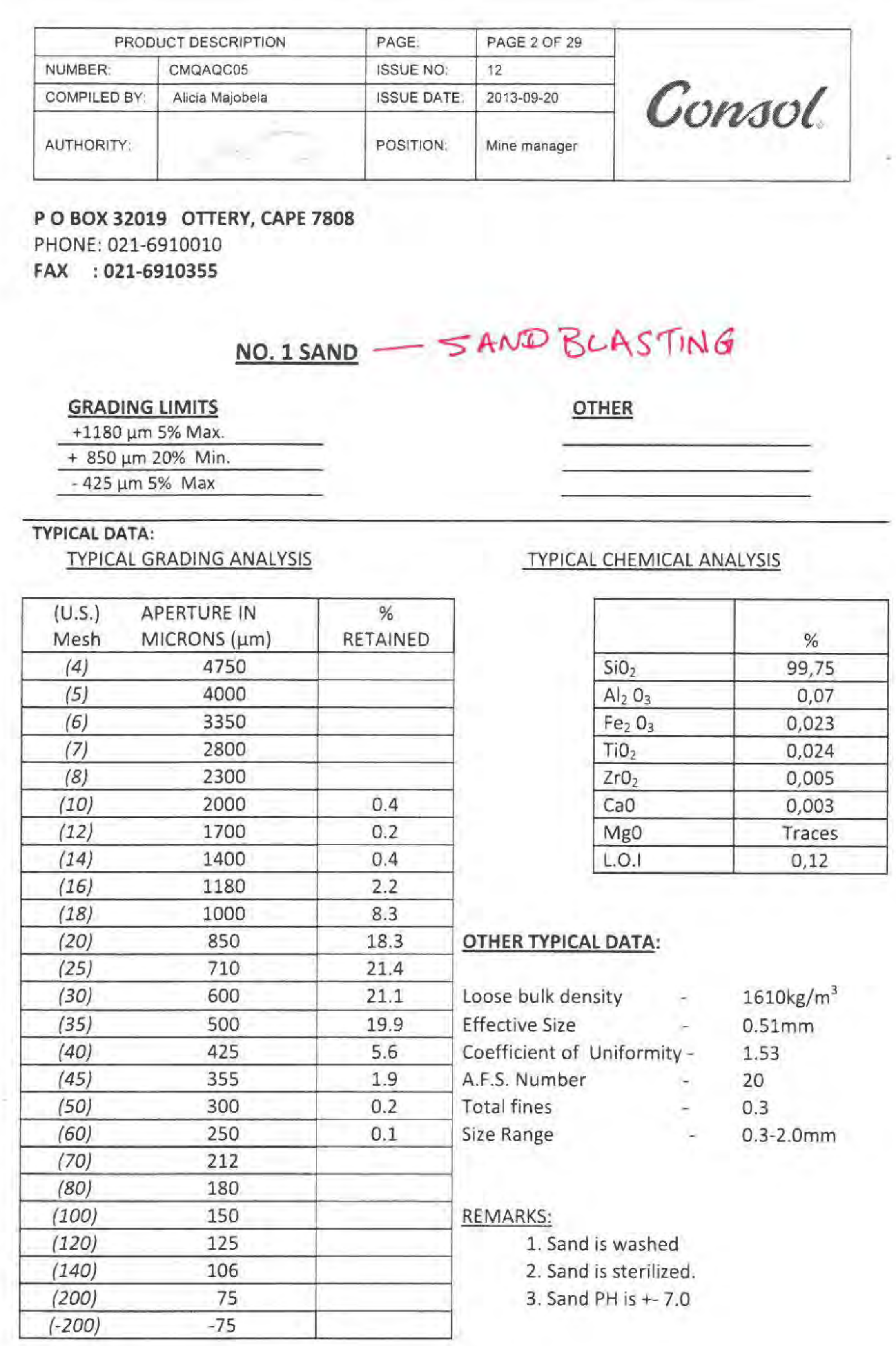
Tested by: Cmay

Finess Modulus: 2.1

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	435.0	435.0	0.0	0.0	0.0	100.0
2.36	415.0	415.0	0.0	0.0	0.0	100.0
1.18	540.0	565.0	25.0	2.5	2.5	97.5
0.6	535.0	790.0	255.0	25.6	28.1	71.9
0.3	485.0	1030.0	545.0	54.8	82.9	17.1
0.15	490.0	655.0	165.0	16.6	99.5	0.5
0.075	465.0	470.0	5.0	0.5	100.0	0.0
PAN	455.0	455.0	0.0	0.0		
		sum mass	995.0			

Remarks:

Sieve analysis: sandblasting sand



PRODUCT DESCRIPTION		PAGE:	PAGE 2 OF 29	Consol
NUMBER:	CMQAQC05	ISSUE NO:	12	
COMPILED BY:	Alicia Majobela	ISSUE DATE:	2013-09-20	
AUTHORITY:		POSITION:	Mine manager	

P O BOX 32019 OTTERY, CAPE 7808
PHONE: 021-6910010
FAX : 021-6910355

NO. 1 SAND — SAND BLASTING

GRADING LIMITS

+1180 µm 5% Max.
+ 850 µm 20% Min.
- 425 µm 5% Max

OTHER

TYPICAL DATA:

TYPICAL GRADING ANALYSIS

(U.S.) Mesh	APERTURE IN MICRONS (µm)	% RETAINED
(4)	4750	
(5)	4000	
(6)	3350	
(7)	2800	
(8)	2300	
(10)	2000	0.4
(12)	1700	0.2
(14)	1400	0.4
(16)	1180	2.2
(18)	1000	8.3
(20)	850	18.3
(25)	710	21.4
(30)	600	21.1
(35)	500	19.9
(40)	425	5.6
(45)	355	1.9
(50)	300	0.2
(60)	250	0.1
(70)	212	
(80)	180	
(100)	150	
(120)	125	
(140)	106	
(200)	75	
(-200)	-75	

TYPICAL CHEMICAL ANALYSIS

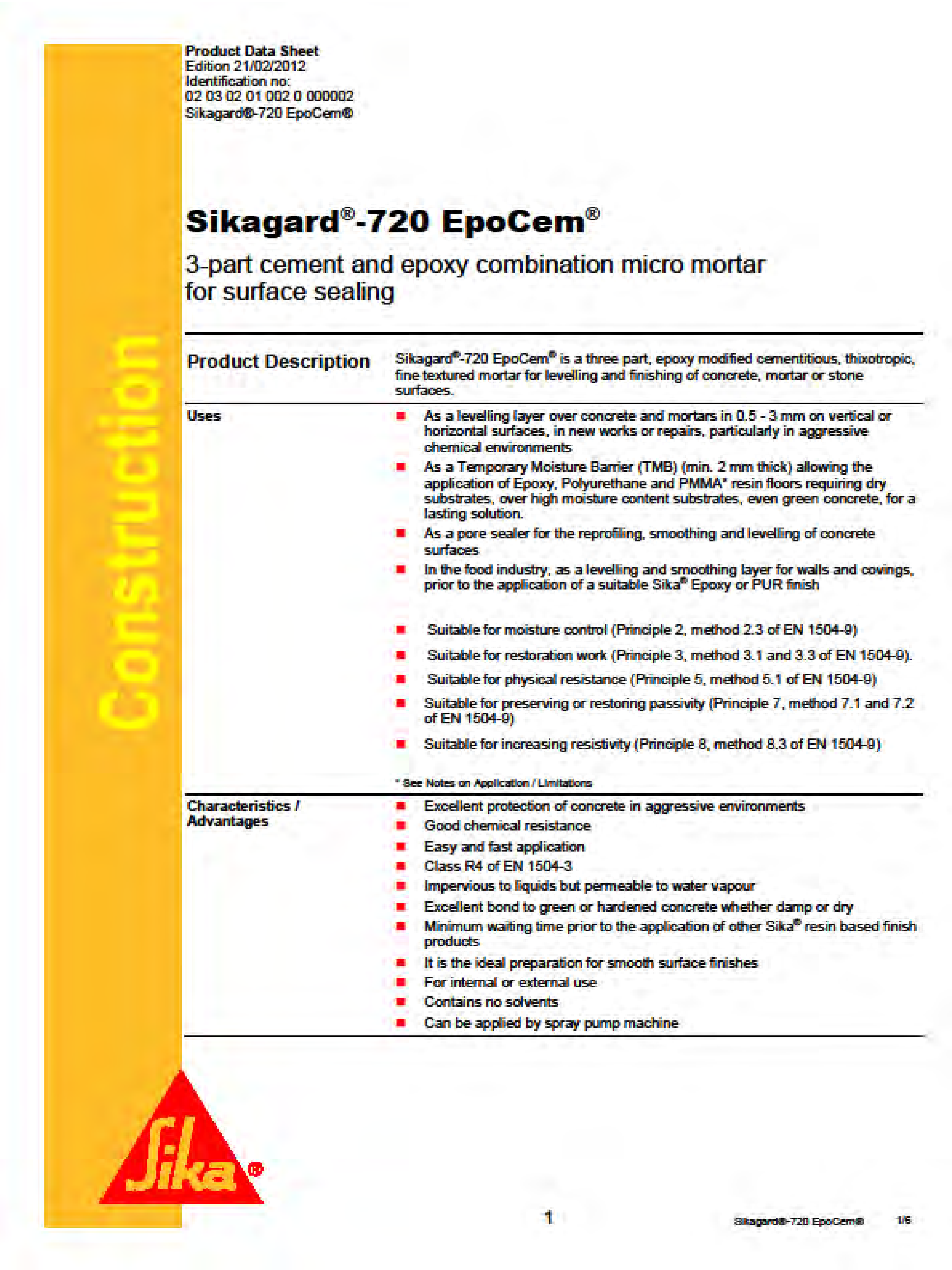
	%
SiO_2	99,75
Al_2O_3	0,07
Fe_2O_3	0,023
TiO_2	0,024
ZrO_2	0,005
CaO	0,003
MgO	Traces
L.O.I	0,12

OTHER TYPICAL DATA:

Loose bulk density - $1610kg/m^3$
Effective Size - 0.51mm
Coefficient of Uniformity - 1.53
A.F.S. Number - 20
Total fines - 0.3
Size Range - 0.3-2.0mm

REMARKS:

1. Sand is washed
2. Sand is sterilized.
3. Sand PH is +- 7.0



Product Data Sheet
Edition 21/02/2012
Identification no:
02 03 02 01 002 0 000002
Sikagard®-720 EpoCem®

Construction

Sikagard®-720 EpoCem®

3-part cement and epoxy combination micro mortar for surface sealing

Product Description	Sikagard®-720 EpoCem® is a three part, epoxy modified cementitious, thixotropic, fine textured mortar for levelling and finishing of concrete, mortar or stone surfaces.
Uses	■ As a levelling layer over concrete and mortars in 0.5 - 3 mm on vertical or horizontal surfaces, in new works or repairs, particularly in aggressive chemical environments ■ As a Temporary Moisture Barrier (TMB) (min. 2 mm thick) allowing the application of Epoxy, Polyurethane and PMMA* resin floors requiring dry substrates, over high moisture content substrates, even green concrete, for a lasting solution. ■ As a pore sealer for the reprofiling, smoothing and levelling of concrete surfaces ■ In the food industry, as a levelling and smoothing layer for walls and covings, prior to the application of a suitable Sika® Epoxy or PUR finish ■ Suitable for moisture control (Principle 2, method 2.3 of EN 1504-9) ■ Suitable for restoration work (Principle 3, method 3.1 and 3.3 of EN 1504-9). ■ Suitable for physical resistance (Principle 5, method 5.1 of EN 1504-9) ■ Suitable for preserving or restoring passivity (Principle 7, method 7.1 and 7.2 of EN 1504-9) ■ Suitable for increasing resistivity (Principle 8, method 8.3 of EN 1504-9) * See Notes on Application / Limitations
Characteristics / Advantages	■ Excellent protection of concrete in aggressive environments ■ Good chemical resistance ■ Easy and fast application ■ Class R4 of EN 1504-3 ■ Impervious to liquids but permeable to water vapour ■ Excellent bond to green or hardened concrete whether damp or dry ■ Minimum waiting time prior to the application of other Sika® resin based finish products ■ It is the ideal preparation for smooth surface finishes ■ For internal or external use ■ Contains no solvents ■ Can be applied by spray pump machine

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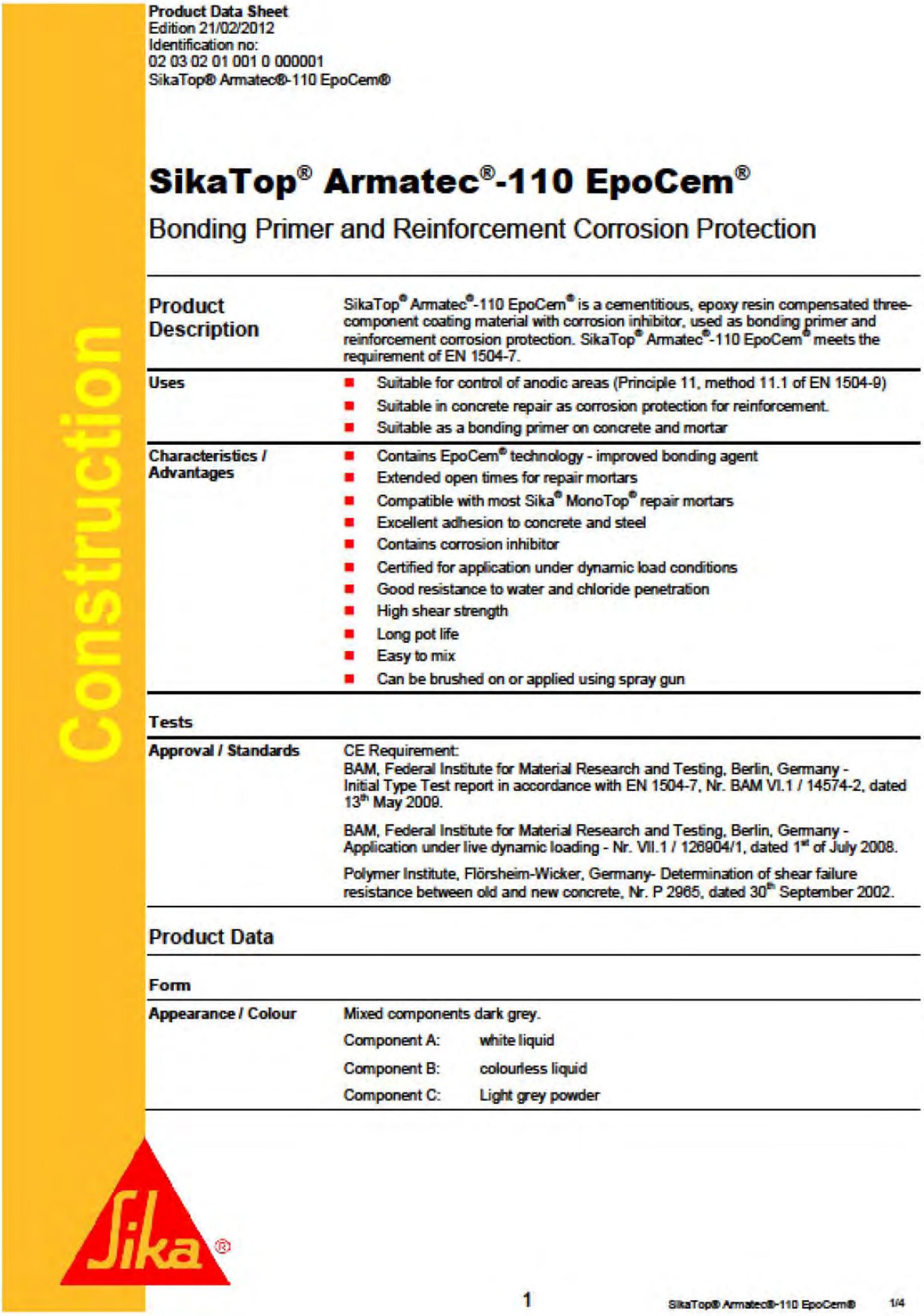
Sikagard®-720 EpoCem® 1/6



Product Data Sheet
Edition 21/02/2012
Identification no:
02 03 02 01 001 0 000001
SikaTop® Armatec®-110 EpoCem®

Construction

SikaTop® Armatec®-110 EpoCem®

Bonding Primer and Reinforcement Corrosion Protection

Product Description	SikaTop® Armatec®-110 EpoCem® is a cementitious, epoxy resin compensated three-component coating material with corrosion inhibitor, used as bonding primer and reinforcement corrosion protection. SikaTop® Armatec®-110 EpoCem® meets the requirement of EN 1504-7.
Uses	■ Suitable for control of anodic areas (Principle 11, method 11.1 of EN 1504-9) ■ Suitable in concrete repair as corrosion protection for reinforcement. ■ Suitable as a bonding primer on concrete and mortar
Characteristics / Advantages	■ Contains EpoCem® technology - improved bonding agent ■ Extended open times for repair mortars ■ Compatible with most Sika® MonoTop® repair mortars ■ Excellent adhesion to concrete and steel ■ Contains corrosion inhibitor ■ Certified for application under dynamic load conditions ■ Good resistance to water and chloride penetration ■ High shear strength ■ Long pot life ■ Easy to mix ■ Can be brushed on or applied using spray gun

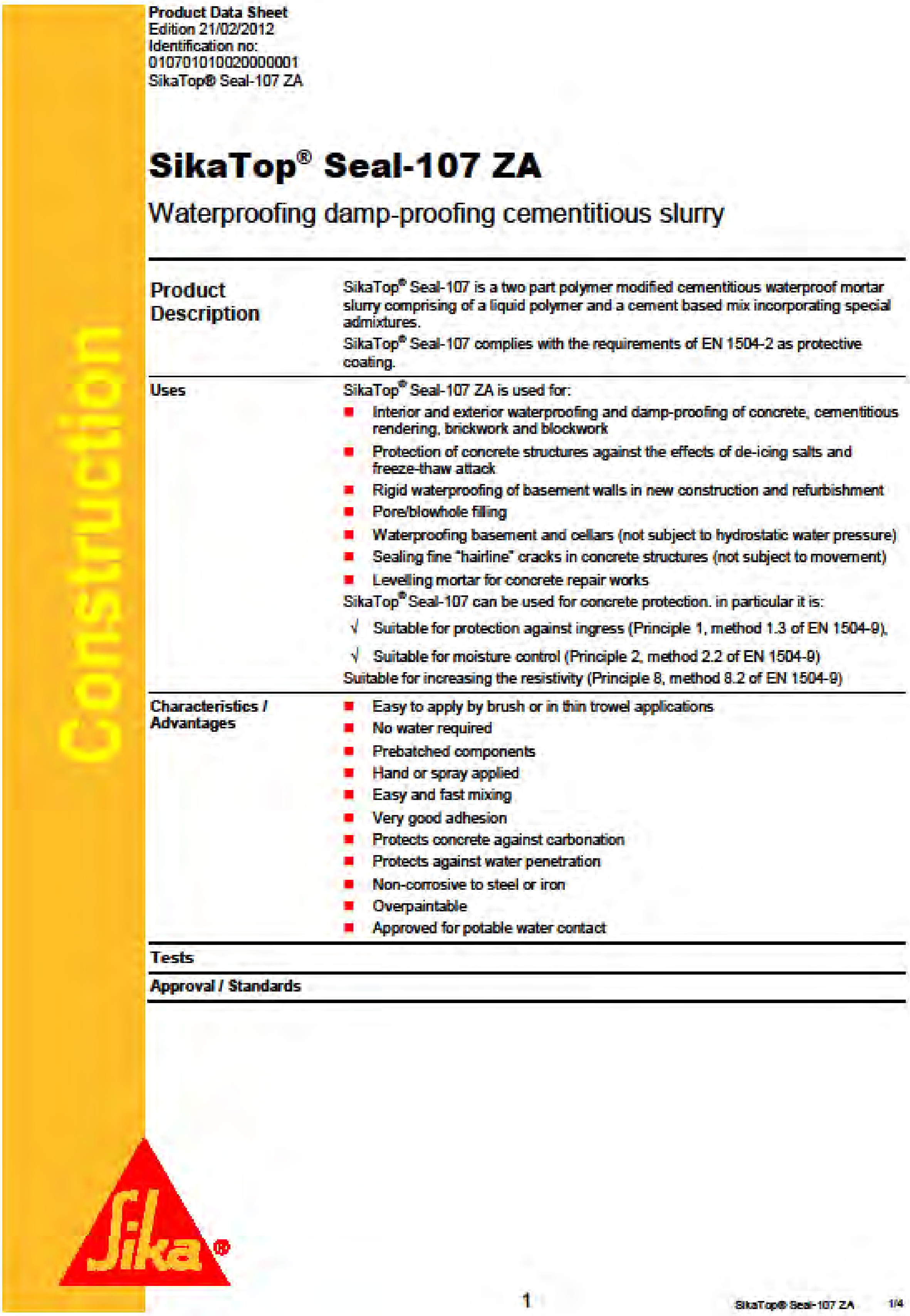
Tests

Approval / Standards	CE Requirement: BAM, Federal Institute for Material Research and Testing, Berlin, Germany - Initial Type Test report in accordance with EN 1504-7, Nr. BAM VI.1 / 14574-2, dated 13th May 2009. BAM, Federal Institute for Material Research and Testing, Berlin, Germany - Application under live dynamic loading - Nr. VII.1 / 126904/1, dated 1st of July 2008. Polymer Institute, Flörsheim-Wicker, Germany- Determination of shear failure resistance between old and new concrete, Nr. P 2965, dated 30th September 2002.

Product Data

Form

Appearance / Colour	Mixed components dark grey.	
	Component A:	white liquid
	Component B:	colourless liquid
	Component C:	Light grey powder



Product Data Sheet
Edition 21/02/2012
Identification no:
010701010020000001
SikaTop® Seal-107 ZA

SikaTop® Seal-107 ZA

Waterproofing damp-proofing cementitious slurry

Product Description

SikaTop® Seal-107 is a two part polymer modified cementitious waterproof mortar slurry comprising of a liquid polymer and a cement based mix incorporating special admixtures.

SikaTop® Seal-107 complies with the requirements of EN 1504-2 as protective coating.

Uses

SikaTop® Seal-107 ZA is used for:

- Interior and exterior waterproofing and damp-proofing of concrete, cementitious rendering, brickwork and blockwork
- Protection of concrete structures against the effects of de-icing salts and freeze-thaw attack
- Rigid waterproofing of basement walls in new construction and refurbishment
- Pore/blowhole filling
- Waterproofing basement and cellars (not subject to hydrostatic water pressure)
- Sealing fine "hairline" cracks in concrete structures (not subject to movement)
- Levelling mortar for concrete repair works

SikaTop® Seal-107 can be used for concrete protection. in particular it is:

√ Suitable for protection against ingress (Principle 1, method 1.3 of EN 1504-9),

√ Suitable for moisture control (Principle 2, method 2.2 of EN 1504-9)

Suitable for increasing the resistivity (Principle 8, method 8.2 of EN 1504-9)

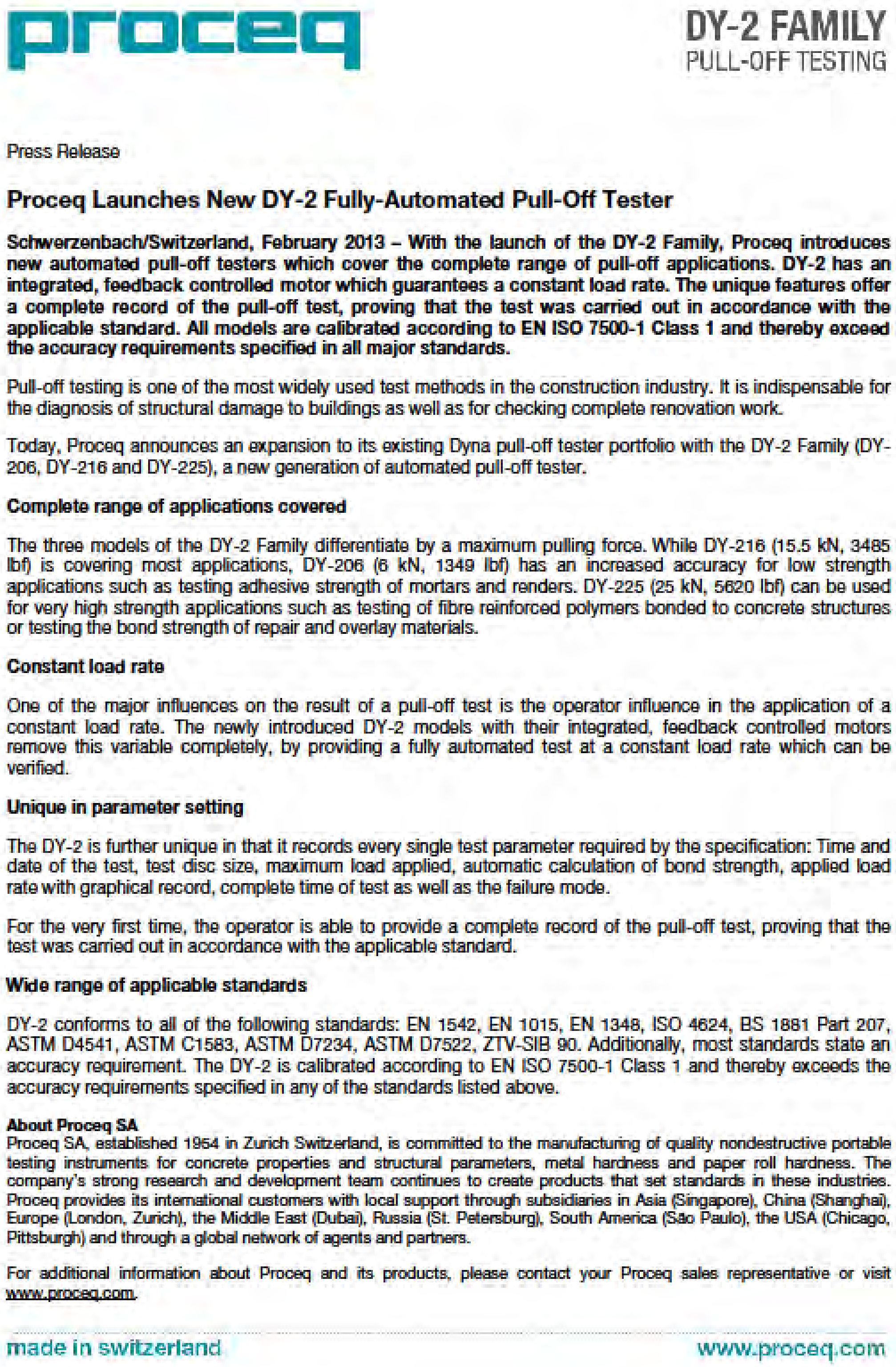
Characteristics / Advantages

- Easy to apply by brush or in thin trowel applications
- No water required
- Prebatched components
- Hand or spray applied
- Easy and fast mixing
- Very good adhesion
- Protects concrete against carbonation
- Protects against water penetration
- Non-corrosive to steel or iron
- Overpaintable
- Approved for potable water contact

Tests

Approval / Standards

Proceq DY-216



DY-2 FAMILY
PULL-OFF TESTING

Press Release

Proceq Launches New DY-2 Fully-Automated Pull-Off Tester

Schwerzenbach/Switzerland, February 2013 – With the launch of the DY-2 Family, Proceq introduces new automated pull-off testers which cover the complete range of pull-off applications. DY-2 has an integrated, feedback controlled motor which guarantees a constant load rate. The unique features offer a complete record of the pull-off test, proving that the test was carried out in accordance with the applicable standard. All models are calibrated according to EN ISO 7500-1 Class 1 and thereby exceed the accuracy requirements specified in all major standards.

Pull-off testing is one of the most widely used test methods in the construction industry. It is indispensable for the diagnosis of structural damage to buildings as well as for checking complete renovation work.

Today, Proceq announces an expansion to its existing Dyna pull-off tester portfolio with the DY-2 Family (DY-206, DY-216 and DY-225), a new generation of automated pull-off tester.

Complete range of applications covered

The three models of the DY-2 Family differentiate by a maximum pulling force. While DY-216 (15.5 kN, 3485 lbf) is covering most applications, DY-206 (6 kN, 1349 lbf) has an increased accuracy for low strength applications such as testing adhesive strength of mortars and renders. DY-225 (25 kN, 5620 lbf) can be used for very high strength applications such as testing of fibre reinforced polymers bonded to concrete structures or testing the bond strength of repair and overlay materials.

Constant load rate

One of the major influences on the result of a pull-off test is the operator influence in the application of a constant load rate. The newly introduced DY-2 models with their integrated, feedback controlled motors remove this variable completely, by providing a fully automated test at a constant load rate which can be verified.

Unique in parameter setting

The DY-2 is further unique in that it records every single test parameter required by the specification: Time and date of the test, test disc size, maximum load applied, automatic calculation of bond strength, applied load rate with graphical record, complete time of test as well as the failure mode.

For the very first time, the operator is able to provide a complete record of the pull-off test, proving that the test was carried out in accordance with the applicable standard.

Wide range of applicable standards

DY-2 conforms to all of the following standards: EN 1542, EN 1015, EN 1348, ISO 4624, BS 1881 Part 207, ASTM D4541, ASTM C1583, ASTM D7234, ASTM D7522, ZTV-SIB 90. Additionally, most standards state an accuracy requirement. The DY-2 is calibrated according to EN ISO 7500-1 Class 1 and thereby exceeds the accuracy requirements specified in any of the standards listed above.

About Proceq SA
Proceq SA, established 1954 in Zurich Switzerland, is committed to the manufacturing of quality nondestructive portable testing instruments for concrete properties and structural parameters, metal hardness and paper roll hardness. The company's strong research and development team continues to create products that set standards in these industries. Proceq provides its international customers with local support through subsidiaries in Asia (Singapore), China (Shanghai), Europe (London, Zurich), the Middle East (Dubai), Russia (St. Petersburg), South America (São Paulo), the USA (Chicago, Pittsburgh) and through a global network of agents and partners.

For additional information about Proceq and its products, please contact your Proceq sales representative or visit www.proceq.com.

made in switzerland www.proceq.com

Cube strength test results

- 7 day:

30MPa	Saturated mass	Compression test	
	kg	kN	MPa
Cube 1	2.19	230	23
Cube 2	2.29	230	23
Cube 3	2.33	233	23.3

40MPa	Saturated mass	Compression test	
	kg	kN	MPa
Cube 1	2.225	320.6	32.1
Cube 2	2.25	335.5	33.6
Cube 3	2.33	350.3	35

- 28 day:

30MPa	Saturated mass	Compression test	
	kg	kN	MPa
Cube 1	2.32	311	31.1
Cube 2	2.32	311	31.1
Cube 3	2.35	284	28.4

40MPa	Saturated mass	Compression test	
	Kg	kN	MPa
Cube 1	2.34	400	40
Cube 2	2.33	404	40.4
Cube 3	2.42	402	40.2

Statistical Analysis results:

Excel t-test results

Coating 1:

- Moisture condition 1

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	1.386667	2.51
Variance	0.064933	0.3753
Observations	3	3
Pooled Variance	0.220117	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.93243	
P(T<=t) one-tail	0.021355	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.04271	
t Critical two-tail	2.776445	

- Moisture condition 2

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	2.393333	2.883333
Variance	0.009733	0.155033
Observations	3	3
Pooled Variance	0.082383	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.09085	
P(T<=t) one-tail	0.052365	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.104731	
t Critical two-tail	2.776445	

- Moisture condition 3

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	2.59	2.426667
Variance	0.0567	0.132933
Observations	3	3
Pooled Variance	0.094817	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.649648	
P(T<=t) one-tail	0.27567	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.55134	
t Critical two-tail	2.776445	

Coating 2:

- Moisture condition 1

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	1.076667	1.356667
Variance	0.090533	0.031633
Observations	3	3
Pooled Variance	0.061083	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.38753	
P(T<=t) one-tail	0.118789	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.237577	
t Critical two-tail	2.776445	

- Moisture condition 2

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	1.753333	2.02
Variance	0.794433	0.1764
Observations	3	3
Pooled Variance	0.485417	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.46877	
P(T<=t) one-tail	0.331821	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.663643	
t Critical two-tail	2.776445	

- Moisture condition 3

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	2.356667	2.133333
Variance	0.590033	0.047633
Observations	3	3
Pooled Variance	0.318833	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.484415	
P(T<=t) one-tail	0.32671	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.653421	
t Critical two-tail	2.776445	

Coating 3:

- Moisture condition 1

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	0.18	0.18
Variance	0.0019	0.0061
Observations	3	3
Pooled Variance	0.004	
Hypothesized Mean Difference	0	
df	4	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	2.131847	
P(T<=t) two-tail	1	
t Critical two-tail	2.776445	

- Moisture condition 2

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	0.153333	0.443333
Variance	0.006633	0.003033
Observations	3	3
Pooled Variance	0.004833	
Hypothesized Mean Difference	0	
df	4	
t Stat	-5.10882	
P(T<=t) one-tail	0.00347	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.00694	
t Critical two-tail	2.776445	

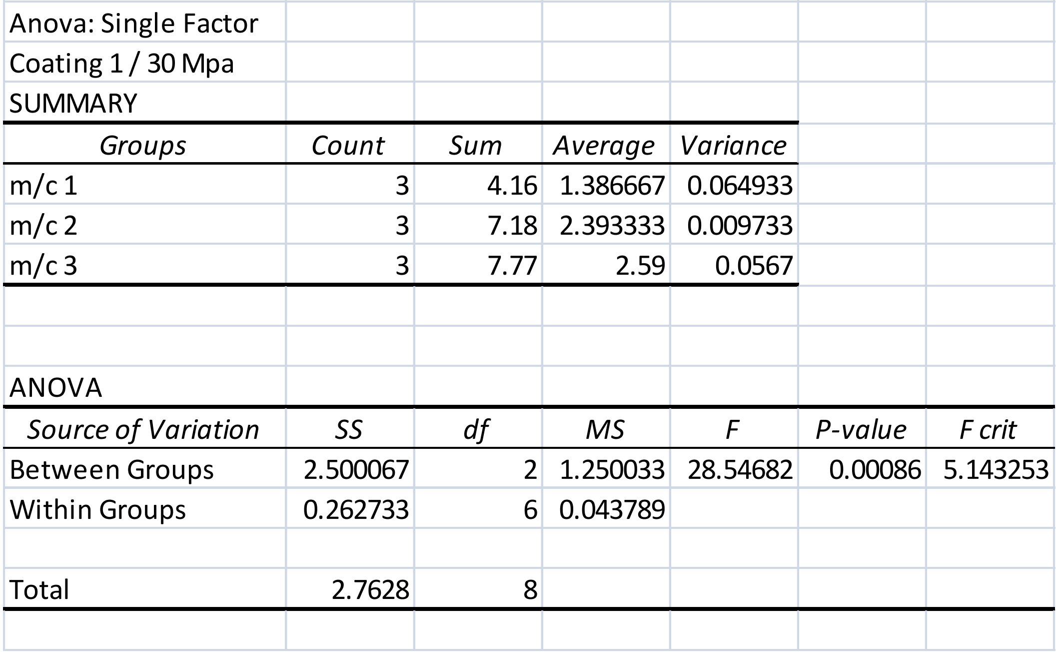
- Moisture condition 3

t-Test: Two-Sample Assuming Equal Variances		
	30MPa	*40MPa*
Mean	0.426667	0.743333
Variance	0.028933	0.003033
Observations	3	3
Pooled Variance	0.015983	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.06771	
P(T<=t) one-tail	0.018688	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.037376	
t Critical two-tail	2.776445	

Excel ANOVA summary:

Coating 1:

- 30 MPa substrate



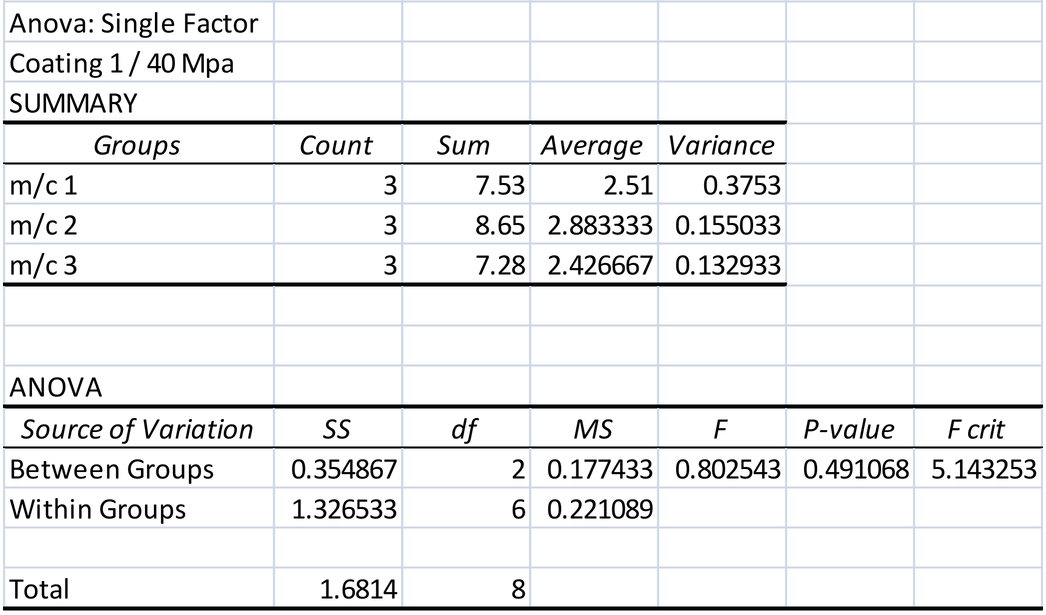
Anova: Single Factor
Coating 1 / 30 Mpa
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
m/c 1	3	4.16	1.386667	0.064933
m/c 2	3	7.18	2.393333	0.009733
m/c 3	3	7.77	2.59	0.0567

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.500067	2	1.250033	28.54682	0.00086	5.143253
Within Groups	0.262733	6	0.043789			
Total	2.7628	8				

- 40 MPa substrate



Anova: Single Factor
Coating 1 / 40 Mpa
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
m/c 1	3	7.53	2.51	0.3753
m/c 2	3	8.65	2.883333	0.155033
m/c 3	3	7.28	2.426667	0.132933

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.354867	2	0.177433	0.802543	0.491068	5.143253
Within Groups	1.326533	6	0.221089			
Total	1.6814	8				

Coating 2:

- 30 MPa substrate

Anova: Single Factor						
Coating 2 / 30 Mpa						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
m/c 1	3	3.23	1.076667	0.090533		
m/c 2	3	5.26	1.753333	0.794433		
m/c 3	3	7.07	2.356667	0.590033		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.460289	2	1.230144	2.501989	0.162108	5.143253
Within Groups	2.95	6	0.491667			
Total	5.410289	8				

- 40 MPa substrate

Anova: Single Factor						
Coating 2 / 40 Mpa						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
m/c 1	3	4.07	1.356667	0.031633		
m/c 2	3	6.06	2.02	0.1764		
m/c 3	3	6.4	2.133333	0.047633		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.056067	2	0.528033	6.195958	0.034719	5.143253
Within Groups	0.511333	6	0.085222			
Total	1.5674	8				

Coating 3:

- 30 MPa substrate

Anova: Single Factor
Coating 3 / 30 Mpa
SUMMARY

Groups	Count	Sum	Average	Variance
m/c 1	3	0.54	0.18	0.0019
m/c 2	3	0.46	0.153333	0.006633
m/c 3	3	1.28	0.426667	0.028933

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.136267	2	0.068133	5.455516	0.044663	5.143253
Within Groups	0.074933	6	0.012489			
Total	0.2112	8				

- 40 MPa substrate

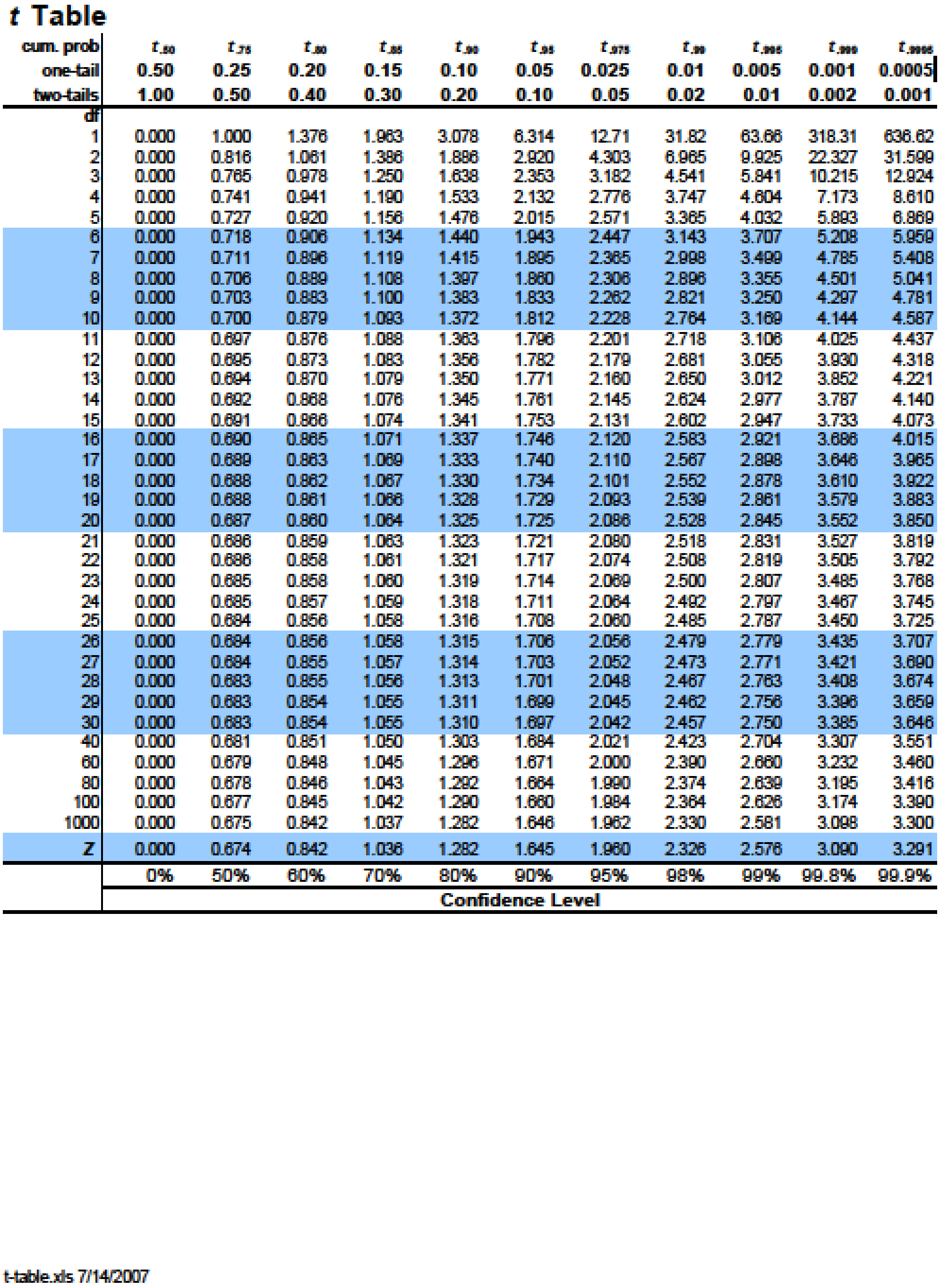
Anova: Single Factor
Coating 3 / 40 Mpa
SUMMARY

Groups	Count	Sum	Average	Variance
m/c 1	3	0.54	0.18	0.0061
m/c 2	3	1.33	0.443333	0.003033
m/c 3	3	2.23	0.743333	0.003033

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.476689	2	0.238344	58.76986	0.000115	5.143253
Within Groups	0.024333	6	0.004056			
Total	0.501022	8				

t-test table



t Table

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	0.50	0.25	0.20	0.15	0.10	0.05	0.025	0.01	0.005	0.001	0.0005
two-tails	1.00	0.50	0.40	0.30	0.20	0.10	0.05	0.02	0.01	0.002	0.001
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
Z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

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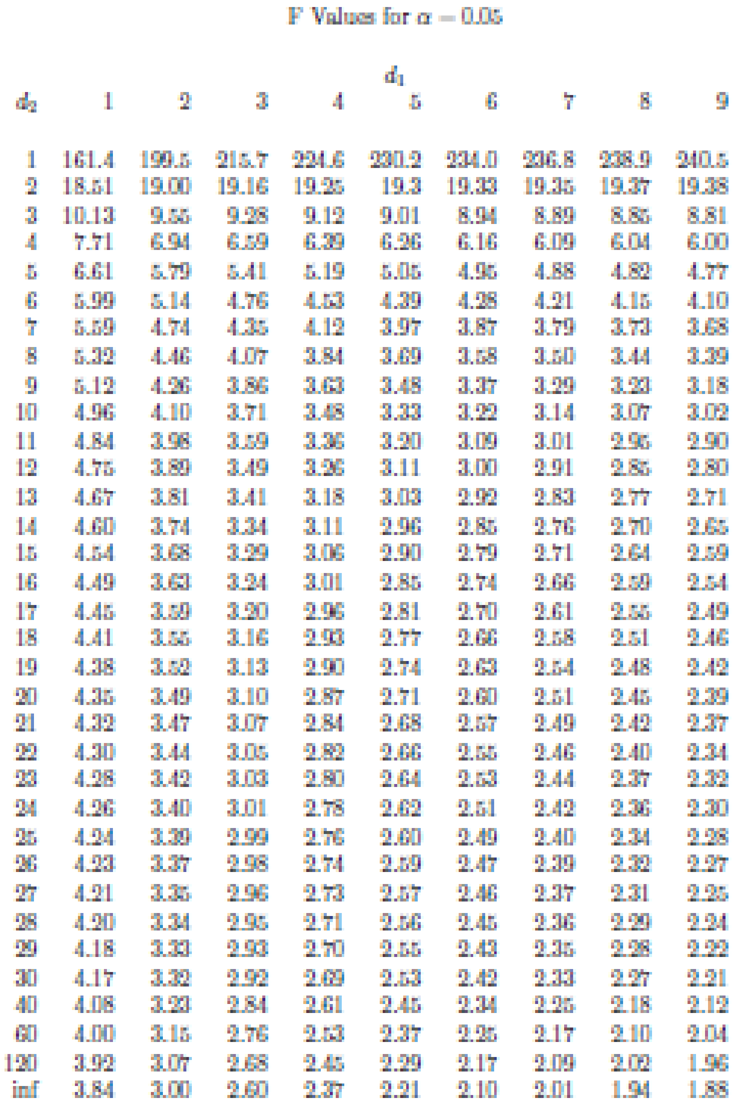
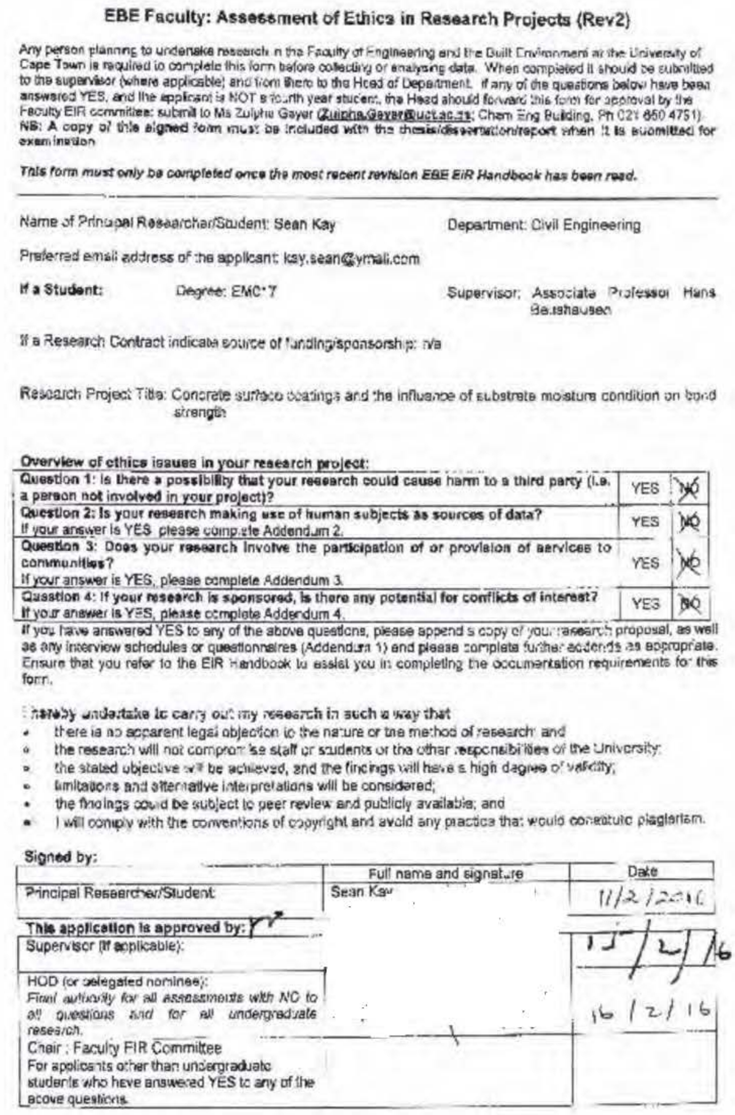
F table



F Values for $\alpha = 0.05$

					d_1				
d_2	1	2	3	4	5	6	7	8	9
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5
2	18.51	19.00	19.16	19.25	19.3	19.33	19.35	19.37	19.38
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04
120	3.92	3.07	2.68	2.45	2.29	2.17	2.09	2.02	1.96
inf	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88



EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Gayer (Zulpha.Gayer@uct.ac.za; Chem Eng Building, Ph 021 650 4751).
NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination

This form must only be completed once the most recent revision EBE EiR Handbook has been read.

Name of Principal Researcher/Student: Sean Kay Department: Civil Engineering

Preferred email address of the applicant: kay.sean@ymail.com

If a Student: Degree: EMC17 Supervisor: Associate Professor Hans Beushausen

If a Research Contract indicate source of funding/sponsorship: n/a

Research Project Title: Concrete surface coatings and the influence of substrate moisture condition on bond strength

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	[✓ NO]
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES please complete Addendum 2.	YES	[✓ NO]
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	[✓ NO]
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	[✓ NO]

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EIR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student	Sean Kay [redacted]	11/2/2016
This application is approved by:		
Supervisor (if applicable):	[redacted]	15/2/16
HOD (or delegated nominee): *Final authority for all assessments with NO to all questions and for all undergraduate research.*	[redacted]	16/2/16
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		

ADDENDUM 1:
Please append a copy of the research proposal here, as well as any interview schedules or questionnaires:

University of Cape Town

CIV5017Z

Minor Dissertation

Research Proposal:

Concrete Surface Coatings and the influence of substrate moisture condition on bond strength

Contents

1. Introduction and Problem Statement

Concrete elements if designed correctly can last for its entire lifespan without the need for additional protection against the environment within which it is exposed to. However, due to many unforeseen circumstances the elements may need this protection in order to maintain its integrity and overall appeal. Unforeseen circumstances can be a result of a lack of supervision during the construction phase of the element, inadequate element design size due to a more aggressive environment, accidental damage, dramatic changes in the ambient conditions surrounding the element, inferior material quality used as well as increased loads imposed onto the element during and after its construction to name a few. Surface coatings can be and is in some cases the easiest and usually cheaper option for decorating and/or protecting these elements. This being said implies that if the coating is compatible with the concrete surface and is sufficiently resilient to the environment it is to be exposed to, it will effectively allow the element to remain intact and continue to function regardless of the external environment. The structural integrity can also be maintained using various surface coatings that involve reinforced membranes but this is out of the scope of this research proposal and as such will not be considered. The function or intended function of the surface coating will also not be a focal point for this research as the intent is not to provide verification of the coatings ability to function but rather on its ability to adhere to the concrete substrate to which it is applied. The preparation of the concrete substrate and its condition prior to the application of various surface coatings is the key to this investigation as well as to evaluate the effect (if any) of obtaining a substrate that is saturated but surface dry prior to coating application. Similar research has been done but the immediate coating of a prepared substrate (after 28 day moist curing) has not been evaluated. Benn (2008) used specimens that had been cured at various levels and had been left exposed to the Johannesburg Highveld climate for a year prior to any testing. Previous investigations with regard to bonded overlays have also been done at the University of Cape Town by Talotti (2014). He investigated the influence of substrate moisture preparation on concrete overlay bond strength and found that saturated surface dry concrete had no beneficial influence on bond strength. In some instances the effect had a negative influence on the bond strength when compared to the drier substrate specimens.

2. Research Focus

The overall focus of this research thesis is to establish a specification for each of the chosen coatings with regard to ideal concrete substrate surface preparation as well as to investigate the effect of pre-wetting the concrete substrate in order to achieve a saturated surface dry condition prior to application of the chosen coatings. The coatings will be of both the inorganic and organic types (where possible) and will be specified further into the proposal.

Available methods for surface profiling and preparation will be used for the experimental part of this research proposal and will be in line with common construction practice in order to improve the practicality of the results. The notion that the concrete substrate should have a minimum compressive strength of 25MPa and a minimum substrate cohesive strength of 1.5MPa (Sika, 2004) in order to be successfully coated will also be assessed in this investigation. The ultimate outcome of the research will however still be on the effective bond strength created by each of the chosen coating systems and the corresponding influences of the concrete substrates to which they are applied.

3. Research Aim

The aim of this research proposal is to investigate the effects different concrete substrate preparation methods (done according to standard such as EN 1504), different concrete substrate quality and the effect of pre-wetting the cured (28 day cured) concrete substrate has on the bond strength achieved by applying various surface coating systems to these conditions and subsequently testing the adhesive strength using a pull-off testing machine (proceq DY216). The results will be documented and analysed in order to link the findings to any theory of relevance and provide a guideline for achievable maintenance goals.

4. Hypothesis

The research was obtained through the hypothesis that surface preparation techniques such as wire brushing and sandblasting will indeed affect the bond strength achieved by the coating provided the concrete substrate had been made sound identically in all cases prior to the profiling methods used. The condition for pre-wetting the substrate in order to achieve a saturated surface dry substrate needs further investigation as it is said to be a minimum requirement (Williams, n.d.) in some instances but in light of the moisture related problems many coating systems face it is likely to have a negative effect for majority of the coating systems and hence needs to be evaluated.

5. Research Methodology

Since experimental work will be carried out under controlled laboratory conditions there will be certain assumptions and limitations to the work being undertaken. This is important when relating experimental results to theory and ultimately to practice. The experimental work will involve the following aspects:

- Obtaining mix design for concrete of medium quality (30MPa) and good quality (40MPa). This will then be followed by the selection of appropriate concrete raw materials.

- Establishing the concrete substrate specimen size needed to accurately use the pull-off tester. This is dependent on the available size discs. Approximate specimen size of 150mmx150mmx75mm will be assumed initially.

- The specimens will be prepared according to SABS methods described by Addis (2008) as follows:

    1. The consistency and workability of the fresh concrete mix must be assessed and recorded by doing the slump test. Once the results are acceptable then the mix may be used to make the required specimens.

    2. Ensure the moulds to be used are clean and lightly smeared with release oil on the inside. Provided the moulds are level, fill the moulds with the well mixed concrete in 50mm layers. Tamp each layer at least 45 times with the round end of the tamping rod to ensure no air bubbles are present. The last layer should more than fill the mould/required level. After tamping this layer, use a steel float to remove the excess concrete.

       Cover the cube/mould with damp sacking followed by a sheet of plastic and store it in the shade and away from any wind. Indoors is preferable in cold weather conditions. Allow to sit for 24hours.

       Once 24hours have passed, loosen the mould gently in order to free the concrete specimen. Label the specimen. The specimen can now be placed into water. The water should be between 22 and 25 degrees celcius and left to hydrate and cure for 28 days before removed for testing.

- Each of the chosen coatings will be applied to dry and saturated surface dry specimens that have been profiled using three different methods (to be finalised after proper consultation) and to one specimen that has not been altered in any way. This will be done for both medium and good quality concrete substrates.

  In order to achieve the dry conditions the specimen will be oven dried and dried under ambient conditions (details to be finalised once this has been decided upon as the preferred methods) and for the saturated surface dry (SSD) condition the specimen will be removed from the water and allowed to dry under ambient conditions until it is dry to the touch (time will be recorded and evaluated before applying to any further specimens). Once the 28 day strength has been verified then the coatings will be applied.

- Surface preparation methods to be used for profiling the concrete specimens will include: wire brush, mechanical grinding and sandblasting techniques as these are common practice by contractors. In the event that excess bleed water has resulted in the formation of laitance on the surface then mechanical methods such as grinding or sandblasting will be used to remove this layer and then the specimen will subsequently be cleaned according to the methods previous described in the literature review section. Methods will be considered and the best available method will be chosen.

- Three cubes will be cast for each set of specimens in order to verify their 28 day compressive strengths. Cubes will be in a saturated condition when tested.

- Prior to any coatings the concrete substrate moisture content should be measured and recorded. This can be done using a moisture meter. Further consultation will be required on this matter.

- The coatings to be used will be of the Sika brand. Sika coatings of both the inorganic and organic categories will be used (consultation on the best possible coatings relevant to this research will be sort). Inorganic and organic coatings have been categorised further by Bassi and Roy (2002) and this can be seen as follows:

  Inorganic coatings: include masonry type cement based paints and polymer-modified cementitious type coatings.

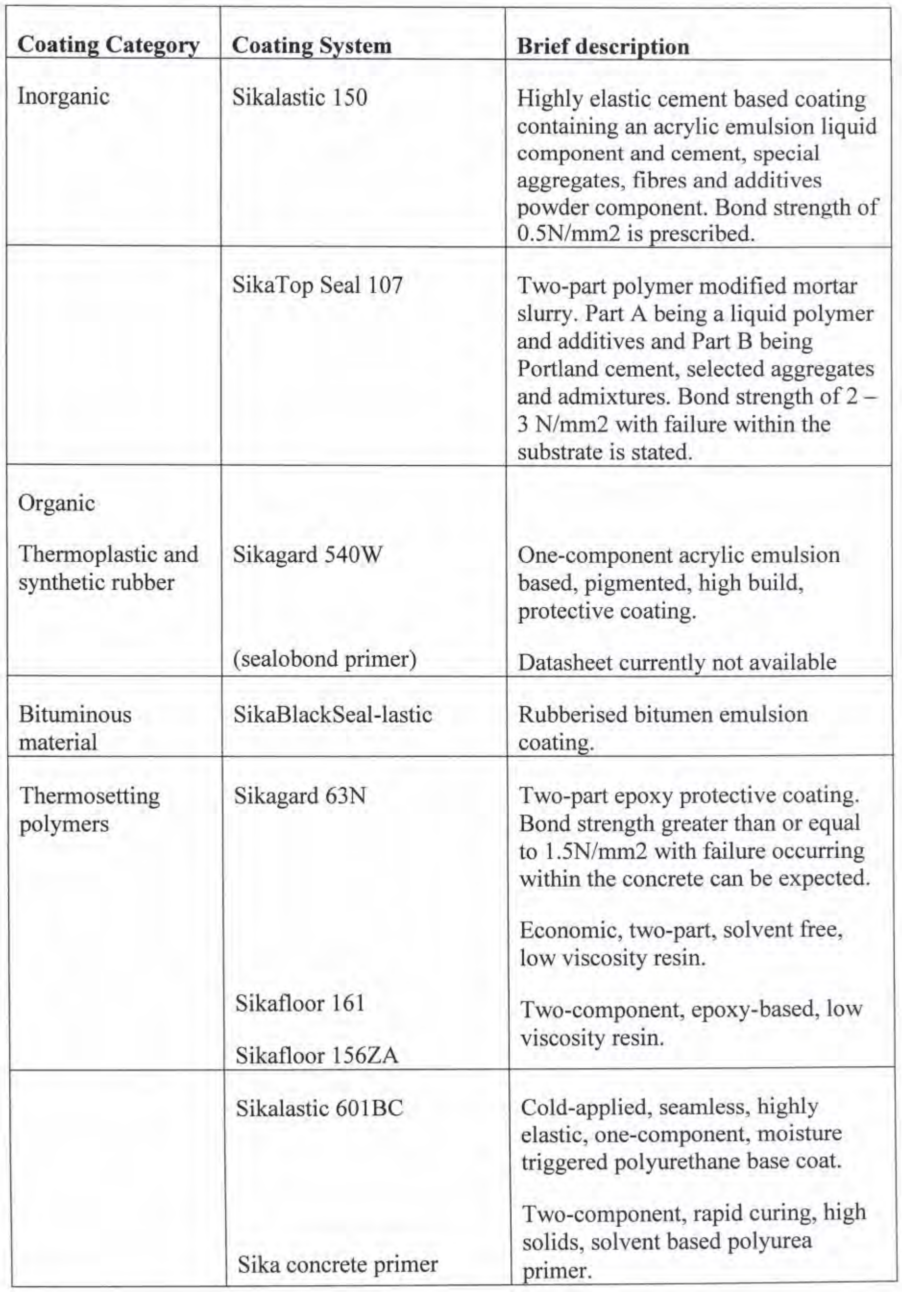
  Organic coatings: include thermoplastic and synthetic rubber (usually based upon acrylic polymers), Alkyds and drying oils, Bituminous materials (hot or cold applied systems), and thermosetting polymers (typically based on epoxy and polyurethane resins).

  Corresponding Sika products to be considered for this investigation include:

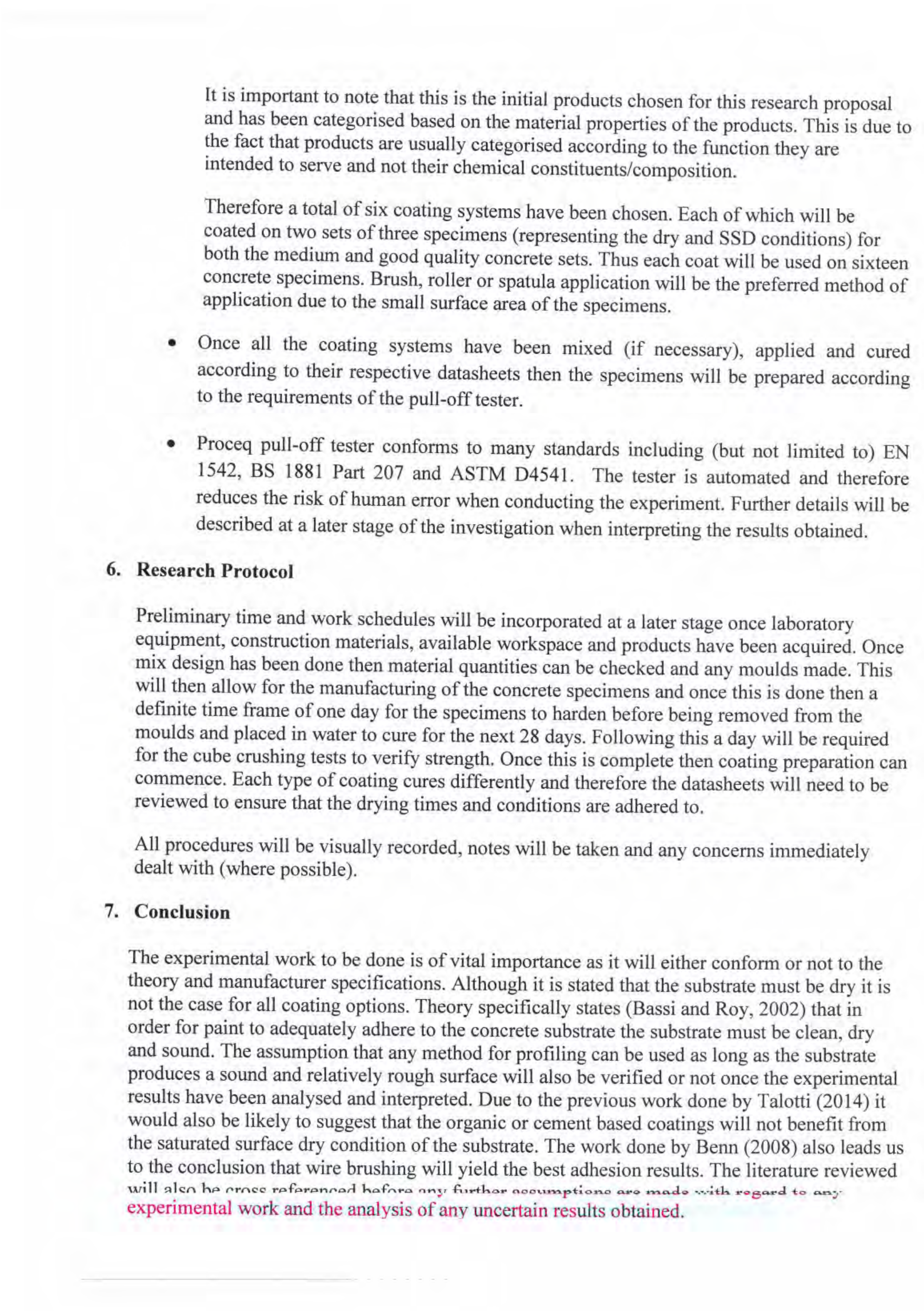
  - Inorganic types: Sikalastic 150 and SikaTop Seal 107
  - Organic types: Sikagard 540W, (no available Alkyd and drying oil types), SikaBlackSeal-lastic, Sikagard 63N and Sikalastic 601BC (both have corresponding Primers (SikaFloor 161 and Sika concrete primer respectively)).

Tabulated as follows:

Table 1: available products



Coating Category	Coating System	Brief description
Inorganic	Sikalastic 150	Highly elastic cement based coating containing an acrylic emulsion liquid component and cement, special aggregates, fibres and additives powder component. Bond strength of 0.5N/mm2 is prescribed.
	SikaTop Seal 107	Two-part polymer modified mortar slurry. Part A being a liquid polymer and additives and Part B being Portland cement, selected aggregates and admixtures. Bond strength of 2 – 3 N/mm2 with failure within the substrate is stated.
Organic Thermoplastic and synthetic rubber	Sikagard 540W (sealobond primer)	One-component acrylic emulsion based, pigmented, high build, protective coating. Datasheet currently not available
Bituminous material	SikaBlackSeal-lastic	Rubberised bitumen emulsion coating.
Thermosetting polymers	Sikagard 63N Sikafloor 161 Sikafloor 156ZA	Two-part epoxy protective coating. Bond strength greater than or equal to 1.5N/mm2 with failure occurring within the concrete can be expected. Economic, two-part, solvent free, low viscosity resin. Two-component, epoxy-based, low viscosity resin.
	Sikalastic 601BC Sika concrete primer	Cold-applied, seamless, highly elastic, one-component, moisture triggered polyurethane base coat. Two-component, rapid curing, high solids, solvent based polyurea primer.



It is important to note that this is the initial products chosen for this research proposal and has been categorised based on the material properties of the products. This is due to the fact that products are usually categorised according to the function they are intended to serve and not their chemical constituents/composition.

Therefore a total of six coating systems have been chosen. Each of which will be coated on two sets of three specimens (representing the dry and SSD conditions) for both the medium and good quality concrete sets. Thus each coat will be used on sixteen concrete specimens. Brush, roller or spatula application will be the preferred method of application due to the small surface area of the specimens.

- Once all the coating systems have been mixed (if necessary), applied and cured according to their respective datasheets then the specimens will be prepared according to the requirements of the pull-off tester.
- Proceq pull-off tester conforms to many standards including (but not limited to) EN 1542, BS 1881 Part 207 and ASTM D4541. The tester is automated and therefore reduces the risk of human error when conducting the experiment. Further details will be described at a later stage of the investigation when interpreting the results obtained.

6. Research Protocol

Preliminary time and work schedules will be incorporated at a later stage once laboratory equipment, construction materials, available workspace and products have been acquired. Once mix design has been done then material quantities can be checked and any moulds made. This will then allow for the manufacturing of the concrete specimens and once this is done then a definite time frame of one day for the specimens to harden before being removed from the moulds and placed in water to cure for the next 28 days. Following this a day will be required for the cube crushing tests to verify strength. Once this is complete then coating preparation can commence. Each type of coating cures differently and therefore the datasheets will need to be reviewed to ensure that the drying times and conditions are adhered to.

All procedures will be visually recorded, notes will be taken and any concerns immediately dealt with (where possible).

7. Conclusion

The experimental work to be done is of vital importance as it will either conform or not to the theory and manufacturer specifications. Although it is stated that the substrate must be dry it is not the case for all coating options. Theory specifically states (Bassi and Roy, 2002) that in order for paint to adequately adhere to the concrete substrate the substrate must be clean, dry and sound. The assumption that any method for profiling can be used as long as the substrate produces a sound and relatively rough surface will also be verified or not once the experimental results have been analysed and interpreted. Due to the previous work done by Talotti (2014) it would also be likely to suggest that the organic or cement based coatings will not benefit from the saturated surface dry condition of the substrate. The work done by Benn (2008) also leads us to the conclusion that wire brushing will yield the best adhesion results. The literature reviewed will also be cross referenced before any further assumptions are made with regard to any experimental work and the analysis of any uncertain results obtained.

8. Amendments to research proposal

After careful consideration of the requirements of the minor dissertation and discussion with Professor Hans Beushausen (2015) the following amendments to the initial research proposal is now proposed:

Three modified cementitious based concrete surface coatings will be used due to the rigid nature and applicability to bond strength testing. These coatings will be applied to concrete specimens having compressive strengths of 30MPa and 40MPa (common strengths used in practice). Both of these strength types will be lightly wet sandblasted to obtain sound concrete at all of the specimen surfaces and will then be subjected to three differing moisture conditions prior to coating application. Therefore a total of 9 substrate specimens will be cast for each strength type.

7 and 28 day cube tests will be done to verify the substrate strength. Suitable moulds will be chosen for the specimens and surface areas will be checked for the requirements of the pull-off tester.

The section on experimental work and interpretation will explain in detail the materials used, equipment used, methods of application, results as well as detailed interpretation of the results achieved by the pull-off tests.

9. References

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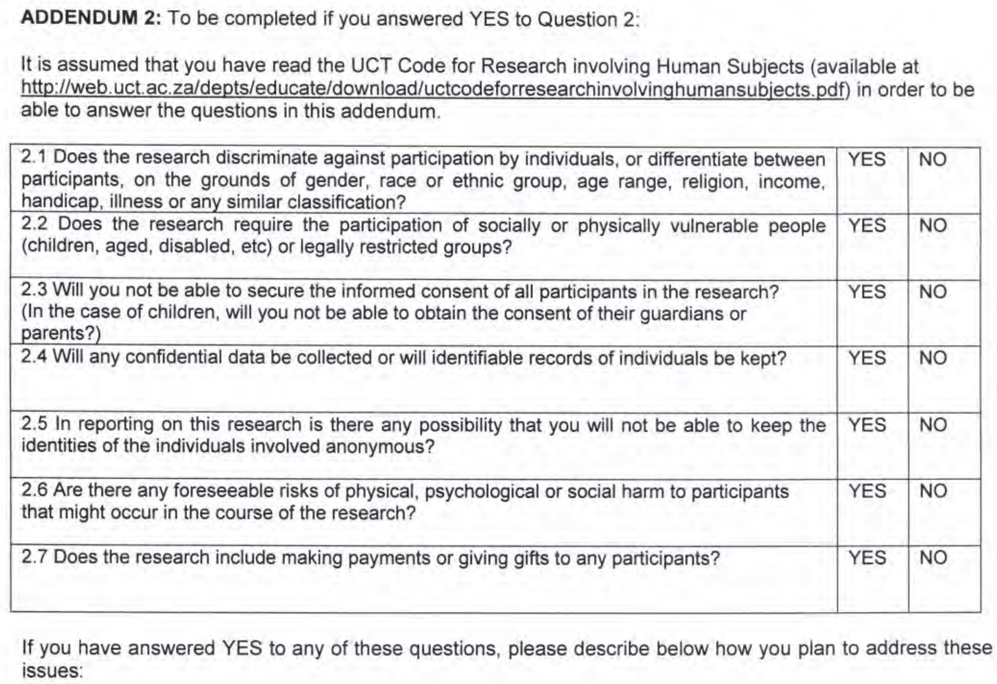


ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

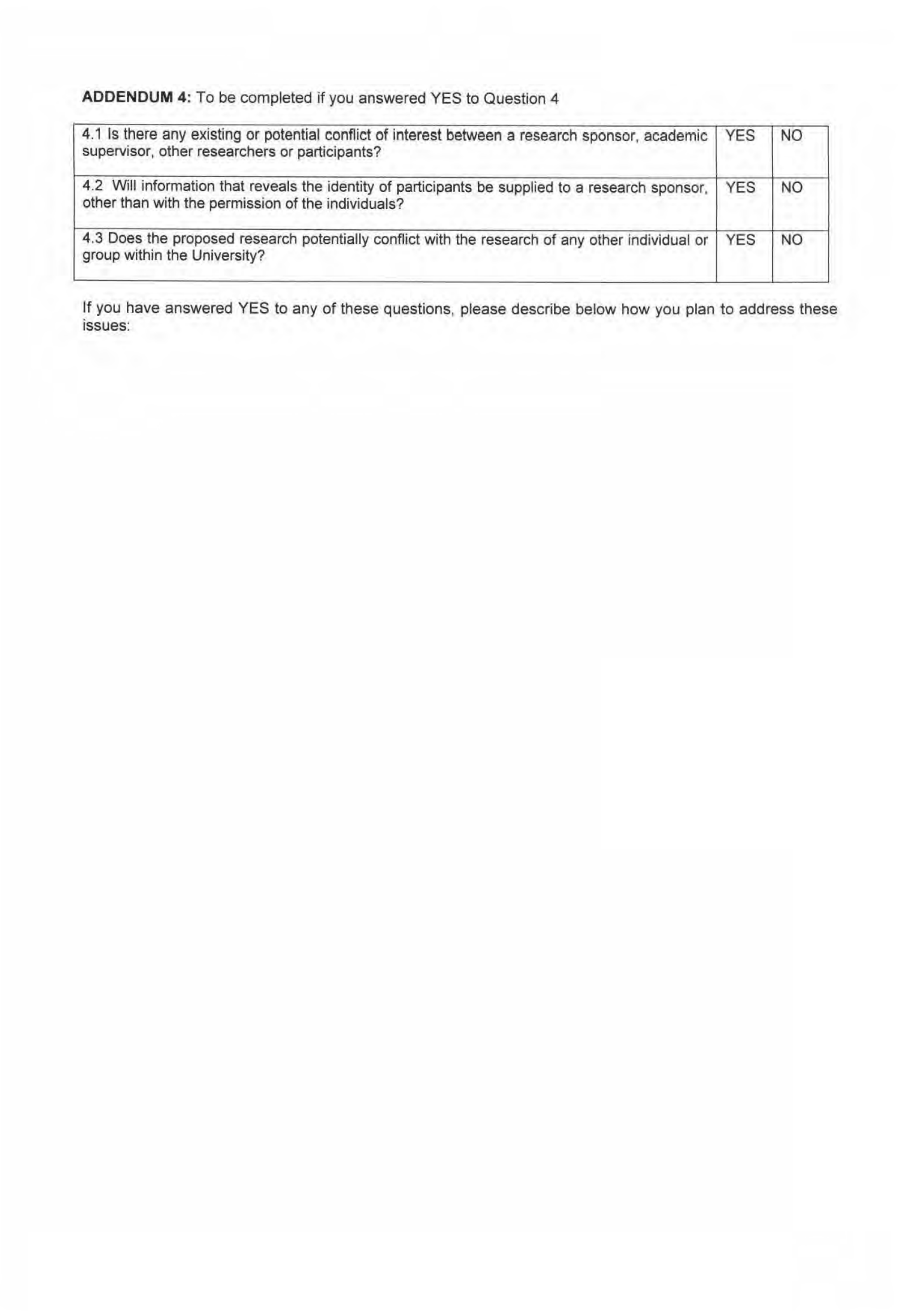
2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:



ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: