CONCRETE REPAIR PROCEDURES SUITABLE FOR TYPICAL SOUTH AFRICAN CONDITIONS

by

A.J.C. JOOSTE

A project investigation submitted in partial fulfilment of the requirements for the degree of

Magister Ingenieria

in the

Faculty of Engineering

of the

Rand Afrikaans University

2001

Supervisor: Mr D. Kruger
Acknowledgements

The writer would like to thank the following people for their contributions to the study:

- Mr D Kruger, the author's study leader, for his advice, guidance and contributions.
- Mr J Bester, for assisting me with the practical work.
- Mr C Hoffend, from Sika (South Africa), for providing the necessary materials.
- Mr R von Eck, from Sika (South Africa), for his assistance with the research.
- Mr N Wylde, from Sika (South Africa), for the opportunity and sponsorship of this research.
- Mr H Banziger, from Sika (Switzerland), for providing the necessary guidance during the trial section at RAU.
- Mr D Temple and K Malcomson, from SNA Civil and Development Engineers (PTY) LTD.
- Mrs F Velosa, for professional language editing.
- Mrs M Jooste, my wife, for her continual support over the past two years.
- Prof. C.J. Jooste, my father, for his help with the questionnaire.
Summary

It is generally accepted that successful concrete repair is dependent on seven steps. All seven steps of the concrete repair process were investigated in depth. From the seven steps, three of the steps (removal, application and curing) were selected for experimental investigation. Firstly, the removal of damaged concrete was simulated under laboratory conditions. Concrete blocks were prepared through different removal techniques. Repair material was placed on the blocks, and the adhesion between the concrete repair material and the concrete substrate was determined. Secondly, different repair mortar application methods were used, and the effect of application methods on adhesion strengths was determined. Thirdly, the effect of curing on adhesion was determined by curing samples under different conditions. Some in situ test repairs were done at RAU to get an indication of the appropriate repair systems to be used on the RAU buildings. A questionnaire was given out to the industry and analyzed to get an indication of the common practice used for concrete repair in South Africa.

Opsomming

Dit word algemeen aanvaar dat die sukses van betonherstel afhanklik is van sewe stappe. Al sewe stappe van die betonherstel proses is in diepte ondersoek. Van die sewe stappe is drie gekies (verwydering, aanwending en nabehandeling) vir verdere eksperimentele ondersoek. Eerstens is die verwydering van beskadigde beton gesimuleer onder laboratorium toestande. Betonblokke is voorberei deur van verskillende verwyderings tegnieke gebruik te maak. Betonherstel materiaal is geplaas op die blokke en die adhesie tussen die beton substraat en die beton herstelmateriaal is bepaal. Tweedens is verskillende aanwendings tegnieke gebruik en die effek wat aanwendings tegnieke het op adhesie is bepaal. Derdens is die effek van nabehandeling op adhesie bepaal deur monsters onder verskillende toestande te nabehandel. In situ herstelwerk is gedoen op die RAU om 'n herstelprosedure vas te stel. 'n Vraelys is aan die industrie uitgedeel en ontleed om 'n idee van die algemene praktyk vir betonherstel in Suid Afrika te verkry.
# Table of contents

Acknowledgements

Summary/Opsomming

List of figures

List of tables

## CHAPTER 1. REASONS FOR THE EXECUTION OF THIS RESEARCH PROJECT

1.1. Introduction

1.2. Goal of this research work

1.2.1. Introduction

1.2.2. General layout of the research

## CHAPTER 2. CONCRETE DETERIORATION

2.1. Introduction

2.2. Symptoms of concrete deterioration

2.2.1. Cracks

2.2.1.1. Drying shrinkage cracks

2.2.1.2. Plastic shrinkage cracks

2.2.1.3. Shifting form cracks

2.2.1.4. Reinforcing steel cracks

2.2.1.5. Plastic settlement cracks

2.2.1.6. Stress cracks

2.2.2. Surface deterioration

2.2.3. Discoloration

2.2.4. Pop-outs

2.2.5. Cavitation

2.2.6. Efflorescence

2.2.7. Seepage

2.2.8. Distortion

2.3. Causes of concrete deterioration

2.3.1. Bleeding

2.3.2. Corrosion of reinforcement

2.3.3. Honeycombing

2.3.4. Cold joints

2.3.5. Segregation

2.3.6. Aggressive chemical exposure

2.3.6.1. Acid attack

2.3.6.2. Sulphate attack

2.3.6.3. Alkali-silica reaction

2.3.6.4. Alkali carbonate reaction

2.3.7. Temperature gradients

2.3.8. Faulty workmanship

2.3.9. Shrinkage

2.3.9.1. Plastic shrinkage

2.3.9.2. Drying shrinkage

2.4. Summary
CHAPTER 3. THE CONCRETE REPAIR PROCESS

3.1. Introduction
3.2. Analysis, strategy and design of a concrete repair
3.3. Different evaluation techniques
   3.3.1. Corrosion activity measurements
   3.3.2. Determining the depth of carbonation
   3.3.3. Impact echo method
   3.3.4. Ultrasonic pulse velocity method
   3.3.5. Covermeters
   3.3.6. Chaining
   3.3.7. Hammer
   3.3.8. Core sampling
3.4. Summary

CHAPTER 4. THE REMOVAL OF DAMAGED CONCRETE

4.1. Introduction
4.2. Surface layout for patch repair
4.3. Concrete removal techniques
   4.3.1. The chipping hammer or jackhammer
   4.3.2. Hydro demolition
   4.3.3. Pneumatic scablers
   4.3.4. Milling machines
   4.3.5. Mounted breakers
   4.3.6. Splitters
4.4. Micro-cracking
4.5. Cleaning and protection of reinforcement
4.6. Summary

CHAPTER 5. SELECTION OF A SUITABLE CONCRETE REPAIR MATERIAL

5.1. Introduction
5.2. The range of concrete repair materials available
   5.2.1. Non-shrink cementitious grouts
   5.2.2. Non-shrink epoxy grout
   5.2.3. Polymers in concrete
   5.2.4. Superplasticized Dense Concrete (SDC)
   5.2.5. Microsilica Modified Concrete (MMC)
   5.2.6. Magnesium phosphate cements
5.3. Test procedures to measure the properties of concrete repair materials
   5.3.1. Effective bearing area-ASTM C827-97 (standard test method for change in height at early ages of cylindrical specimens from cementitious mixtures)
   5.3.2. Compressive Strength- SABS Method 863
   5.3.3. Workability
   5.3.4. Segregation
   5.3.5. Durability
   5.3.7. Bleeding
5.4. Summary

CHAPTER 6. APPLICATION OF CONCRETE REPAIR MATERIALS

6.1. Introduction
6.2. The bond between repair materials and the concrete substrate
6.3. Placement methods
6.3.1. Dry packing
6.3.2. Form and cast in place
6.3.3. Form and pump
6.3.4. Grouted preplaced aggregate
6.3.5. Dry mix shotcrete
6.3.6. Wet mix shotcrete
6.3.7. Full depth repair
6.3.8. Overlays
6.3.9. Hand-applied techniques

6.4. Summary

CHAPTER 7. CURING
7.1. Introduction
7.2. The factors affecting the evaporation of water from cementitious repair materials
7.3. The effect of curing on the outer surface of cementitious materials
7.4. Different curing techniques
7.5. Duration of curing
7.6. Summary

CHAPTER 8. PROPERTIES OF MATERIALS USED IN THIS RESEARCH PROJECT
8.1. Introduction
8.2. Material A (repair mortar)
8.3. Material B (bonding bridge)
8.4. Material C (repair mortar)
8.5. Material used as a concrete substrate

CHAPTER 9. EXPERIMENTAL WORK: EFFECT OF THE REMOVAL OF DAMAGED CONCRETE ON THE BOND STRENGTH
9.1. Goal of the experiment
9.2. Experimental procedure
9.3. Testing equipment used
9.3.1. Pull-off tester
9.4. Results obtained
9.5. Discussion of results
9.5.1. The tensile strength of different concrete substrates before the application of repair materials
9.5.2. The tensile strength of different concrete substrates after the application of repair materials
9.6. Conclusion

CHAPTER 10. EXPERIMENTAL WORK: APPLICATION OF REPAIR MATERIALS
10.1. Goal of the experiment
10.2. Experimental procedure
10.3. Results obtained
10.4. Discussion of results
10.5. Conclusion
## List of figures

<table>
<thead>
<tr>
<th>Figure 1</th>
<th>Schematic representation of the various types of cracking that can occur in concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2</td>
<td>Shrinkage cracks</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Spalling of concrete</td>
</tr>
<tr>
<td>Figure 4</td>
<td>The delamination of concrete</td>
</tr>
<tr>
<td>Figure 5</td>
<td>The formation of ferrous ions at the anodic site</td>
</tr>
<tr>
<td>Figure 6</td>
<td>The formation of atomic hydrogen at the cathodic site</td>
</tr>
<tr>
<td>Figure 7</td>
<td>The depolarization of the cathodic surface by oxygen</td>
</tr>
<tr>
<td>Figure 8</td>
<td>The formation of the rust products</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Depth of carbonation</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Concrete damage due to reinforcement corrosion</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Alkali Silica reaction</td>
</tr>
<tr>
<td>Figure 12</td>
<td>The general repair process</td>
</tr>
<tr>
<td>Figure 13</td>
<td>The repair vs. repair and protect strategy</td>
</tr>
<tr>
<td>Figure 14</td>
<td>The correct surface layout for concrete repair</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Repair geometry</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Depth of removal (wrong method)</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Depth of removal (option 1)</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Depth of removal (option 2)</td>
</tr>
<tr>
<td>Figure 19</td>
<td>The bruising of concrete</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Schematic stress-strain diagram of concrete in micro-cracking</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Relation between the observed length of cracks in an area of 100mm² and the stress/strength ratio in compression</td>
</tr>
</tbody>
</table>
Figure 22  Test method for change in height at early ages of cylindrical specimens of cementitious mixtures.

Figure 23  Workability vs. working time.

Figure 24  Shotcrete application

Figure 25  Poor compaction behind reinforcement caused by hand application

Figure 26  The influence of relative humidity of air on the loss of water from concrete in the early stages after placing

Figure 27  The influence of the temperature of air and concrete on the loss of water from concrete in the early stages after placing

Figure 28  The influence of wind velocity on the loss of water from concrete in the early stages after placing

Figure 29  The relation between oxygen permeability and compressive strength for concretes cured for 28 days and in air at a relative humidity of 65%

Figure 30  The relation between the depth of carbonation and the compressive strength of concrete cured in water for 28 days and concrete cured in dry air at a relative humidity of 65%

Figure 31  The influence of the length of moist curing on time to the initiation of corrosion

Figure 32  Placement of concrete driveway blocks in a steel mould

Figure 33  The average tensile strength of concrete substrates prepared with different preparation methods before the application of repair materials

Figure 34  Comparison of tensile strengths before and after the application of repair materials

Figure 35  The section under repair

Figure 36  The spalling of surface concrete

Figure 37  Corroded reinforcement

Figure 38  Cutting of edge with grinder

Figure 39  Removal of damaged concrete by hand-held jackhammers

Figure 40  Sprinkler system

Figure 41  Sections covered by plastic sheets

Figure 42  Sprinklers on and sections protected by plastic sheets
Figure 67 Are pre-wet surfaces allowed to dry partially before application? 133
Figure 68 Are applications of repair materials done in the shade? 134
Figure 69 How are repair materials applied in general? 134
Figure 70 Are applications done in layers? 135
Figure 71 The average thickness of the layers 135
Figure 72 Is the floating of the final surface by using water as a wetting agent allowed? 136
Figure 73 Does your company have any fixed specifications regarding the placement of concrete repair materials? 136
Figure 74 Are concrete repairs protected from wind and direct sunlight? 137
Figure 75 How is water applied to the surface of a concrete repair? 139
Figure 76 Duration of application of water if used as a curing agent 139
Figure 77 Level of education of workers who do concrete repairs 140
Figure 78 Are workers trained before they start doing concrete repairs? 141
Figure 79 Is work done under the supervision of a supervisor? 141
Figure 80 The level of education of superiors doing supervision 142
### List of tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>The classification of cracks</td>
<td>8</td>
</tr>
<tr>
<td>Table 2</td>
<td>The meaning of different pH levels</td>
<td>17</td>
</tr>
<tr>
<td>Table 3</td>
<td>Removal method: blasting</td>
<td>44</td>
</tr>
<tr>
<td>Table 4</td>
<td>Removal method: cutting</td>
<td>44</td>
</tr>
<tr>
<td>Table 5</td>
<td>Common available repair materials and their properties</td>
<td>57</td>
</tr>
<tr>
<td>Table 6</td>
<td>Properties of polymer concrete and polymer modified concrete</td>
<td>61</td>
</tr>
<tr>
<td>Table 7</td>
<td>Properties of Magnesium-Phosphate cements</td>
<td>62</td>
</tr>
<tr>
<td>Table 8</td>
<td>Description of workability and magnitude of slump</td>
<td>64</td>
</tr>
<tr>
<td>Table 9</td>
<td>Suggested ranges for durability classification using index values</td>
<td>66</td>
</tr>
<tr>
<td>Table 10</td>
<td>Suggested minimum moist curing periods</td>
<td>83</td>
</tr>
<tr>
<td>Table 11</td>
<td>Technical information about material A</td>
<td>85</td>
</tr>
<tr>
<td>Table 12</td>
<td>Technical information about material B</td>
<td>86</td>
</tr>
<tr>
<td>Table 13</td>
<td>Technical information about material C</td>
<td>87</td>
</tr>
<tr>
<td>Table 14</td>
<td>Average tensile strength of prepared concrete substrates</td>
<td>91</td>
</tr>
<tr>
<td>Table 15</td>
<td>Pull-off test results, 28 days after the repair material was placed on concrete substrates prepared with different removal techniques</td>
<td>93</td>
</tr>
<tr>
<td>Table 16</td>
<td>Pull-off test results obtained by using different application methods</td>
<td>98</td>
</tr>
<tr>
<td>Table 17</td>
<td>Estimated bond strengths for different application methods</td>
<td>102</td>
</tr>
<tr>
<td>Table 18</td>
<td>Pull-off test results obtained by using different curing techniques</td>
<td>104</td>
</tr>
<tr>
<td>Table 19</td>
<td>Estimated bond strengths obtained by using different curing methods</td>
<td>108</td>
</tr>
<tr>
<td>Table 20</td>
<td>Repair materials used</td>
<td>116</td>
</tr>
<tr>
<td>Table 21</td>
<td>Results obtained through visual inspection and sounding after 28 days</td>
<td>122</td>
</tr>
<tr>
<td>Table 22</td>
<td>The suitability of different repair systems for the RAU</td>
<td>122</td>
</tr>
<tr>
<td>Table 23</td>
<td>Repair system recommended for RAU</td>
<td>123</td>
</tr>
<tr>
<td>Table 24</td>
<td>The main causes of concrete repair failure</td>
<td>127</td>
</tr>
<tr>
<td>Table 25</td>
<td>The importance of different concrete repair steps as rated on a five-point scale</td>
<td>128</td>
</tr>
<tr>
<td>Table 26</td>
<td>What protection is used against wind and sunlight?</td>
<td>138</td>
</tr>
<tr>
<td>Table 27</td>
<td>Curing methods used</td>
<td>138</td>
</tr>
</tbody>
</table>
CHAPTER 1
REASONS FOR THE EXECUTION OF THIS RESEARCH PROJECT

1.1. Introduction

In the past few years, extensive research has been undertaken in the field of concrete repair by the Civil Engineering Department of the Rand Afrikaans University. Projects to determine the effect of concrete substrate strength on the bond between concrete and the repair material were undertaken. At the same time, some in situ testing of different concrete repair materials was undertaken on the buildings of the university. On both the “Banziger blocks” and the repair sections, the chosen repair materials did not perform as expected. All the bond strength results obtained from the research were well below the specifications of the manufacturers. In general, problems with cracking were experienced on the in situ sections. The question “why” was asked.

The biggest problem is the unrefined repair methods used in South Africa. Many of the repair materials are supplied from overseas and applied in typical South African construction style. The problem is not the materials, but the general repair system used in South Africa. Not one of the steps of concrete repair was done in the correct way. In each step, things were done that could cause the possible failure of the concrete repair in the future. It is necessary to know the substrate that is going to be repaired. Without knowledge of the substrate, a good repair is almost impossible. The correct removal technique must be used to remove the damaged concrete. For example, mechanical methods cause micro-cracks in concrete that will cause a certain failure of the repair. Sandblasting or hydro jetting would seem the best option. The depth of removal also plays an important role in the success of a repair. The reinforcement should be thoroughly cleaned. Currently, the reinforcement is cleaned in most instances with a steel brush. This cleaning method is totally inadequate. Clean reinforcement will ensure that a proper bond will be formed. The repair materials must be applied in layers not thicker than 30mm. This assures good bonding and fewer cracks. It is advisable to do one layer per day. Currently, most of the repairs are done by hand. This causes bad compaction around the reinforcement. Proper curing is essential for the success of a repair. Without proper curing, cracks will start to form after 24 hours. Finally, the repair must be covered with PVC sheets. This is an important step that is neglected on many job sites. The repair must be protected from wind and sunlight. Both wind and sunlight cause the rapid evaporation of water from the repair. The exposure of a repair to sun and wind is one of the major causes of concrete repair failure.
Concrete repair is a very delicate process. Each step must be done thoroughly. If one step is neglected or ignored the repair will most certainly fail. The current problem is the unrefined construction methods used in South Africa. We cannot expect repair materials to perform to standard if the repair process is inadequate. In retrospect, the problem is not the materials, but the negative attitude of the applicators towards the proper concrete repair process. For concrete repair to be successful, a paradigm shift towards the entire concrete repair process is essential.

1.2. Goal of this research work

1.2.1. Introduction

From previous research and personnel experience, it became clear that many inadequacies exist in the current concrete repair systems used by the concrete repair industry. Many of the inadequacies are easy to correct, because basic mistakes are made due to the lack of proper training or knowledge. A major problem is the unrefined repair methods used in general. Concrete repair materials are complex and sensitive to the type of repair system used.

The repair process can be summarized in seven basic steps:

1. Diagnosis of the current concrete substrate
2. Removal of the damaged concrete
3. Cleaning of the reinforcement
4. Protection of the reinforcement
5. Application of the repair material
6. Curing and protection of the repaired section
7. Quality and durability checks over the lifetime of the repaired section

Each step in a repair system needs to be refined to suit a particular repair situation. From the basic seven steps of concrete repair, the following three steps seem to cause the most problems:

- Removal of damaged concrete
- Application of repair materials
- Curing

The purpose of this research project is to investigate the entire repair process, with particular focus on the above-mentioned three steps. A better understanding and application of these
three steps would already result in a considerable decrease in the amount of concrete repair failures experienced currently. It is important to realize that the problem is not necessarily the materials, but the repair systems used. There are some very difficult factors influencing South African repairs that need to be addressed. For concrete repair to be successful in South African, a rather new approach is needed, which takes into account all the different factors that make concrete repair such a challenge.

1.2.2. General layout of the research

The layout of the research work is as follows:

- **Literature:** The symptoms of concrete deterioration
  The causes of concrete deterioration
  The concrete repair process
  Removal of damaged concrete and preparation of the concrete substrate
  Selection of a suitable concrete repair material
  Application of concrete repair materials
  Curing
- **Materials used for the research project**
- **Experimental work:** Removal of damaged concrete
  Application of repair materials
  Curing
- **In situ testing of concrete repair materials**
- **Questionnaire**
- **General discussion and conclusion**

It is very important to know the symptoms and causes of concrete deterioration. The difference between the causes and symptoms of concrete deterioration must be clearly understood. It will not help to treat the symptom. The causes of concrete deterioration must be eliminated, otherwise the problem will simply recur. Without this knowledge, it is impossible to do an adequate diagnosis of a structure. To make an applicable and correct recommendation to a client, it is necessary to understand the entire repair process and all the factors that can lead to the success and failure of a repair. This is why each step in the repair process will be discussed in detail.

It must be remembered that new and advanced technology will not always work under South African conditions. The workforce and the money shortages in the construction industry are a
reason for this limitation. Because of restricted budgets, cheap and unskilled labour is often used on construction sites, resulting in ineffective operations and inadequate or non-existent use of machinery that requires technical skills. Difficult and complex repair techniques cannot be used, because failure of the repair can almost be guaranteed when such systems are specified. Therefore, affordable removal techniques is a must for South Africa.

Currently, removal is mostly done by so-called mechanical methods, i.e. grinder, jackhammer or chisel. These are easy and affordable techniques, but they have drawbacks, for example: the formation of micro-cracks resulting in low bond strengths. These mechanical techniques can only work if used in conjunction with sandblasting or hydro jetting. We know that the construction industry uses mechanical removal techniques, but what is the best way to use these mechanical methods? How can we limit the amount of micro-cracking or bruising of the concrete substrate?

Application will in most circumstances be done by hand in South Africa. This causes problems with compaction and proper bonding to the substrate. The best application will most certainly be done by the shotcrete method. This method is again expensive and requires trained staff. If we assume that most applications will be done by hand, what is the best way to do an application?

In general, scaffolding must be used to cover the entire building under repair. Plastic sheets must then cover the scaffolding. Sprinkler systems are then put up for curing purposes. This means that repair work is done under almost ideal conditions. Again, the cost of such an operation is immense. In South Africa, clients usually cut on these costs. This means that mostly curing agents, plastic sheets with no curing or plastic sheets with wetting at intervals of two days are used for curing. In general, curing is the most important neglected part of construction. In Switzerland, repair work is done only in the shade. The construction workers move with the sun during the day. We do not have the money to go to these extreme measures, but there must be an acceptable alternative.

The knowledge of repair materials and systems in South Africa in general is not enough to ensure proper repair performance. This is a new and fast expanding field that needs more knowledge of the finer details of concrete repair. If this expertise is not obtained and fine-tuned in the next few years, there will be further unexpected problems with the deterioration and repair of concrete structures in South Africa.
2.1. Introduction

Concrete structures, if properly designed and constructed, are long lasting and should require almost no maintenance over their lifetime. In practice, this is not always true. Incorrect design and construction methods in many cases lead to durability problems in concrete structures. These durability problems in turn lead to high maintenance costs and reduce the service life of a structure. Durability can be defined as follows: "The capability of maintaining the serviceability of a product, component assembly or construction over a specified time." Durability can be seen as an indication of the deterioration of a concrete structure over time. Concrete is seen as durable if it reaches a minimum level of quality after its service life has been reached. Durability of concrete is an interaction between the concrete and its external environment. The concrete system determines the ability of a structure to withstand external attacks, while the environment determines the aggressiveness of an attack.

Why do we then have so many problems with concrete durability these days? This can be attributed to a lack of knowledge of the stresses a structure has to withstand in its lifetime. Designing and building concrete structures requires more than just a few mathematical equations. It is necessary to foresee problems, during construction and during the service life of the structure. If this is properly done, most of the problems we experience today will almost be eliminated.

The fact is that there will always be problems with the durability of concrete structures. Therefore, it is very important to distinguish between the symptoms and the causes of concrete deterioration. It is necessary to treat the cause of the problem and not the symptom. By treating the symptom, the problem will recur after a period. Deal with the cause of the problem!

The following are symptoms of concrete deterioration:

- Cracks
- Concrete wear
- Discoloration
- Pop-outs
- Dusting
- Cavitation
- Efflorescence
• Spalling
• Seepage
• Distortion
• Delamination

The following are the causes of concrete deterioration:
• Bleeding
• Corrosion
• Honeycombing
• Cold joints
• Segregation
• Aggressive chemical exposure
• Freeze thaw disintegration
• Moisture and temperature gradient
• Faulty workmanship
• Shrinkage

In the evaluation of the condition of the concrete substrate, the symptom and the cause can very easily be mistaken for each other. If the symptom is identified as a cause, it can lead to the formulation of a totally incorrect remedy. For example, if a concrete panel cracks because of thermal movement, it is in most instances a design fault. The contraction and expansion joints are spaced too far apart. The wrong assumption would be that the cracks were caused by shrinkage. Repairing the cracks would not resolve the problem. The cracks would simply re-appear after a huge fluctuation in temperature. The cause, thermal movement, needs to be addressed. After the problem of thermal movement is solved, the cracks can be repaired successfully. An-in depth knowledge of the causes and symptoms of concrete deterioration is therefore necessary. Without this, knowledge it would almost be impossible to conduct a proper diagnosis of the state of a concrete structure.
2.2. Symptoms of concrete deterioration

2.2.1. Cracks

The present trend is towards the better utilization of concrete strength, the use of super strength concretes of 138 MPa and higher, the use of high strength reinforcement, more pre-stressed concretes and the increased use of limit state theories. All these trends require the closer control of serviceability requirements in the cracking and deflection behaviour. Hence, knowledge of the crack behaviour of concrete elements becomes essential. It is fundamental that hardened reinforced concrete cracks, in tensile zones when subjected to externally imposed structural loads. The truth is that concrete will crack because of its brittle nature. By means of appropriate design and detailing techniques, these cracks can be limited to acceptable levels in terms of structural integrity and aesthetics. Cracking plays a very important role in the durability of a concrete structure. Cracking will negatively affect watertightness, appearance and porosity. With respect to appearance, the acceptable crack width depends on the distance from which it is viewed and on the function of the structure.

Cracks can be regarded as a failure if they:
- are aesthetically unacceptable,
- make the structure non watertight,
- affect the durability of a structure, and
- are structurally significant

There are two classes of cracks: active and dormant. A dormant crack does not change in character. A crack that lengthens and widens or shows movement is considered to be active. Active cracks should be repaired as soon as possible, as they may lead to major problems in the future.

Cracks are caused by:
1. Settlement
2. Improper sub-base
3. Formwork problems
4. Reinforcement absent or wrongly placed
5. Rust on reinforcement
6. Improper vibration  
7. Lack of curing  
8. Shrinkage  
9. Stripping of formwork before the proper setting of concrete  
10. Lack of expansion joints

Various types of cracks are described in Table 1 and shown schematically in Figure 1.

<table>
<thead>
<tr>
<th>Type of cracking</th>
<th>Symbol in Figure 1</th>
<th>Subdivision</th>
<th>Most common location</th>
<th>Primary cause</th>
<th>Secondary cause</th>
<th>Remedy</th>
<th>Time of appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PLASTIC SETTLEMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Over reinforcement</td>
<td>Deep sections</td>
<td>Excess bleeding</td>
<td>Rapid early drying conditions</td>
<td>Reduce bleeding or re-vibrate</td>
<td>10 min to 3 hrs</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Arching</td>
<td>Top of columns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Change of depth</td>
<td>Trough and waffle slabs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Diagonal</td>
<td>Pavements and slabs</td>
<td>Rapid early bleeding</td>
<td>Low rate of bleeding</td>
<td>Improve early curing</td>
<td>30 min to 6 hrs</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Random</td>
<td>Reinforced concrete slabs</td>
<td>Rapid early drying</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Over reinforcement</td>
<td>Reinforced concrete slabs</td>
<td>Rapid early drying or steel near surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PLASTIC SHRINKAGE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>External restraint</td>
<td>Thick walls</td>
<td>Excess heat generation</td>
<td>Rapid cooling</td>
<td>Reduce heat and/or insulate</td>
<td>1 day to two weeks</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Internal restraint</td>
<td>Thick slabs</td>
<td>Excess temperature gradients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EARLY THERMAL CONTRACTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>Thin slabs and walls</td>
<td>Inefficient joints</td>
<td>Excess shrinkage</td>
<td>Inefficient curing</td>
<td>Reduce water content</td>
<td>Several weeks to months</td>
</tr>
<tr>
<td>J</td>
<td>Against formwork</td>
<td>Walls</td>
<td>Impermeable formwork</td>
<td>Rich mixes</td>
<td>Poor curing</td>
<td>Improve curing and finishing</td>
<td>1 to 7 days</td>
</tr>
<tr>
<td>K</td>
<td>Floated concrete</td>
<td>Slabs</td>
<td>Over trowelling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Carbonation Chloride</td>
<td>Columns and beams</td>
<td>Inadequate cover</td>
<td>Poor quality concrete</td>
<td>Eliminate causes listed</td>
<td>More than 2 years</td>
<td></td>
</tr>
<tr>
<td><strong>CORROSION OF REINFORCEMENT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Damp locations</td>
<td></td>
<td>Reactive aggregate plus high alkali cement</td>
<td></td>
<td>Eliminate causes listed</td>
<td>More than 5 years</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Slabs</td>
<td>Trapped bleed water</td>
<td></td>
<td>Use of metal float</td>
<td>Eliminate causes listed</td>
<td>Upon touching</td>
<td></td>
</tr>
<tr>
<td><strong>ALKALI-AGGREGATE REACTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Free edges of slab</td>
<td>Frost damaged aggregate</td>
<td></td>
<td>Reduce aggregate size</td>
<td></td>
<td>More than 10 years</td>
<td></td>
</tr>
</tbody>
</table>

Time of appearance:  
- Over 30 minutes to 3 hours  
- 1 day to 2 weeks  
- Several weeks to months  
- 1 to 7 days  
- More than 2 years  
- More than 5 years  
- Upon touching  
- More than 10 years
2.2.1.1. Drying shrinkage cracks

Shrinkage can be defined as the change in volume of concrete caused by the movement of moisture in and out of a structure. The outflow of moisture from the concrete to the environment causes a decrease in concrete volume. The free shrinkage strain of concrete usually exceeds the tensile strain capacity, which will cause restrained concrete to crack. This process is called drying shrinkage and causes drying shrinkage cracks. These cracks are usually random, straight, hairline cracks that extend to the perimeter of a slab. The correct placement of reinforcement steel in the member distributes the shrinkage stresses and controls the crack widths.
2.2.1.2. Plastic shrinkage cracks

These cracks are caused by plastic shrinkage. Plastic shrinkage is caused by the rapid evaporation of water from fresh concrete. When the rate of evaporation exceeds the rate of bleeding, the surface concrete loses water and decreases in volume. The shrinkage produces tension stresses greater than the stress capacity of the newly placed concrete. These are wide cracks emerging parallel to each other or perpendicular to the direction of the wind. They are normally spaced 0.3m to 1m apart and can be of considerable depth. The cracks can range in width from 0.1mm to 3mm.

2.2.1.3. Shifting formwork cracks

It is very important that all formwork must be placed with enough support so that the movement of the formwork is restrained to a minimum. Any movement of the formwork used will introduce cracks. This is true for freshly placed horizontal concrete members. If the tensile stresses caused by the movement of the formwork are in excess of the resisting tensile stress in the concrete, the concrete member will crack. Total failure of the member is even possible. The proper design of formwork is therefore a must. It is also the responsibility of the resident engineer to ensure that formwork is propped until the fresh concrete attains a certain strength.
2.2.1.4. Reinforcing steel cracks
Due to poor construction, cracks appear just above the reinforcement, and voids just beneath the reinforcement. Enough cover to the reinforcement can avoid these cracks. High slump concrete will also help, because the concrete will fill the voids behind the reinforcement easier. Proper compaction of low slump concrete is therefore necessary. Shrinkage will also lead to the formation of cracks in the vicinity of reinforcement. The products of corrosion occupy a volume several times larger than the original steel. This causes cracking, spalling and delamination.

2.2.1.5. Plastic settlement cracks
Plastic settlement cracking is caused by the tendency for solid particles to settle. These particles displace water that will then move to the surface. Settlement under the horizontal reinforcement occurs much more than on top. This will cause cracks to form immediately in the vicinity of the reinforcement or where changes in sections occur in for example concrete slabs.

2.2.1.6. Stress cracks
Overloading in relation to the strength of a member can cause cracking. Inadequate design or construction not conforming to specification causes stress cracks to form. Surface cracking is therefore inevitable, but with proper design and detailing, these cracks will be shallow and narrow. Stress-induced cracks have a maximum width at the surface of the concrete, which tapers towards the reinforcement. The crack width at the surface is greater as the cover to the reinforcement increases. It is easier to extend an existing crack than to form a new one. The total number of cracks developed is determined by the size of the concrete member. The distance between cracks depends on the maximum size of the aggregate used. It is therefore desirable to have more cracks of smaller widths. The provision of reinforcement will control the width of cracks. External loads result in direct and bending stresses causing flexural, bond and diagonal tension cracks. Immediately after the full development of the first crack in a reinforced concrete element, the stress in the cracking zone is reduced to zero, and it is assumed by the reinforcement.

Flexural crack control is essential in structural floors. Cracks at service loads and overload conditions can be serious in office buildings, schools, parking garages, etc. Such cracks can have a detrimental effect on the integrity of the total structure, particularly in adverse conditions.
environmental conditions. In the long term, there is an increase in crack widths. The increase in crack width can vary considerably in cases of cyclic loading, such as bridges. In most cases, the doubling of a crack width after several years under sustained loading is not unusual.

2.2.2. Surface deterioration

Wear is a process over time in which a concrete surface is damaged by external forces. Concentrated loads under wheels are a very good example of a force that will cause wear over a period. Although the concrete may not display distress in the first few years of service, sudden wear is not uncommon. Sudden wear usually begins when the amount of design wheel loads is exceeded. The entire surface or only certain spots can show wear.

The following could contribute to wear:
1. Late trowelling
2. Dusting a surface with dry cement to stop bleeding
3. The use of water on freshly placed concrete to ease the trowelling process
4. Overtrowelling
5. Temperatures
6. Using heavy applications of salts and de-icing chemicals
7. High slump concrete
8. Lack of curing

If a concrete surface is trowelled after initial set has occurred, the bond between the upper layer of the concrete and the inner concrete is weakened. Initially, this weak bond will not show signs of distress, but under heavy loading stresses, the design service life of the concrete surface will be shortened. In many instances, when trowelling a concrete surface, contractors take dry cement and spread it over the surface. The contractors then sprinkle water over the cement and start the trowelling process. This leads to a high water/cement ratio in the top 5mm to 10mm of the concrete surface. This means that the top 10mm will be weaker than the lower concrete. The weakened layer will, under heavy and repetitive loads, start to dust and flake. Over-trowelling of fresh concrete has the effect of almost shearing the top layer of concrete from the underlying concrete. As can be seen, trowelling influences the quality of the final concrete surface.

Fresh concrete cured under high temperatures will provide a high early age strength, but a lower final strength. The rapid hydration process results in a poor physical structure with
more pores than concrete hydrating at room temperature. Verbeck and Helmuth suggest that the rapid rate of initial hydration produces a non-uniform distribution of the products of hydration. There is insufficient time for the products of hydration to diffuse away from the cement particles. This leads to a concentration of hydration products around the cement particles. The result is concrete of lower strength than expected. High slump concrete usually has a very high water/cement ratio leading to low strength concrete. Curing is a very important factor affecting the final durability of a concrete member. Curing has very little effect on the final strength of a concrete member, but influences the outer concrete strength. Curing is needed for the full hydration process to be completed in the surface layer. This leads to higher strength and lower permeability. Scaling is a common type of wear. The surface erosion begins as flaking of the concrete surface.

Spalling is when a fragment detaches from a larger mass of concrete for one of the following reasons:
- By a blow
- By pressure
- By expansion
- Corrosion of reinforcement
- Fire
- Carbonation

Spalling due to corrosion can be seen in figure 3. In many cases spalling does not lead to the structural failure of concrete. Spalling is detrimental to the appearance of a concrete structure. The reinforcement is exposed to the environment, accelerating the process of corrosion. If left untreated, the structure will slowly decompose.

![Figure 3: Spalling of concrete](image-url)
If the temperature of concrete rises rapidly, as in the case of a fire, the moisture in the concrete will expand. This expansion of the moisture can lead to explosive spalling. The permeability of the concrete influences the magnitude of spalling. In permeable concrete the pressure developed by the evaporation of the moisture in the concrete will escape. If the pressure is not relieved, the pressure can cause explosive spalling.

Delamination is the separation of concrete along a plane parallel to a surface, as can be seen in figure 4. Corrosion is one of the main causes of delamination.

![Figure 4 The delamination of concrete](image)

### 2.2.3. Discoloration
The following could cause discoloration:

1. Dusting dry cement on a wet concrete surface
2. Over-trowelling
3. Using different slumps in the same area
4. Changing the cement brand in one project
5. Adding calcium chloride to concrete
6. Placing concrete on a wet subgrade with puddles of water

Different w/c ratios will lead to different colours of concrete. In general, darker concrete can be assumed to be of a higher quality, because of the higher cement content. Dusting, over-trowelling, different slump concretes and the placing of concrete on a wet subgrade will lead to changes in the w/c ratio. In the above-mentioned cases, the final concrete will be lighter in colour and thus of lower quality. Changing the brand of cement can also lead to durability problems. It is very important to make trial batches and test the new cement for changes in quality. A cement brand that leads to lower durability characteristics should not be used, or the concrete mix must be adjusted. The addition of calcium chloride will lead to the movement of water to the top layer of concrete. The top layer is lighter in colour because of
the increased w/c ratio. The result is lower quality concrete than anticipated during the original design of the concrete mix.

2.2.4. Pop-outs
Pop-outs can be defined as the breaking away of small portions of a concrete surface due to localized internal pressure that leaves a shallow conical depression. Pop-outs are caused by contaminated, unsound coarse aggregate particles near the surface of the concrete. These particles readily absorb water and expand under freezing conditions. This causes the thin surface layer of mortar above the aggregate to pop off. The hole that is formed can hold water. This will cause further destruction at freezing temperatures.

2.2.5. Cavitation
Cavitation occurs where there is a flow of water passing a protruding object at high velocities. The high velocity flow and direction changes cause low pressure, which in turn causes vapour pockets to form. The pockets formed by the protrusion will flow until they reach a region of pressure for condensation to take place. The pockets collapse and surrounding fluids rush in to fill the void. The implosions of the pockets cause the erosion of the concrete surface and the matrix. The formation of vapour pockets and their subsequent collapse is called cavitation. This phenomenon is common in hydraulic structures and will over time lead to the pitting of the concrete surface.

2.2.6. Efflorescence
Efflorescence is a white salty stain on concrete surfaces created by the absorption of moisture by the salt particles in the concrete. The increased moisture content causes the leaching of the lime products in a concrete structure. It is a common phenomenon in poorly compacted concrete or at joints in concrete structures. Calcium carbonate formed by the reaction of Ca(OH)₂ with CO₂ is left behind on the concrete surface as a white deposit. Concrete with a porous surface will increase the magnitude of efflorescence. Wet cool weather followed by dry warm weather will aggravate the situation even further. Sea-dredged sand must be cleaned before use in concrete. Water containing large amounts of chlorides (seawater) will also cause efflorescence. Efflorescence only affects the appearance of concrete. In most instances water and soap can be used to wash off these stains. If this problem persists, apply diluted muriatic acid and then rinse it off with water. Because of the removal of lime from the concrete surface by the acid, the concrete will be darker in colour.
2.2.7. Seepage

Seepage is the movement of liquids through the pores of concrete. Big problems occur in general at construction joints. The joints are often poorly constructed and maintained. Rainwater starts moving through the joints, which helps the degradation of the joints. Seepage only affects the appearance of a concrete structure. In general, seepage is an indication that the replacement of joints in bridges is necessary.

2.2.8. Distortion

Distortion is the change in alignment of the components of a structure. In most instances, misalignment is caused by the subsidence of foundations due to the settlement of the ground under the foundation.

2.3. Causes of concrete deterioration

2.3.1. Bleeding

Bleeding occurs mostly in concrete with a high slump. The aggregate particles are no longer in suspension and they settle. This causes the displacement of water. This water channels to the surface. The water that reaches the surfaces dilutes the paste. This causes a less durable surface. The bond between aggregate, cement and reinforcement is weakened because water gets trapped around the particles and reinforcement creating weak bond surfaces. The channels that form during bleeding are a way for moisture to reach the reinforcement.

Bleeding has the following beneficial effects on concrete:

- The W/C ratio is lowered, while the strength of the concrete under the surface layer increases.
- The film of water on the surface reduces the drying out of the concrete, thus decreasing the probability of plastic shrinkage.

Bleeding has the following harmful effects:

- Bleed water gets trapped under the reinforcement and stone particles, thus creating weak internal surfaces.
- Where the settlement caused by bleeding is restrained, cracking may occur.
- The bleeding water creates a surface with a high W/C ratio, thus forming a weakened surface.
At this stage it is important to define what is meant by the w/c ratio. By increasing the amount of cement, the w/c is lowered, leading to a stronger gel structure. This leads to the improved quality and strength of the hardened concrete. The same can be achieved by reducing the amount of water in the mix.

The following factors tend to increase bleeding:

- High aggregate relative density
- Lack of very fine material in a mix
- High water content
- Delayed setting

Aggregate with a high density tends to be heavy. Heavy aggregate settles easily in a concrete mix, forcing the mixing water to the surface. Heavy aggregate will increase the amount of bleeding. By using finer cement, the rate of hydration is increased and set will occur earlier, thus the sedimentation of heavier particles is restrained. The use of finer cement will decrease the amount of bleeding. By putting more water into a mix, the tendency of aggregate to settle is increased, leading to increased bleeding. The longer the setting process of fresh concrete take, the longer can the settlement of the aggregate particles take place. The increased settlement will lead to increased bleeding.

2.3.2. Corrosion of reinforcement

Most concrete elements must have steel reinforcement to carry the loads that cause bending and subsequent tensile stresses. A big problem with reinforcement is corrosion due to inadequate concrete cover. Concrete is a high alkalinity material. The pH of newly produced concrete is usually between 12 and 13. The embedded steel is thus protected from corrosion by a passivating film bonded to the surface of the reinforcement. If this film is disturbed, corrosion will take place.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The meaning of different pH levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PH</strong></td>
<td><strong>Meaning</strong></td>
</tr>
<tr>
<td>10-14</td>
<td>The steel is passivated, corrosion not likely</td>
</tr>
<tr>
<td>4-10</td>
<td>Steel corrosion independent of pH, corrosion will occur if O₂ is present</td>
</tr>
<tr>
<td>0-4</td>
<td>Active steel corrosion regardless of the presence of O₂</td>
</tr>
</tbody>
</table>
Corrosion is an electrochemical process requiring an anode, a cathode and an electrolyte. A moist concrete matrix forms an electrolyte and the reinforcement provides an anode and a cathode. Electric current flows between the cathode and the anode. The reaction leads to an increase in metal volume as the Fe is oxidized to Fe(OH)$_2$ and Fe(OH)$_3$ and precipitated as FeO OH (rust colour). The entire process can be seen in Figures 5 to 8.

**Figure 5** The formation of ferrous ions at the anodic site.

**Figure 6** The formation of atomic hydrogen at the cathodic site.

**Figure 7** The depolarization of the cathodic surface by oxygen.
There are two main causes of corrosion:
- Electrical current
- Corrosive contaminants, e.g. Chlorides\textsuperscript{10}

Carbonation is a very important issue as it lowers the pH of concrete creating conditions for corrosion to take place.

**Carbonation**
Carbonation of concrete is a reaction between acidic gases in the atmosphere and the products of cement hydration. Carbon dioxide penetrates into the pores of concrete by diffusion and reacts with the Calcium hydroxide dissolved in the pore water. As a result of this reaction, the pH of the concrete is reduced. Consequently, concrete protection is lost. The passivity of the protective layer is destroyed\textsuperscript{11}.

\[ \text{CO}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \]
Electric current

Metals of different electro-chemical potential are connected to each other in the concrete, and corrosion occurs. Corrosion can also be due to electric currents from transmission networks. This occurs mostly when two different metals are cast into a concrete structure. This type of corrosion is known as galvanic corrosion\textsuperscript{12}. Each metal has a unique tendency to promote electrochemical activity. The less active metal is corroded away.

Corrosive contaminants

Chlorides accelerate the corrosion process. At above 0.2-0.4%, they break down the passive oxides. The chlorides can come from marine exposure, accelerators and admixtures.

The time of chloride penetration depends on the following:

- The amount of chlorides coming into contact with the concrete
- The permeability of the concrete
- The amount of moisture present

Impermeability is the resistance of concrete to the flow of gasses or liquids. This property is important in aggressive environments and where the structure has to retain fluids. Enough chlorides are eventually in contact with the reinforcement for corrosion to start in the presence of moisture and oxygen. The concentration of chlorides necessary to promote corrosion is greatly affected by the concrete's pH. Their use to accelerate the setting of concrete, at low temperatures, in reinforced concrete structures is now mostly banned. The main problems caused by corrosion are cracking and spalling\textsuperscript{12}.

Cracking and spalling of concrete induced by steel corrosion is a function of the following variable:

- Concrete tensile strength
- Quality of concrete cover over the reinforcement
- Bond or condition of the interface between the rebar and surrounding concrete
- Diameter of the reinforcement
- Percentage of corrosion by weight of the reinforcement

Corrosion also leads to a loss in structural capacity. Research conducted on flexural beams found that steel with more than 1.5% corrosion resulted in the ultimate load capacity
beginning to fall. It can be summarized that, in compressive members, cracking and spalling reduce the effective cross-section, thereby reducing the ultimate compressive load capacity.\(^{11}\)

**Figure 10**  Concrete damage due to reinforcement corrosion.\(^{11}\)

### 2.3.3. Honeycombing.

Honeycombing is a void left in concrete due to the failure of the mortar to fill the spaces among coarse aggregate particles effectively. Honeycombing is unattractive in appearance, and most of the time a weak link in a structure.
Honeycombing could be caused by one of the following:

1. Design of members
2. Formwork
3. Construction condition
4. Properties of fresh concrete
5. Placement
6. Consolidation

2.3.4. Cold joints
Cold joints are caused by the improper placement of fresh concrete. Cold joints form when fresh concrete is placed after the concrete to which it has to bond has already set. This causes places of discontinuity within the member where concrete may not tightly bond to the adjoining concrete. Delays in placement, the failure to place the concrete in horizontal lifts and inadequate vibration cause cold joints to form.

2.3.5. Segregation
Segregation is the separation of different ingredients in concrete. The stone usually separates from the mortar. This causes upper surfaces to have excessive paste and fines. The result is that the concrete may lack durability. The main causes for segregation are poor mix proportioning and over vibration or jolting. Jolting occurs mostly during the transportation of concrete, where the concrete mix is rocked left to right by the movement of the delivery truck.

2.3.6. Aggressive chemical exposure
Aggressive chemical exposure can cause the concrete to alter its chemical makeup, resulting in changes in its mechanical properties. Depending on the type of attack, the concrete can soften or disintegrate.

The following chemical reactions could occur:

- Acid attack
- Aggressive water attack
- Alkali-carbonate rock reaction
- Alkali-silica reaction
- Miscellaneous chemical attack
- Sulphate attack
2.3.6.1. Acid attack
An acid attack on concrete is the reaction between the acid and the calcium hydroxide of the hydrated Portland cement. The reaction produces water-soluble calcium compounds, which are leached away. Limestone or dolomitic aggregates may be dissolved totally\textsuperscript{11}.

2.3.6.2. Sulphate attack
The presence of soluble sulphates is common in areas of mining operations and chemical and paper milling industries. Sodium and calcium are the most common sulphates in soils. Magnesium sulphates are less common, but more destructive. The sulphate reacts chemically with the cement paste's hydrated lime and hydrated calcium aluminate.

\text{Sulphate + calcium hydroxide} = \text{gypsum}
\text{Gypsum + calcium aluminate} = \text{ettringite}

As a result of the reaction, solid products with a volume greater than the products entering the reaction are formed. The formation of gypsum and ettringite expands, pressurizes and disrupts the paste. As a result surface scaling and disintegration set in\textsuperscript{16}.

2.3.6.3. Alkali-silica reaction
This type of deterioration is activated by moisture and causes severe cracking of concrete structures and pavements. Certain aggregates, such as reactive forms of silica, react with potassium, sodium and calcium hydroxide from the cement, and form a gel around the reacting aggregates. When the gel is exposed to moisture, it expands, creating forces that cause tension cracks to form around the aggregate. Concrete undergoing this reaction shows signs of surface map cracking\textsuperscript{16}.

![Figure 11](image)

\textbf{Figure 11} Alkali-silica reaction.
2.3.6.4. Alkali carbonate reaction

This is the reaction between the alkali in cement and the carbonate in certain rocks\textsuperscript{10}.

2.3.7. Temperature gradients

The main effect of temperature changes is the change in concrete volume. An increase in temperature leads to an increase in concrete volume, whereas a decreasing temperature will lead to a decreasing volume of concrete. The relationship of volume to temperature is expressed by the coefficient of thermal expansion/contraction\textsuperscript{11}. Temperature gradients exist in many structures. The top surface is warm, whereas the bottom surface is cold. This causes the top surface to have a tendency to expand more than the bottom surface. This results in an upward movement during heating and a downward movement during cooling. Volume changes create stress when the concrete is restrained. The resulting stresses can be of any type: tension, compression, shear, etc. These stresses normally lead to cracking, spalling and excessive deflection. Freshly placed concrete undergoes a temperature rise from the heat generated by the cement hydration. The heat rise occurs in the first few hours after casting, and then cools to the surrounding ambient temperature.

A further factor that could lead to large temperature gradients in structures is fire. Fire will cause the aggregates to swell, water will change to steam and there will be a chemical change in the matrix of the concrete. The temperature gradients tend to separate the hot surface layers from the cooler interior. If the temperature gradient caused by fire exists for a long time the concrete matrix will start to disintegrate fully. In general, a temperature higher than 600°C of the concrete itself is detrimental. This will lead to extensive spalling and damage to the reinforcing steel. The time over which the heat is applied to a concrete surface is also very important. A very high temperature can be applied to concrete for a short period as long as the concrete does not reach a temperature of higher than 600°C.

2.3.8. Faulty workmanship

The following faulty workmanship can cause problems with concrete:

- Improper reinforcing steel placement. The reinforcement needs adequate cover to protect it from corrosion.
- Highly congested reinforcement. The concrete mix can thus not pass through during placement, leading to voids around the reinforcement.
- Premature removal of formwork.
- Improper column form placement.
Improper grades of slab surfaces. This can result in standing water that saturates the concrete. The longer the water stands on the concrete, the more leakage will occur through cracks and joints.

- Construction tolerances.

- Adding more water to concrete than is needed or specified in the design of the concrete mix.

- Improper alignment of formwork.

- Improper curing.

- Movement of formwork.

2.3.9. Shrinkage

There are basically two types of concrete shrinkage:

- Plastic shrinkage
- Drying shrinkage

2.3.9.1. Plastic shrinkage

Plastic shrinkage is caused by the very rapid loss of moisture out of the concrete that is not yet fully rigid. The concrete is said to be in a plastic state. The magnitude of plastic shrinkage is determined by the amount of water lost on the surface. The amount of plastic shrinkage is determined by the rigidity of the concrete mix. If the amount of water lost on the surface exceeds the amount of water brought to the surface by bleeding, plastic shrinkage cracks will form. This rapid loss of moisture causes a differential volume change, which in turn causes the surface layer of the concrete to crack.

The magnitude of moisture loss is influenced by:

- High temperatures
- Low humidity
- Wind velocity
- Suction of moisture by underlying concrete or soil

All these factors contribute to an accelerated setting process that leads to a lower long-term strength. A drop in ambient humidity further encourages the formation of these cracks. The situation will worsen further if wind speeds are in excess of 4.5 m/s. Complete prevention of evaporation after casting of concrete will prevent the formation of shrinkage cracks. The rate of evaporation should not be more than 1 kg/m². The rate of evaporation is increased when the
temperature of the concrete is higher than the ambient temperature. The higher the cement content of the concrete mix, the greater will be the amount of plastic shrinkage.

2.3.9.2. Drying shrinkage

The drying shrinkage process can be described as follows:

- Repair materials with drying shrinkage will contract in volume if unrestrained.
- Most of the shrinkage will take place in the first 30 days.
- Repair materials are not free to shrink because they are bonded to an existing substrate.
- Since the shrinkage is restrained from occurring by the substrate, the repair material will accumulate internal tensile stresses.
- The repair material has no tensile strength when first placed, but begins to gain tensile strength as the material matures.
- As the repair material is stretched, it also relaxes from tensile creep factors reducing the tensile stress to a net tensile stress.
- If the net tensile stress exceeds the tensile capacity, the repair material will crack.

The following factors influence the magnitude of drying shrinkage:

- Cement: Fineness
  Chemical composition
- Aggregate: Compressibility
  Absorption capacity
  Size
  Bond
- Modulus of elasticity
- Creep
- w/c ratio
- Size of concrete element
- Relative humidity
- Admixtures

Finer cement leads to a stronger reaction with alkali-reactive aggregates and makes the cement paste exhibit increased shrinkage. The larger the cement particles, the bigger the restraining force developed against the forces of shrinkage. The amount of gypsum in cement
influences the amount of shrinkage. Cements deficient in gypsum will show increased shrinkage. Shrinkage of concrete made by high-alumina cement is of the same magnitude as if using Portland cement, but the rate of shrinkage is increased. Fly ash and ground granulated blast furnace slag will increase shrinkage. Silica fume increases the long-term shrinkage of a concrete member.

Aggregate determines the magnitude of shrinkage that is possible. Aggregate provides restraint against shrinkage. By using larger and more aggregate, shrinkage can be minimized. The aggregate in itself can also display shrinkage characteristics. It is therefore necessary to use aggregates with high compressibility and low shrinkage characteristics. Shrinking aggregates are mainly some dolerites, basalts, mudstones and greywackes. Granite, limestone and quartzite can be used as non-shrink aggregates.

The water content of a mixture plays an important role in the magnitude of shrinkage. By increasing the amount of water, the magnitude of shrinkage will be increased, because there is so much more water that can evaporate into the atmosphere. The fact is that the w/c ratio determines the amount of water that will evaporate from a concrete mix and the rate at which this evaporation will take place.

The correlation between shrinkage and the modulus of elasticity of concrete depends on the compressibility of the aggregate used in the mix. The lower the modulus of elasticity, the lower the tensile stresses that will be developed in the concrete. High creep will cause the tensile stresses developed in concrete to be relaxed. In both situations, it will lead to the formation of fewer cracks.

The size of a concrete object leads to the phenomenon of differential shrinkage. Moisture loss only takes place at the surface. This leads to a moisture gradient over the depth of a concrete member. The progress of shrinkage extends gradually from the drying surface to the interior of the concrete member. Bigger members are thus less susceptible to drying shrinkage cracking.

The relative humidity of the atmosphere surrounding a concrete member greatly influences the magnitude of shrinkage that will take place. Concrete placed in dry conditions will shrink, whereas the same concrete placed under 100% relative humidity will swell. Water reducing admixtures generally cause an increase in shrinkage. The effect of admixtures is
indirect. The admixture either influences the water content or the cement content or both. Superplasticizers can increase shrinkage by as much as 20%. Calcium chloride can increase shrinkage by up to 50%. This is probably because of the formation of a finer gel.

2.4. Summary
To make a proper diagnosis of the current state of the concrete substrate, it is necessary to distinguish between the cause and symptoms of concrete deterioration. It is important to identify the cause of concrete deterioration for a proper and long-lasting solution to the problem to be formulated. If the symptom of concrete deterioration is resolved the problem will just recur within a few years time.
3.1. Introduction
The surface repair of concrete has been practised ever since the first concrete placement. The process was once simple, with few choices for materials and placement techniques.

The current practice of surface repair is far more complex than in the past, for a number of reasons:

- Design practice is more precise.
- Concrete is used for many applications involving aggressive environments.
- Atmospheric pollution is more prevalent.
- Structures are more complex.
- A wide variety of repair materials is available for repair.
- More placement techniques are available for repair.

The successful repair of concrete structures that have been damaged or have deteriorated requires professional assessment, and then the design, supervision and execution of a technically correct strategy.

The basic repair process can be seen in figure 12.

3.2. Analysis, strategy and design of a concrete repair
The malfunctioning of concrete structures usually occurs in some form of visible distress, such as cracking, leaching, spalling, scaling, stains, disintegration, wear, settlement or deflection. The evaluation of concrete can either be a reactive or proactive process. Generally, evaluation takes place as a result of some visible sign of distress, causing structural and durability concerns or poor functional performance. The evaluation process is important in determining factors such as the cause of malfunctioning and structural safety. Without a proper evaluation, it is almost guaranteed that a concrete repair will fail in the not too distant future. When it is necessary to repair a “repair”, the previous effort to resolve the problem was totally inadequate and a waste of time and money.
THE CONCRETE REPAIR PROCESS

EVALUATION OF THE EXISTING STRUCTURE

EFFECT
- Leakage
- Settlement
- Deflection
- Wear
- Spill
- Disintegration
- Cracking

CAUSE

DEFECT
- Design
- Construction
- Materials

DAMAGE
- Overloading
- Chemical Spill
- Earthquake
- Fire

DETERIORATION
- Freeze/Thaw
- Abrasion
- Corrosion

IS REPAIR REQUIRED??
- Safety
- Structural Catastrophe
- Use disfunction
- Leakage
- Effects on environment
- Aesthetics
- Preventative maintenance

NO

CONTINUED ON NEXT PAGE

YES
Figure 12 The general repair process.
The process of evaluation must include the following steps:

• What is the effect?
• What is the cause of the effect?
• Is repair required?
• Assessment survey of the current condition of the structure.
• Determine the repair and protection objectives (repair analysis).
• Select the appropriate repair and protection strategy.
• What will the future maintenance requirements be?

The effect of concrete deterioration could be one of the following:

• Cracking.
• Surface distress.
• Water leakage.
• Movement.
• Metal corrosion.
• Leakage.

Fixing the effect without understanding the cause will lead to the premature failure of a repair.

The cause could be one of the following:

• A defect: Design
  Construction
  Materials
• Damage: Overloading
  Chemical spill
  Earthquake
  Fire
• Deterioration: Freeze/thaw
  Abrasion
  Corrosion

The next step is to determine whether it is necessary to do a concrete repair at all. There are many factors that determine a positive or negative answer to this question.
The following questions need to be answered:

- Will the safety of people be jeopardized if no repair is carried out?
- Is a structural catastrophe possible in the not too distant future?
- Will the structure have a use malfunction?
- What will the effect of failure be on the environment?
- Is the structure aesthetically acceptable?
- Will preventative maintenance be enough?

It is also very important to take the wishes of the owner into account. Many owners have the attitude of: why should they fix a problem? The other problem is the availability of finance to fix the problem. Many owners have funds available, but not enough to do a proper repair job.

The steps in a typical condition survey of a concrete structure are:

- Visual inspection.
- Review of engineering data.
- Final quantification of data.
- Condition survey report.

Any thorough condition survey begins with a visual inspection of the conditions. Visual examination, mapping the location of problems on paper, and then reviewing these along with as built drawings and construction records can provide a general scope of the problems and causes. Following the review of the original design, the construction methods, the construction programme, and the condition survey, the “root cause” of the damage must be determined. There are different evaluation techniques that could be used to get to the heart of the problem.

These include the following:

- Non-destructive testing methods
- Coring
- Laboratory testing
The following non-destructive test methods could be used:

- Corrosion activity measurements
- Impact echo method
- Ultra sonic pulse velocity method
- Cover meters
- Resistivity measurements

It is very important to understand the relationship between the cause and the effect.

After the condition survey, it is necessary to begin the repair analysis. One must give attention to the owner and engineering considerations. With most damaged or deteriorated structures, the owner has a number of options that will effectively decide the appropriate repair and protection strategy to meet the future requirements of the structure.

The options include:

- Do nothing.
- Downgrade the structure or its capacity.
- Prevent or reduce further damage without repair.
- Improve, refurbish or strengthen all or part of the structure.
- Demolition.

It is necessary to clarify the owner's requirements and instructions in relation to:

- The required durability, requirements and performance.
- Intended design life
- How loads will be carried before, during and after repair.
- The possibility for future repairs including access and maintenance.
- Costs of alternative solutions.
- The consequences and likelihood of structural failure.
- The consequences and likelihood of partial failure.

The following engineering criteria must be adhered to:

- Structural requirements
- Effect on structure
• Constructability
• Repair environment
• Safety

And environmentally:
• The need for protection from the sun, rain, frost, wind, salt and/or other pollutants during the works.
• The environmental impact or restrictions on the works in progress (particularly the noise and the time taken to carry out the work).
• The likely environmental/aesthetic impact of the improved/reduced appearance of alternative solutions.

After all the data is collected and analyzed, it is necessary to decide on a repair strategy. The final design presents a solution based on considerations of durability and compatibility with the existing structure. It is important that the cost of the repair strategy is fully understood. From Figure 13, it is very clear that a repair and protect strategy has a high initial cost, but that the service life of the strategy is almost double that of the repair strategy alone. It is very important to compare the cost of all possible strategies. The cheapest option is not always the best option.

Finally, it is necessary to determine future maintenance requirements.
This will include the following:

- What are the mode and result of the elected material deterioration, i.e. chalking, embrittlement, discoloration or delamination?
- Which surface preparation and access systems will eventually be required and when?
- Who is responsible for the maintenance, and how will it be financed?\(^\text{12}\)

### 3.3. Different evaluation techniques

#### 3.3.1. Corrosion activity measurements

When steel corrodes in concrete, an electric potential difference exists between the anodic half-cell area and the cathodic areas on the steel. This difference can be detected by placing a copper-coppersulfate half cell on the surface of the concrete and measuring the electro potential differences between the steel and a wet sponge on the concrete surface. The reference cell connects the concrete surface to a high impedance voltmeter, which is also electrically connected to the reinforcement mat. The voltmeter then reads the electro potential difference at the test location. Three readings are converted into a potential gradient mapping.

The half-cell potential measurements can be interpreted as follows:

- Less negative than \(-0.20\) volts indicates a 90% probability of no corrosion.
- Between \(-0.20\) and \(-0.35\) volts, corrosion activity is uncertain.
- More negative than \(-0.35\) volts is indicative of a greater than 90% probability that corrosion is occurring\(^\text{11}\).

#### 3.3.2. Determining the depth of carbonation

To determine the depth of carbonation, a fresh concrete surface must be exposed. This can be done by core drilling the suspicious surface area. The position of carbonation can be determined by spraying the concrete surface with an acid-based indicator that changes colour at a \(\text{pH}\) of about 10, indicating the interface between carbonated and uncarbonated zones\(^\text{11}\).

#### 3.3.3. Impact echo method

The impact echo technique locates voids, cracking and honeycombing by impacting the concrete surface with a short duration stress pulse that is reflected from defects and external boundaries back to the receiver. The signals received are converted into a frequency spectrum and displayed on a computer screen.
3.3.4. Ultrasonic pulse velocity methods
Pulse velocity is the measurement of the transit time of an ultrasonic pulse between the transmitter and the receiver. If the distance between the transmitter and the receiver is known the velocity of the pulse can be determined. In general, the denser and stronger the concrete being tested, the higher the velocity of the pulse. The velocity of sound waves through the concrete is reduced by the presence of voids and cracks.

3.3.5. Covermeters
Magnetic devices, known as covermeters, are used to locate the position of embedded steel. The accuracy of these devices is dependent on the amount of reinforcing present in the concrete.

3.3.6. Chaining
Chaining is a very effective and easy method to use on flat concrete surfaces. In general, this method must be used first, to obtain an indication of the magnitude of delamination on a concrete structure. By dragging the chains over a concrete surface, the change in sound will tell an experienced listener a great deal about voids and delamination of the underlying concrete.

3.3.7. Hammer
The hammer works on the same principle of change in sound as the method of chaining. By lightly hitting the concrete surface with a hammer, delamination of the surface concrete can be picked up. A hollow sound is an indication of delamination. It is a very cheap and easy method to use. Although this is a very primitive method to use, the results generally are more reliable than those given by sophisticated testing methods.

3.3.8. Core sampling
By drilling cores, the depth of carbonation and chloride penetration can be determined. The cores can also be used to do a Petrographic analysis.

3.4. Summary
The concrete repair process must include the following:
1. Evaluate the existing concrete structure.
2. What is the effect?
3. What caused the effect?
4. Is repair required?
5. If the answer is "No", evaluate the structure again in a few years.
6. If the answer is "Yes", do a condition survey.
7. Do a repair analysis.
8. Prepare the repair strategy.
9. Do the actual repair.
10. Remind the client that future maintenance is a possibility.
CHAPTER 4
THE REMOVAL OF DAMAGED CONCRETE

4.1. Introduction
Surface preparation involves the process of conditioning the existing concrete to receive repair materials. The deteriorated, contaminated or damaged concrete must be removed to provide surfaces that will promote good bonding. Unfortunately, there is very little guidance available to provide assistance in the selection of a proper removal technique. Almost all literature states that all deteriorated concrete must be removed. But what is enough? Some literature states that removal must take place until the aggregate begins to fracture. This will definitely not work for low strength concretes. The stresses needed to fracture the aggregate will be greater than the tensile stresses developed by the cement paste binding the aggregate together. All concrete will be destroyed before the fracture of the aggregate can begin. Concrete removal techniques that are effective, safe, economical and minimise the damage to the existing concrete must be selected. The engineer in charge of the design should specify the desired result to be achieved by a certain concrete removal technique. The mechanical properties of the concrete provide information required to determine the removal technique and the cost of the removal process. Both an improper surface preparation and failure to follow the instructions of the manufacturers will lead to a short-lived solution.

The following must be done for a proper surface preparation:

- All loose material should be removed.
- The old surface must be cleaned by sandblasting, waterblasting or jackhammer.
- The problem area must be cleaned of any old existing coatings.

To promote good bonding between repair materials and the existing concrete, the following are required:

- A clean sound substrate
- A rough profile for a good mechanical interlock
- An open-pore structure
- Repair material absorption into the substrate
- Intimate contact

The removal technique plays a very important role in obtaining the above-mentioned characteristics required for good bonding.
It is very important for the substrate to be of sound quality after the removal of damaged concrete. If deteriorated concrete is left behind, problems with bonding, surface cracking, and later, the full delamination of the patch will be experienced. Therefore, the entire area under reparation should be evaluated after the removal operation. This can be done visually or by sounding. Near surface damage will be indicated by a microscopic examination or bond testing.

Sub-surface evaluation could be accomplished by one of the following methods:
- Cores
- Pulse velocity tests
- Pulse echo tests

Many techniques are available to perform surface preparations. Much of the removal work is still done by small hand-held chipping hammers, because of their mobility and versatility.

4.2. Surface layout for patch repair

The deterioration of concrete surfaces is generally not uniform. The layouts of patch repairs should be designed to reduce boundary edge length. Complex edge conditions result in shrinkage stress concentrations and cracking. The outside edge of a concrete repair area must be saw cut about 20mm deep to prevent the formation of feather edging. The concrete surface layout should be made as simple as possible.

There are two mindsets that could be followed:
- Remove all damaged concrete.
- Remove only the damaged areas that affect serviceability.

The first viewpoint is to remove all the damaged concrete from a structure. No attention is given to the magnitude of deterioration. Is the deterioration detrimental to the serviceability of the structure? Even if the deteriorated concrete does not affect the serviceability, it is still removed. There are two sides to the coin. The process is very expensive, because the quantities of removal are large. On the other hand, the process of deterioration is terminated or retarded over the entire structure. Although the cost may be high at present, future maintenance costs will be much lower. The interval between routine maintenance will also be longer. In most instances, only the deteriorated concrete that influences the serviceability of a
structure is removed and repaired. The main reason for removing only the deteriorated concrete that influences serviceability is to keep the initial cost low. Under financial restrictions, this option is the most viable one. The problem is that the process of deterioration continues in the unrepaired sections. If the damaged concrete is only partially removed the rest of the concrete is for example, still in a state of carbonation, and if left unprotected, it will result in problems in a few years. This makes routine maintenance a must. The structure needs to be evaluated over time to see if the unrepaired sections do not affect the serviceability of the structure. Although the initial cost is low, the long-term cost of routine maintenance is higher. All these facts must be communicated to the client. At the end of the day, the client must carry the financial consequences of his decisions.

Figure 14  The correct surface layout for concrete repair.

beam section  column section

slab or wall section  edge section

Figure 15  Repair geometry.

The depth of removal also plays a vital role in the success of a repair project. The wrong method of removal is shown in figure 16. Firstly, the depth behind the reinforcement should
not exceed 10mm. Anything larger than 10mm will only lead to the wastage of the repair material. In practice, it is very difficult to get the edges square. The only way is by using a grinder. This will cause a lack of bond between the concrete and the repair material. The only way to improve the bond is by roughening the surface. It will improve the mechanical bond.

![Figure 16 Depth of removal (wrong method)](image)

There are two correct methods of concrete removal as can be seen in Figures 17 and 18. For option one, all the concrete around the steel bar must be removed. There should be a gap of 10mm between the reinforcement and the concrete.

![Figure 17 Depth of removal (option 1)](image)
Option two is to keep two thirds of the reinforcement covered by concrete. If the concrete is only deteriorated to the depth of the reinforcement, it is not necessary to remove the concrete to 10mm behind the reinforcement. Compaction is improved, because it is not necessary to compact behind the reinforcement. The removal technique used for this is very important. The use of mechanical methods will disturb the bond between the reinforcement and the concrete. Under heavy hammering, the reinforcement can become totally dislodged from the concrete behind the reinforcement. It is important for the bond between the reinforcement and the concrete to be of sufficient strength.

![Figure 18 Depth of removal (option 2).](image)

### 4.3. Concrete removal techniques

There are several methods of concrete removal. These methods could be categorised by the way they act on the concrete.

These categories are: Blasting
- Gritblasting
- Sandblasting
- Cutting
- Impacting
- Milling
- Splitting

---

43
### Table 3  Removal method: blasting\(^8\).

<table>
<thead>
<tr>
<th>Use rapid expanding gas confined within holes to produce a controlled fracture</th>
<th>Feature</th>
<th>Limitations/Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Removal of large volumes of concrete</td>
<td>Requires highly skilled personnel</td>
</tr>
<tr>
<td></td>
<td>Good fragmentation of concrete for easy removal</td>
<td>Stringent safety regulations needed for use of explosives</td>
</tr>
<tr>
<td></td>
<td>Explosives</td>
<td>May cause damage to surrounding buildings or concrete</td>
</tr>
</tbody>
</table>

### Table 4  Removal method: cutting\(^8\)

<table>
<thead>
<tr>
<th>Use perimeter cuts to remove large pieces of concrete</th>
<th>Feature</th>
<th>Limitations/Considerations</th>
</tr>
</thead>
</table>
|  | **Diamond saw**:  
  - Can make cuts through slabs, decks etc.  
  - Make precision cuts  
  - No heat and dust |  
  - Limited to thin sections  
  - Type of diamonds determines effectiveness  
  - The higher the percentage of reinforcement cut the higher the cost |
|  | **Diamond wire cutting**:  
  - Can cut large and thick pieces of concrete  
  - Diamond wire can be infinitely long  
  - No vibration and dust  
  - Cutting operation equally effective in any direction |  
  - Cutting chain must be continuous  
  - Drill holes through concrete necessary  
  - Water must be available to the chain  
  - Wastewater may be a problem  
  - The harder the aggregate the higher the cost.  
  - Type of diamonds determines effectiveness |
<table>
<thead>
<tr>
<th>Use perimeter cuts to remove large pieces of concrete</th>
<th><strong>Mechanical shearing:</strong></th>
<th><strong>Stitch drilling:</strong></th>
<th><strong>Thermal cutting:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Can cut large and thick pieces of concrete</td>
<td>- Can make cut-outs in concrete where only one face is accessible</td>
<td>- Can make cut-outs through heavily reinforced concrete</td>
</tr>
<tr>
<td></td>
<td>- Can cut steel reinforcement</td>
<td>- The depth of the cut is dependent on the accuracy of the equipment</td>
<td>- Can cut irregular shapes</td>
</tr>
<tr>
<td></td>
<td>- No vibration and dust</td>
<td>- Hearing protection needed due to high noise levels</td>
<td>- Minimal noise, vibrations and dust</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Not commercially available</td>
<td>- Damage to existing concrete substrate is extensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reinforcement can be damaged</td>
<td>- Produces smoke and fumes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Concrete is damaged</td>
<td>- Protection from heat is needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Concrete is damaged</td>
<td>- Feather edges are formed</td>
</tr>
</tbody>
</table>

**Use perimeter cuts to:**

- **Mechanical shearing:**
  - Can cut large and thick pieces of concrete
  - Can cut steel reinforcement
  - No vibration and dust

- **Stitch drilling:**
  - Can make cut-outs in concrete where only one face is accessible

- **Thermal cutting:**
  - Can make cut-outs through heavily reinforced concrete
  - Can cut irregular shapes
  - Minimal noise, vibrations and dust

- Limited to thin sections where an edge or hole is available to start a cut
- Reinforcement can be damaged
- Concrete is damaged
- Feather edges are formed

- An economical method, but it causes vast damage to the concrete substrate
- The depth of the cut is dependent on the accuracy of the equipment
- Hearing protection needed due to high noise levels

- Not commercially available
- Damage to existing concrete substrate is extensive
- Produces smoke and fumes
- Protection from heat is needed
4.3.1. The chipping hammer or jackhammer

The chipping hammer is the most common removal tool for surface repair. The hammer is light enough for use on vertical and overhead surfaces. Large jackhammers may be too heavy to use for overhead applications. They have a drawback in that they cause micro-cracking in the surface of the concrete substrate. In effect, the jackhammer causes the bruising of the concrete.

Very fine cracks exist on the interface between aggregates and the cement paste. They are caused by interfacial shear and tensile stresses due to early volumetric change without the presence of external loads. Volume change caused by hydration and shrinkage could create tensile and bond stresses of sufficient magnitude so as to cause failure at the aggregate-mortar interface. As an external load is applied, mortar cracks develop due to an increase in compressive strength, propagating continuously through the cement matrix up to failure.

Micro-cracks are the main cause of low tensile strengths of concrete. An upper limit in size of 1mm is suggested. These cracks will remain stable up to about 30% of the ultimate load, after which there will be an increase in the crack width, length and number. At 70-90% of the ultimate load, these cracks will propagate to the surface to form a permanent crack pattern. This is the fast crack propagation stage. The stress level at the onset of this stage is higher in high strength concretes. If the load is sustained, failure may take place. These cracks lead to problems with the bond between the concrete substrate and the repair material.

The tensile strength is influenced by three factors:

- The repair material
- The bonding coat
- The concrete substrate

The weakest of these three will determine the quality of the bond achieved. Micro-cracks tend to make the concrete substrate the weak link. In doing pull-off tests, the fracture will occur in the first few millimetres of the concrete substrate. It is caused by the low tensile strength of the concrete substrate, which is in turn caused by micro-cracking. A consequence of the development of the cracks is a reduction in the effective area resisting the applied load. The development of cracks reduces the number of load-carrying paths, and eventually the ultimate strength of the specimen is reached.
It is therefore recommended to use a lightweight hand-held jackhammer that will cause minimal bruising of the concrete. The use of sandblasting is a must when using a hammer and chisel. The use of waterjetting or sandblasting will remove the weak upper 3-5mm of the concrete substrate. The micro-cracks are therefore removed and a proper bond between the repair material and the concrete substrate will be achieved. By using sandblasting, the problem of micro-cracks will disappear.

Figure 19  The bruising of concrete.

4.3.2. Hydro demolition

Water is a modern-day force that can be used for demolition. With hydro demolition equipment, high-pressure water is used to remove concrete effectively. Sand can be added to the high pressure water, so-called gritblasting. The lance-cutting head must be kept stable and close to the work area, and the back thrust created by the hydraulic cutting force must be resisted. For maximum hydro-demolition efficiency, the orifice of the cutting tip should always be as close as possible to the concrete surface. This is referred to as the “optimum stand-off distance”. It is always necessary to use guards for protection against flying debris. The work area should be coned and the immediate area of demolition should be restricted to operators only. The industry standard for high-pressure hoses always provides for a safety factor of 3:1 in the design of the hose to the operation of the hose. A pressure relief valve, tested, and set at 15% over the operating pressure conditions should protect the entire system. Water pressure of at least 500 bar is needed to remove all the damaged concrete. If the above control measures are taken, the debris is contained in the immediate area of demolition, and the system is protected. The removed material is easily swept, tested for hazardous containment, and disposed of. The surface produced by hydro-demolition is excellent for bonding between concrete and repair materials.
The following are advantages of hydro-demolition:

- No vibration fractures.
- Dust free.
- Environmentally friendly.
- Water is recycled.
- No bruising of the concrete.

If the "stand-off distance" is maintained, the nozzles are kept in good shape to guarantee laminar flow, and the basic power units and filters are maintained, hydro-demolition is an efficient and competitive work tool. It can be used for repair to concrete surfaces, whether they are on bridge decks, bridge columns, parking decks, airports, steel plants, or many other surfaces.

Hydro demolition has the following disadvantages:

- High volume of water is needed.
- The water must be disposed of in an acceptable manner.
- A slurry is left behind and must be removed.

4.3.3. Pneumatic scablers

The pneumatic scablers utilize reciprocating brushing tools hitting the concrete surface. Again, the formation of micro-cracks may cause problems for the future durability of a concrete repair.

The cleaning of the surface must be done in one of the following ways to remove the bruised concrete:

- Sandblasting
- Waterblasting
- Shotblasting

4.3.4. Milling machines

Milling machines are available in all sizes for varying field situations. Most of them utilize carbide-mounted tips on a rotary drum. The drum rotates, causing the carbide to chip away at the concrete surface.
4.3.5. Mounted breakers

Mounted breakers are effective high volume removal tools. They are generally found on backhoes and skid steer loaders. This method can also lead to the formation of micro-cracks. Sandblasting or waterblasting must be used to remove the bruised concrete.

4.3.6. Splitters

Splitters are tools used to fracture concrete into easily removable debris.

Splitters are available in three types:

- Hydraulic wedges
- Fluid pressure
- Expansive cements

Abrasives mixed with pressurized air and projected through a nozzle work the best.¹⁸

4.4. Micro-cracking

Micro-cracks can be defined in two categories:

- Bond cracks at the aggregate-mortar interface.
- Paste cracks within the mortar matrix.

Very fine cracks exist on the interface between aggregates and the cement paste. They are caused by interfacial shear and tensile stresses due to an early volumetric change without the presence of external loads. Volume change caused by hydration and shrinkage could create tensile and bond stresses of sufficient magnitude so as to cause failure at the aggregate-mortar interface.

As an external load is applied, mortar cracks develop due to an increase in the compressive strength, propagating continuously through the cement matrix up to failure. A typical stress-strain diagram is shown in Figure 20.

Micro-cracks are the main cause of low tensile strengths of concrete. An upper limit in width of 1mm is suggested⁴. These cracks will remain stable up to about 30% of the ultimate load, after which there will be an increase in the crack width, length and number. At 70-90% of the ultimate load, these cracks will propagate to the surface to form a permanent crack pattern.
If the load is sustained, failure may take place. Figure 21 shows the relation between observed crack lengths and the stress/strength ratio. It can be seen that there was little increase in length between the beginning of the loading and a stress equal to 85% of the prism strength. A further increase in the load resulted in a large increase in the crack length.

Figure 20  Schematic stress-strain diagram of concrete in micro-cracking\(^{21}\).

Figure 21  Relation between the observed length of cracks in an area of 100mm\(^2\) and the stress/strength ratio in compression\(^{22}\).
The development of micro-cracking means that the stored energy strain energy is transformed into the surface energy of the new crack faces. Because the cracks develop progressively at interfaces, making varying angles with the applied load, there is a progressive increase in the local stress intensity and in the magnitude of the strain. A consequence of the development of the cracks is a reduction in the effective area resisting the applied load. The development of cracks reduces the number of load-carrying paths, and eventually the ultimate strength of the specimen is reached. Micro-cracks are a general feature of concrete and as long as they are stable, they will cause no harm.

4.5. Cleaning and protection of reinforcement

The reinforcement also needs cleaning, repair and protection. Corroded or otherwise damaged reinforcing steel is usually found in concrete in conjunction with concrete deterioration. Heavy rust layers that build up on reinforcing steel during the corrosion process are the cause of concrete delamination and spalling. The removal of oxide build-up is critical to the long-term success of surface repairs. The proper cleaning of corroded bars requires the removal of concrete around the full circumference of the bar.

There are two reasons for this:

- To allow the repair material to encapsulate the bar, providing a relatively uniform electrochemical environment.
- To anchor the repair to the substrate.

Whenever bars corrode, they also lose valuable section, thereby reducing the ultimate load-carrying capacity. If the reinforcing steel has lost more than 25% of its cross-section, reinforcing steel repair is generally required.

One of the following methods should be used:

- Supplemental bar over affected length.
- Complete bar replacement.

The following could be used to clean steel reinforcement:

- Needle scalers.
- High-pressure water cleaning.
- Abrasive blast cleaning.
- Power wire brushing.
Needle scalers are pneumatic tools utilising a group of small diameter steel rods powered by an internal piston. The steel rods hit the surface, causing the removal of surface materials.

There are four categories of steel protection:

- **Encapsulation.** Insulating the bar from electrical currents in the surrounding concrete can be accomplished by encapsulating the bar with epoxy.

- **Cathodic protection/sacrificial anode.** Protecting bars from corrosion can be accomplished by coating them with a sacrificial metal. Zinc is the metal commonly used for this purpose. The service life is dependent on the degree of exposure to a corrosive environment and the anode activity.

- **Cathodic protection/impressed current.** Protecting bars from corrosion can be accomplished by reversing the electrical current flow that causes the corrosion process. Anodes are installed on and near the concrete surface, and electrically connected to the reinforcing steel. Electric current is pumped into the circuit, protecting the bars.

- **Alkaline slurry coating**.

4.6. Summary

Surface preparation is the process of conditioning the existing concrete to receive concrete repair materials. To assure a good bond between the concrete and the repair material, all the damaged concrete must be removed. Only sound good-quality concrete should be left after the removal of the damaged concrete. The concrete patch layout must be made as simple as possible. The aim is to keep the boundary edge length to a minimum. The choice between the removal of all the damaged concrete and simply removing the concrete that affects the serviceability of the structure must be made. Budget constraints will determine the magnitude of the removal in most instances. The concrete should be removed to a depth of around 10mm behind the reinforcement.

The different removal techniques that could be used are:

- Blasting
- Gritblasting
- Sandblasting
- Cutting
- Impacting
- Milling
- Presplitting
The problem with the use of mechanical methods is the formation of micro-cracks in the first few millimetres of the concrete substrate being prepared. The first few millimetres must be removed by either hydro-jetting or sandblasting. Mechanical methods must never be used on their own. The reinforcement must be cleaned properly with either sandblasting or hydro-jetting. If the reinforcement is not properly cleaned the bond between the reinforcement and the repair material will be weak. The proper removal of damaged or contaminated concrete is essential for the long-term success of a concrete repair project.
5.1. Introduction

Selecting repair materials for surface repair is an important and complex process involving an understanding of what is required of the repair by the owner and the engineer, service and exposure conditions, and installation technique. After the requirements are established and the material properties are defined, the selection of specific materials can be made. The final selection of materials is made based on the relationship between cost, performance and risk. An understanding of material behaviour in the cured and uncured states is needed for material selection. One of the biggest problems with repair materials is their dimensional behaviour relative to the substrate. High internal stresses may result in tension cracks, the loss of load-carrying capabilities, and delamination or deterioration. Attention must be given to materials that address relative dimensional behaviour properly. Another problem is selecting surface repair materials for structural applications.

There are two obstacles to achieving success:

- What external loads are initially placed on the repair?
- How will the dimensional behaviour relative to the substrate affect the stress levels within the repair material?

The cost of grouting and the material itself is small if compared to the total cost of a concrete repair project. This is the reason behind the neglect of this very important step in the concrete repair process. The long-term success of a concrete repair project is subject to a thorough investigation of the correct repair material to be used.

Selecting repair materials that will successfully perform under anticipated service and exposure conditions requires an understanding of how the service and exposure conditions affect the repaired member. Understanding the repair material's response to a given service/exposure condition helps in determining required material properties for a successful repair.
The following physical properties need to be considered when choosing a suitable concrete repair material:

- Shrinkage
- Workability
- Versatility
- Reliability
- Durability
- Strength
- Chemical resistance
- Compatibility with substrate

The use of low shrink concrete repair materials is recommended, because shrinkage induces stresses in the concrete repair material. These stresses cause the cracking of the repair material that is detrimental to the durability and chemical resistance of the repair material. Compressive strength is usually the least important property of a concrete repair material. Of far more importance is the flexure/tensile strength. These two factors play an important role in the control of crack formation. As long as the tensile capacity of the repair material is larger than the tensile stresses induced by external factors, the repair material will not crack.

In general, the modulus of elasticity must be the same or similar to that of the substrate concrete. Materials with the same modulus of elasticity tend to have the same elastic behaviour under loads. The modulus of elasticity is a good indication of whether two materials are compatible with each other. The amount of creep allowed by a concrete repair material must also be known. Creep has the tendency to relieve the stresses developed in a concrete repair material. For a concrete repair to be durable, it must have low permeability, resistance to UV rays, and, if exposed to wear, it must have a high abrasion resistance. In aggressive acidic environments, the repair material must have a high chemical resistance.

A concrete repair material must be compatible with the substrate in the following four ways:

- Coefficient of thermal expansion/contraction
- Magnitude of shrinkage
- Modulus of elasticity
- Alkalinity

Concrete repair materials need to be reliable. This means that the materials used must have an extensive track record. This record must be built up by the supplier from experience with
the particular product in the industry. Versatility of products is more important to the manufacturer. One single product must be able to withstand different exposure conditions. The product must have good workability to ease the application process. If a material is difficult to apply, problems with acceptable levels of workmanship will be experienced.

5.2. The range of concrete repair materials available
One of the biggest problems with the selection of repair materials is maintaining their relative dimensional compatibility with the substrate. Moisture-related volume changes in repair materials (drying shrinkage) cause many repair failures. The selection of repair materials with minimal drying shrinkage is critical for durable repairs. Most repair materials that are mixed and placed have an excessive amount of water above what is required for hydration. As the repair is allowed to dry out and assume the humidity of the surrounding environment, the material shrinks in volume and tensile stresses begin to accumulate in the repair material. The repair material resists cracking until the stress exceeds its tensile capacity. Materials that demonstrate drying shrinkage close to 0.00% should be selected. Materials with the same E-modulus as the concrete substrate that is going to be repaired must be used. The two materials are more compatible with each other. This will lead to better results.

Table 5 is a quick reference to the most common concrete repair materials available on the market.

5.2.1. Non-shrink cementitious grouts
It is important to understand the definition of non-shrink. The basic definition is once the grout is placed, there is no plastic or drying shrinkage at any time. As soon as shrinkage takes place, there will be a loss of effective bearing area (EBA). EBA is the percentage final area of the grout in direct contact with a surface. A non-shrink grout should fill a space permanently and yield a high EBA. In the early sixties, hydraulic cement, sand, iron aggregate and aluminum powder were used to give the grouts non-shrink properties. The use of iron aggregate and aluminum powder is banned, because of its unreliability and tendency to shrink. The truth is that total non-shrink repair materials do not exist. Non-shrink cementitious grouts will normally be used for the repair of structural damage to a structure. The coefficient of thermal expansion/contraction, modulus of elasticity and alkalinity is very similar to that of concrete substrates in most instances.
Cementitious grouts have the following advantages:

- Economy
- Ease of installation
- Can be used in a wide variety of applications

Table 5  Common available repair materials and their properties\textsuperscript{11}.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Binder</th>
<th>Additive</th>
<th>Curing</th>
<th>Drying shrinkage*</th>
<th>Coeff. Of thermal expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement mortar</td>
<td>Portland cement</td>
<td></td>
<td>Wet 7 days</td>
<td>Moderate</td>
<td>Equal to substrate</td>
</tr>
<tr>
<td>Portland cement concrete</td>
<td>Portland cement</td>
<td></td>
<td>Wet 7 days</td>
<td>Low</td>
<td>Equal to substrate</td>
</tr>
<tr>
<td>Microsilica modified</td>
<td>Portland cement</td>
<td>Micro silica</td>
<td>Wet 7 days</td>
<td>Low</td>
<td>Equal to substrate</td>
</tr>
<tr>
<td>Portland cement mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latex modified</td>
<td>Portland cement</td>
<td>Latex</td>
<td>Wet 3 days</td>
<td>Low</td>
<td>Compatible with substrate</td>
</tr>
<tr>
<td>Portland cement concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer modified</td>
<td>Portland cement and polymers</td>
<td>Non-sag fillers and polymers</td>
<td>Moderate</td>
<td>Compatible with substrate</td>
<td></td>
</tr>
<tr>
<td>Portland cement mortar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium phosphate</td>
<td>Magnesium phosphate cement</td>
<td></td>
<td>Sheet 45 minutes - 2 days</td>
<td>Moderate</td>
<td>Equal to substrate</td>
</tr>
<tr>
<td>cement concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preplaced-aggregate</td>
<td>Portland cement</td>
<td>Pozzolans</td>
<td>Wet 7 days</td>
<td>Very low</td>
<td>Equal to substrate</td>
</tr>
<tr>
<td>concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy mortar</td>
<td>Epoxy resin</td>
<td></td>
<td>4 hours - 2 days</td>
<td>Low</td>
<td>(1.5-5) * concrete</td>
</tr>
<tr>
<td>Methacrylate</td>
<td>Acrylic resin</td>
<td></td>
<td>1 - 6 hours</td>
<td>Moderate</td>
<td>(1.5-5) * concrete</td>
</tr>
<tr>
<td>concrete (polymer concrete)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shotcrete</td>
<td>Portland cement</td>
<td>Pozzolans</td>
<td>Wet 7 days</td>
<td>Moderate</td>
<td>Equal to substrate</td>
</tr>
</tbody>
</table>

* Drying Shrinkage: Low $< 0.05\%$
  Moderate $0.05\% - 0.10\%$
  High $> 0.10\%$

57
5.2.2. **Non-shrink epoxy grouts**

These materials are used commonly with great success. A common epoxy is the two-component organic system, which produces a 100% solid, modified epoxy resin. This resin is injected into the crack, and is self-bonding. A great advantage of epoxy is that it can be used at very low temperatures. The pot-life of an epoxy is extremely important. Pot-life refers to the time in which a mix is still workable. Epoxy hardens quickly and gains strength within a few hours. It has good adhesion properties, physical stability and resistance to harmful chemicals. It is crack resistant and resists water penetration. The shrinkage is low but, the coefficient of thermal expansion/contraction can be up to 10 times greater than that of concrete.

The following are commonly used epoxy products:

- Penetrating sealers
- Waterproofing systems
- Concrete-steel bonding systems
- Anticorrosive systems
- Concrete-injection systems
- Mortar-patch systems
- Antiskid-surface systems
- Sealers

5.2.3. **Polymers in concrete**

Polymers are widely used in concrete repair materials. These repair materials have been used widely for the repair of concrete buildings, pavements and bridges.

Polymers give repair materials the following properties:

- Rapid curing
- Good bond to existing concrete
- Good mechanical and durability characteristics
- Low permeability
- A wide range of properties such as resistance to ultraviolet rays
- Greater thermal contraction and expansion than concrete
- Greater creep than concrete at higher temperatures
- Reduced strength and stiffness at higher temperatures
There are two categories of concrete polymer materials:

- Polymer concrete
- Polymer-modified concrete

Polymer concrete consists of aggregate with a polymer binder and no cement or water. Polymer-modified concrete consists of cement and some sort of polymer.

The following monomers and resins are used in polymer concrete:

- Methymethacrylate
- Polyester-styrene
- Epoxy
- Furan
- Urethane
- Vinyl ester

The use of curing agents will cause the polymerization of the monomers. Polymerization is the chemical process of linking molecules together. Epoxies need 1-12 hours of curing, whereas Acrylics and Polyesters need 20-60 minutes.

The following polymers are used in Polymer-modified concrete:

- Styrene-butadiene latex
- Acrylic latex
- Polyvinyl acetate
- Ethylene vinyl acetate

Latex-modified concrete is widely used for overlays on bridges, hydraulic structures and buildings. About 15 percent latex solids by weight of cement are used. The latex provides a greater bond and tensile strength and less permeability. On buildings, a thin layer is sprayed onto the surface. This thin layer protects the concrete against the aggressive environment. These materials are less expensive than epoxies and easy to apply, and they perform as well. They are flexible and durable. The problem with these materials is that of colour matching with the existing concrete. Styrene Butadiene is used in fast-setting concrete repair materials. A facility can be back in use 24 hours after application.
SBR concretes are used mostly for the following applications:

- Bridge deck overlays
- Parking garage overlays and repairs
- Spray on repairs for hydraulic structures

Acrylic latexes are used when colour stability is important. In most instances, when a thin protective coating covers buildings, colour compatibility with the existing structure is very important. This type of latex is more expensive than SBR.

Acrylic latexes has the following advantages:

- No curing needed
- Good bond
- Good wear resistance
- Impermeable

The following should be noted before using polymers:

- Higher cost
- Higher coefficient of thermal expansion
- Low softening and melting temperatures

In general, polymers should be used in the following situations:

- Shallow repairs (<10mm)
- Where the repair must be done in a very short time
- Repairs that are exposed to aggressive environments
- Where greater wear resistance, tensile and compressive strengths are required

Polymers are also used successfully for overlays on bridge decks and floors to:

- Restore the original elevation of a worn surface
- Provide a durable low permeable surface
- Provide wear and abrasion resistance
Table 6 Properties of polymer concrete and polymer-modified concrete.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>PORTLAND CEMENT CONCRETE</th>
<th>POLYMER CONCRETE</th>
<th>POLYMER-MODIFIED CONCRETE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>1</td>
<td>1.5-5</td>
<td>1-2</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>1</td>
<td>3-6</td>
<td>2-3</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>1</td>
<td>0.05-2</td>
<td>0.5-0.75</td>
</tr>
<tr>
<td>Water absorption</td>
<td>1</td>
<td>0.05-0.2</td>
<td>-</td>
</tr>
<tr>
<td>Resistance to acid</td>
<td>1</td>
<td>8-10</td>
<td>1-6</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>1</td>
<td>5-10</td>
<td>10</td>
</tr>
</tbody>
</table>

No units are given. Portland cement concrete is the base (1) to which the other two types are related.

Polymer concrete is used for thin applications, whereas polymer-modified concrete will be used for thicker applications. Polymers are also excellent materials with which to repair cracks. Epoxy injection is widely used to seal off cracks. Epoxy injection is very expensive and labour intensive. The monomers will fill cracks as thin as 0.1mm because of their low viscosity. The primary objective is to seal the cracks and prevent the penetration of moisture. The monomer is a high molecular weight methacrylate, with a viscosity of 10 to 20 cps.

5.2.4. Superplasticized Dense Concrete (SDC)

A cement content of between 470 and 490 kg/m³ is recommended. The water/cement ratio must be between 0.3 and 0.36. The air content must not be more than 6%. SDC should not be used without a bonding bridge of normal Portland cement grout. The bonding bridge is a slurry of cement applied in a thin layer to a concrete substrate before the application of the mortar. The bonding bridge prevents the absorption of water from the concrete repair material. The loss of water from the mix will retard the hydration process.

5.2.5. Microsilica Modified Concrete (MMC)

A cement content of 410 kg/m³ is recommended. The micro-silica content must be 10% of the weight of the cement used. The water/cement ratio must be less than 0.36 and the air content less than 6%. Super-plasticizer can also be used, if necessary. Refer to table 5 for further information regarding MMC.
5.2.6. Magnesium Phosphate cements

Magnesium Phosphate cements are a mixture of Magnesium oxide (MgO) and Ammonium dihydrogen phosphate (NH₄H₂PO₄). The blend reacts with water with a rapid strength gain and heat. This product can be bought prepackaged off the shelf. When repairs are deeper than 38mm, it is recommended that 50% coarse aggregate is added to the mix. In many instances, citric acid can be used as a retarder. Refer to table 5 for further information regarding compatibility with existing concrete substrates.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength:</td>
<td></td>
</tr>
<tr>
<td>1 hour</td>
<td>30</td>
</tr>
<tr>
<td>2 hours</td>
<td>41</td>
</tr>
<tr>
<td>3 hours</td>
<td>44</td>
</tr>
<tr>
<td>28 days</td>
<td>64</td>
</tr>
<tr>
<td>Bond strength</td>
<td>16</td>
</tr>
<tr>
<td>Flexural strength @ 28 days</td>
<td>7</td>
</tr>
</tbody>
</table>

5.3. Test procedures to measure the properties of concrete repair materials

There are eight basic physical performance properties that need to be examined when choosing a concrete repair material. These are:

- EBA
- Compressive strength
- Workability
- Segregation
- Durability
- Creep
- Bleeding

5.3.1. Effective bearing area - ASTM C 827-97 (standard test method for change in height at early ages of cylindrical specimens from cementitious mixtures)

A concrete repair material that has no shrinkage will have a high EBA. Since shrinkage can occur at any time in the life cycle of a concrete repair material, it is very difficult to choose the right test method. The ASTM C 827-97 is the only approved method for measuring the volume change of concrete repair materials.
This method has the following advantages:

- It is statistically reliable.
- The method can be extended to 28 days without much loss of accuracy.

For a concrete repair material to be considered non-shrink, the vertical volume must not go below the original placement volume\(^{23}\).

![Diagram](image)

**Figure 22** Test method for change in height at early ages of cylindrical specimens of cementitious mixtures\(^{23}\).

5.3.2. **Compressive strength – SABS Method 863**

50mm x 50mm x 50mm Cubes should be used, and they should be restrained to simulate an in situ concrete repair. The generally acceptable minimum compressive strength is 34.5 MPa.

5.3.3. **Workability**

In general, workability consists of the following:

- Consistency
- Working time
- Placement versatility

Consistency can be defined as the ability of freshly mixed material to flow. Consistency will in general be measured directly after the mixing process. It is advised to use placement aids such as vibrators etc. to make the placement of concrete repair materials easier. The over-watering of a mixture is not advisable, as it will cause shrinkage, segregation, decreased strength and loss of EBA. A grout should provide variable consistencies so that different placement methods can be used. The slump test is used to provide an indication of the workability of a mix. It does not measure workability directly but rather detects variations in
the uniformity of a mix. SABS Method 862 Part I prescribes the method of testing the slump. A 300mm high mould is used. The mould is placed on a flat surface with the smaller opening facing the top. The mould is filled with concrete in three layers. Each layer is rodded with a 16mm steel rod 25 times. Immediately after filling, the mould is slowly lifted and the concrete allowed to slump. The decrease in height is measured to the nearest 5mm. The meaning of different slumps can be seen in table 8.

**Table 8 Description of workability and magnitude of slump.**

<table>
<thead>
<tr>
<th>Description of workability</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No slump</td>
<td>0</td>
</tr>
<tr>
<td>Very low</td>
<td>5-10</td>
</tr>
<tr>
<td>Low</td>
<td>15-30</td>
</tr>
<tr>
<td>Medium</td>
<td>35-75</td>
</tr>
<tr>
<td>High</td>
<td>80-155</td>
</tr>
<tr>
<td>Very high</td>
<td>160 to collapse</td>
</tr>
</tbody>
</table>

Other tests that can be used to provide an indication of workability are:

- Compacting factor test (SABS Method 862 Part IV)
- Flow test (SABS Method 862 Part II)
- Vebe test (SABS Method 862 Part III)
- Ball-penetration test (ASTM C 360-92)

Working time can be defined as the length of time after mixing in which the material can be placed without the formation of cold joints. If working time is short it will in most circumstances lead to poor workmanship, entrapped air, lower EBA and blocked pumps and mixers. Working time must be long enough to give the contractor time to make a proper and economical placement.

Working time can be determined by doing consistency tests on the mixture over an extended period. It is recommended that a concrete repair material should have a working lifetime of at least 45 minutes. Because of the wide range of application methods available, placement versatility plays a very important role. One must be able to pump, vibrate and pour a concrete repair material into place. The grout that provides the most placement versatility will allow a contractor to achieve the best application at the lowest cost.
One needs to investigate all three of these factors in close relation to each other. Evaluating the workability of a concrete repair material by only looking at one of these factors could be very dangerous.

From Figure 23, the following important observations can be made:

- Grout A has an initial high level of workability, but loses its workability quickly by stiffening. The quick loss of consistency indicates poor placeability.
- The contractor will have to place grout A in a very short period. In most cases, this will lead to entrapped air, air bubbles, voids, segregation and high drying shrinkage.
- Long working times will lead to proper placement and high EBA.

5.3.4. Segregation

Segregation is the separation of different sized aggregates from a mix. This is mostly caused by the use of excess water or very large particle sizes. Segregation will lead to shrinkage, low strength and poor durability. Segregation can be visually determined. Concrete repair materials that segregate should never be used.

5.3.5. Durability

Durability is the ability of concrete repair materials to remain in service for a very long time with very little maintenance. Materials with a high volume change should be avoided. To ensure high durability, the properties needed for a certain application should be investigated.
thoroughly. In the past few years, durability index testing methods have been developed. The methods are only indexes that can be used to describe the future performance of concrete.

The three durability index tests are:

- The oxygen permeability test
- The water sorptivity test
- The chloride conductivity test

The oxygen permeability test assesses the overall microstructure and macrostructure of the outer surface. The test is very sensitive to cracks and voids. The test can assess the compaction, the presence of bleed voids and the degree of interconnectedness of the pore structure. The water sorptivity test measures the physical properties of the first few millimetres of the concrete by means of the mechanism of capillary suction. The test provides an indication of the quality of curing on site. The chloride conductivity test provides an indication of the susceptibility of concrete to the ingress of chloride ions.

After the three durability tests have been completed, the durability of concrete can be classified by using table 9.

<table>
<thead>
<tr>
<th>Durability class</th>
<th>OPI (log scale)</th>
<th>Sorptivity (mm/h)</th>
<th>Conductivity (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&gt;10</td>
<td>&lt;6</td>
<td>&lt;0.75</td>
</tr>
<tr>
<td>Good</td>
<td>9.5-10</td>
<td>6-10</td>
<td>0.75-1.5</td>
</tr>
<tr>
<td>Poor</td>
<td>9-9.5</td>
<td>10-15</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Very poor</td>
<td>&lt;9</td>
<td>&gt;15</td>
<td>&gt;2.5</td>
</tr>
</tbody>
</table>

5.3.6. Bleeding

Bleeding is water that accumulates on the surface due to the settlement of the particles in a mixture. A concrete repair material with high bleeding characteristics will be susceptible to increased shrinkage. Increased shrinkage will lower the performance of concrete repair materials, because they will crack more easily than low shrinkage concrete repair materials of the same strength. Bleeding can be expressed as the total settlement per unit height of concrete or as a percentage of the mixing water. Two methods for determining the magnitude of bleeding are described in ASTM C 232-92. The test methods for the bleeding of cement pastes and mortar is prescribed in ASTM C 243- 85.
5.4. **Summary**

The choice of a repair material can be made, based on the relationship of cost, performance and risk. The repair material must be able to withstand the loads applied to it, and must be dimensionally stable.

The following physical properties of concrete repair materials must be investigated:

- Shrinkage
- Workability
- Versatility
- Reliability
- Durability
- Strength
- Chemical resistance
- Compatibility with substrate

Low shrinkage is a must for concrete repair materials to be successful. The modulus of elasticity and coefficient of thermal expansion/contraction must be similar to that of the concrete substrate.
6.1. Introduction

The success of a concrete repair is greatly determined by the proper placement of the concrete repair material.

The following factors play an important role in the choice of a suitable application method:

- Location of concrete repair
- Obstructions in the vicinity of the concrete repair
- The type of concrete repair material used
- Ambient conditions

6.2. The bond between repair materials and the concrete substrate

Achieving an adequate bond between repair materials and existing concrete is a critical requirement for durable surface repairs. The bond at the interface between the repair material and the concrete substrate is subjected to considerable stress from volume changes, freeze-thaw, force of gravity, and sometimes impact and vibration. Repairs that have bond lines in direct tension have the greatest dependency on bonding.

Keys to develop a good bond:

- Clean, sound substrate.
- Roughened profile of substrate for mechanical interlock.
- Open pore structure in the substrate.
- Repair material/bonding agent with sufficient paste for absorption into substrate pores.
- Repair material is applied with sufficient pressure to facilitate contact between the repair material and the substrate at the bond line.

Three main types of bonding agents are frequently used:

- Cement-based slurries.
- Epoxies.
- Latex emulsions.
For Portland cement-based repairs and overlays, cement or sand-cement slurry is used. After the substrate has been prepared, and immediately before placing the repair material, a thin coating of grout can be swept in.

The following latex products can be used as bonding coats:

- Styrene Butadiene.
- Acrylic.
- Polyvinylacetate.

The use of an epoxy-bonding agent may produce a vapour barrier, resulting in the failure of the bond. Epoxies have poor creep properties and should be avoided when the repair is subject to constant loading\(^7\).

6.3. Placement methods

The placement technique must deliver the selected repair material to the prepared substrate with specified results. The repair material must achieve a satisfactory bond to the existing substrate, fill the prepared cavity without segregation, and fully encapsulate exposed reinforcing steel. An adequate force should be applied to the repair material to bring it into intimate contact with the prepared surface.

The selection of a surface repair placement method includes the following steps:

- Selection of a repair material that best reconstitutes the strength, integrity and performance required by the structure's original design and current situation.
- Selection of a method of placement that will successfully deliver the repair material onto the prepared concrete substrate.
- Checking the constructibility of the selected repair material and the installation method.
- Adjusting the material and installation methods to provide a constructible repair.

The following methods of placement can be used:

- Dry pack.
- Form and cast-in-place.
- Grouted pre-placed aggregate.
- Full depth repair
- Form and pump.
- Shotcrete (dry).
• Shotcrete (wet).
• Hand-applied\textsuperscript{11}.

6.3.1. Dry packing
A dry pack mix is a combination of sand and cement and just enough water for it to be workable. The mix should be proportioned in the following ratio: 1 cement to 3 sand. The water must be just enough to produce a mortar that can be moulded into a ball by a slight hand pressure without water penetrating between the fingers. This product was used for many years before the development of specific purpose grouts. It should never be used for shallow repairs because for the material to perform properly, a confined area is needed. The sides of the repair should be vertical up to the full depth of the repair. The repair area should be moist to avoid the absorption of water by the fresh patch. A bonding agent must be applied, and while it is still tacky, the mortar must be compacted into place\textsuperscript{17}. It is inexpensive to use this method and it is unpredictable. It is not always possible to predict the shrinkage of the repair material because the mix can differ each time.

6.3.2. Form and cast in place
One of the most common methods of vertical surface repairs is the placement of formwork and the casting of repair materials into the prepared cavity. This is known as "form and cast-in-place". The repair material must be of low shrinkage and provide the necessary flowability. Rodding or internal vibration is necessary to remove air and provide intimate contact with the current substrate.

Consolidation of the repair material is accomplished with one of the following techniques:
• The repair material is formulated to be extremely flowable and self-consolidating.
• The repair material is placed into the top of the form and free falls into the prepared cavity where conventional internal vibrators are used.
• Rodding of the repair material from an access point in the formwork.
• External vibration of the formwork\textsuperscript{11}.

6.3.3. Form and pump
The "form and pump" technique is a relatively new method developed in the past 20 years, coinciding with the development of variable output concrete and mortar pumps. This technique is used for vertical and overhead applications. This method is a two-step process of constructing formwork and pumping the repair material into the cavity. The necessary requirement for material selection is pumpability. When the cavity is full, pump pressure is
exerted on the form, causing the repair material to consolidate. Provision must be made in the formwork for entrapped air to escape, otherwise voids will be formed.

The advantages include:

- The use of almost any repair material.
- Placement is not limited to the depth or size of the repair.
- Repair materials are premixed and placed to provide a uniform cross-section without segregation in intermediate bond lines.
- The process does not depend on fighting the forces of gravity.
- The pressurization process consolidates the repair material, providing for the full encapsulation of exposed reinforcing steel.
- The formwork protects the repair material during the curing process.
- The process is less subject to operator error.
- Quality assurance of the in-place repair is easier to provide.

6.3.4. Grouted preplaced aggregate

The grouted pre-placed aggregate is a two-step process. The first step involves aggregate placement into the cavity during the erection of the formwork. The second step involves pumping a highly flowable grout through the formwork and into the pre-placed aggregate. The grout flow makes contact with the prepared substrate as the cavity is filled, providing intimate contact and bonding. An advantage of this method is the low drying shrinkage of the repair material due to the point-to-point contact between the coarse aggregates. The aggregate contact restricts the volume change of the cement grout as drying shrinkage occurs.

6.3.5. Dry mix shotcrete

Dry mix shotcrete is a method that involves the premixing of binder and aggregates, which are then fed into a special mechanical feeder metering the premixed materials into a hose. The hose is fitted with a nozzle that is fitted with a water ring where additional water is mixed with the binder and the aggregates. The mix is jetted from the nozzle at high velocity onto the prepared concrete surface.

Some typical problems associated with shotcrete repairs:

- Presence of voids due to encapsulated rebound.
• Shrinkage cracking caused by high cement content, improper curing or excessive water content

6.3.6. Wet mix shotcrete

Wet mix shotcrete is a method that involves premixing of all the ingredients. The premixed repair materials are deposited into a pump or pressure vessel that transports the materials to a nozzle. The repair material is propelled onto the substrate with compressed air. The Shotcrete method is illustrated in figure 24.

Figure 24  Shotcrete application.
6.3.7. **Full depth of repair**

When concrete surfaces have extensive surface damage, it may be better to do a full depth repair. The existing member is demolished by means of mechanical breakers and reconstructed from scratch\(^{11}\).

6.3.8. **Overlays**

Overlays are used to repair concrete structures as a remedy for a variety of problems. Overlays can be constructed from different materials from very thin to very thick. Overlays require special attention to placement techniques so as to prevent various problems such as plastic shrinkage cracking, the lack of consolidation, segregation or poor bonding\(^{11}\).

6.3.9. **Hand-applied techniques**

Hand-applied techniques are used to place non-sag repair materials on vertical and overhead locations. The mixed material is applied to the prepared surface with either a trowel or by hand. The applied pressure drives the repair material into the pore structure of the exposed concrete. The best use of this technique is for cosmetic repairs not involving reinforcing steel. When reinforcement steel is encountered, it is very difficult to consolidate and provide for the complete encapsulation of the reinforcing steel\(^{11}\).

The following problems occur when the application is done by hand:

- No bond between the repair material and the reinforcement
- Compaction
- Layer thickness

The problem of compaction behind the reinforcement when using hand application techniques is illustrated in figure 25.
Figure 25  Poor compaction behind reinforcement caused by hand application.
6.4. Summary

The bond between the concrete repair material and the concrete substrate must be of sufficient strength to transfer the stresses developed. For a proper bond, the concrete substrate must be clean, the profile must be rough, an open pore structure is needed and the repair material must be applied with enough pressure.

The placement technique must deliver the repair material to the concrete substrate. An adequate force must be applied to the repair material to assure intimate contact with the concrete substrate.

The following placement methods could be used:

- Dry pack
- Form and cast-in-place
- Grouted pre-placed aggregate
- Full-depth repair
- Form and pump
- Shotcrete (dry)
- Shotcrete (wet)
- Hand-applied

Most of the applications done in South Africa are done by hand. Applications by hand can cause bonding and compaction problems.
7.1. Introduction

The purpose of curing is to prevent the loss of moisture and to control the temperature of cementitious concrete repair materials. If such moisture is not kept within the cement matrix, the hydration process will be greatly affected. The newly placed cementitious repair materials are vulnerable to water loss. Hydration is greatly reduced if the relative humidity inside the capillary pores of the cement paste drops below 80%. At w/c ratios of smaller than 0.5, extra water from outside the concrete mix may be necessary to keep the hydration process going. It is also important to start curing as soon as the surface is exposed to the atmosphere. If curing is delayed, calcium hydroxide is deposited in the entrances to the capillary pores. This calcium hydroxide is then carbonated by carbon dioxide in the air, sealing the capillaries. Without curing, the quality of cementitious repair materials will be low. Curing is important to ensure the strength development of cementitious repair materials and to ensure impermeable surfaces.

7.2. The factors affecting the evaporation of water from cementitious repair materials

Three factors that influence the evaporation of water from cementitious concrete repair materials are:

- Relative humidity of the atmosphere
- Temperature
- Wind velocity

If the relative humidity of the ambient air is almost 80%, there will be little movement of moisture from the cement paste into the air. If this scenario exists, little or no curing is needed. In many places around the world, the relative humidity drops to below 80%. Proper curing is therefore necessary. The effect of relative humidity, temperature wind velocity on the evaporation of moisture can be seen in figures 26, 27 and 28. The hydration of cementitious materials can take place only in water-filled capillaries.
Figure 26  The influence of relative humidity of air on the loss of water from concrete in the early stages after placing.

Figure 27  The influence of the temperature of air and concrete on the loss of water from concrete in the early stages after placing.
7.3. The effect of curing on the outer surface of cementitious materials

Cementitious materials on the inside of a member are subject to very little movement of moisture. Thus, curing has very little effect on the final strength of a member, except in very thin members. The properties of the outer 30-50mm of cementitious materials are greatly affected by curing.

The following properties are affected:
- Permeability
- Resistance to carbonation
- Resistance to weathering
- Resistance to abrasion
- Resistance to corrosion
In thin members, the loss of strength can be related directly to poor curing. The higher the w/c ratio, the greater the negative effect of poor curing on the final strength of thin cementitious members.

Figure 29 shows the effect of curing on the permeability of cementitious materials cured for 28 days:
- In water
- In air at a relative humidity of 65%

![Graph showing the effect of curing on permeability.](image)

**Figure 29**  The relation between oxygen permeability and compressive strength for concretes cured for 28 days and in air at a relative humidity of 65%.⁴

The factor that controls carbonation is the diffusivity of the hardened cementitious materials. Diffusivity is a function of the type of cement used, the w/c ratio, and the degree of hydration. The outer zone of cementitious materials is greatly affected by curing. The effect of curing on
the depth of carbonation can be seen in figure 30. The absence of curing will cause high permeability, thus accelerating the diffusion of CO₂ into the cementitious repair material.

![Graph showing depth of carbonation vs compressive strength for dry-cured and wet-cured concrete.](image)

**Figure 30** The relation between the depth of carbonation and the compressive strength of concrete cured in water for 28 days and concrete cured in dry air at a relative humidity of 65%.

The influence of the length of curing on time to the initiation of corrosion can be seen in figure 31. By increasing the time of curing, the permeability of cementitious materials is lowered. It makes the diffusion of oxygen difficult. Oxygen plays an important role in the corrosion process.
The influence of the length of moist curing on time to the initiation of corrosion.

7.4. Different curing techniques
There are two broad methods of curing:

- Wet curing
- Membrane curing

The first method requires the surface of cementitious materials to be in contact with water for a specified length of time. For low w/c ratios wet curing is preferable, because of the self-desiccation process. The temperature of the water should not be lower than that of the cementitious material itself. This will prevent thermal shock and steep temperature gradients.

The following are wet curing methods:
- Ponding of water on horizontal surfaces
- Mist spray
- Covering with sand, straw etc. that is kept wet
Membrane curing prevents the loss of water from cementitious materials, but the ingress of water into cementitious materials is not allowed. The materials used to cover concrete repairs must not damage the concrete by staining or contamination. Wet sawdust generally leaves a stain that is unremovable. In most instances mist spray will be adequate. It is important to prevent the damage of concrete repairs by heavy jets or thermal shock.

The following are curing membrane methods:

- Polyethylene sheets
- Covering with waterproof paper
- Retaining forms in place
- Membrane-forming curing compounds

The membrane must be continues and undamaged. The curing compound must be sprayed after bleeding has stopped, but before the surface has dried out. If the compound is applied to a dry surface, it will penetrate the first few millimetres and stop the hydration process. Some curing compounds may even prevent the application of paint or plaster afterwards. Retaining forms in place may be used where the form and cast repair method is used. Timber formwork should be kept moist to prevent the absorption of moisture from the cementitious repair material by the formwork. Polyethylene sheets are best suited for large horizontal repair areas.

7.5. Duration of curing

The duration of curing required is determined by the drying conditions and the durability requirements. The longer the period of curing, the better the quality of the cementitious material. The minimum period of curing should not be less than seven days. Increasing the curing period from one to seven days was found to reduce permeability by a factor of five. Curing delays the start of shrinkage, but the effect of curing on the magnitude of shrinkage is very small.
Table 10  Suggested minimum moist curing periods.

<table>
<thead>
<tr>
<th>Weather</th>
<th>Minimum moist curing period in days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal: 18 to 22°C</td>
<td>5</td>
</tr>
<tr>
<td>65% RH</td>
<td></td>
</tr>
<tr>
<td>Low wind speeds</td>
<td></td>
</tr>
<tr>
<td>Hot: with drying winds</td>
<td>7</td>
</tr>
<tr>
<td>Cold: 5 to 12°C</td>
<td>9</td>
</tr>
</tbody>
</table>

7.6. Summary

The purpose of curing is to prevent the loss of moisture from cementitious concrete repair materials. The moisture is needed to keep the hydration process going. The evaporation of moisture is affected by the relative humidity of the atmosphere, the temperature and the wind velocity. The worst case of evaporation is when the relative humidity is low and the temperature and wind velocity is high. It is important to note that only the first 30-50mm of cover is really affected by curing.

The properties that are affected by curing are:
- Permeability
- Resistance to carbonation
- Resistance to weathering
- Resistance to corrosion
- Resistance to abrasion

Two methods of curing can be used: wet curing or membrane curing. For wet curing, the concrete repair surface should be kept moist for a specified period. Membranes prevent the loss of water from the concrete repair surface. Curing compounds are very sensitive to the time of application and must be used with care. Literature generally recommends a curing period of no less than seven days.
CHAPTER 8
PROPERTIES OF MATERIALS USED IN THIS RESEARCH PROJECT

8.1. Introduction
For the purposes of this research work, only two repair materials (Material A & C) and a bonding bridge (Material B) were used. Material A is used as the repair material and material B as a bonding bridge. The system was used for laboratory work and in situ testing at the Rand Afrikaans University. In all the experiments, the same materials were used to ensure that properties such as E-modulus, chemical composition, etc. are the same. Different factors cannot be related when different repair materials are used. Materials A and B are readily available in South Africa and used on many projects. Material C is not yet available in South Africa. Some in situ test work with this new product was done at the Rand Afrikaans University to determine how it performs under South African conditions.

8.2. Material A (repair mortar)
Material A is a cementitious, polymer-modified repair mortar containing silica fume. It is mainly designed for thick vertical and overhead applications.

The manufacturer claimed that the product has the following advantages:
• Only needs mixing water
• Easily applied in layers of thickness of up to 70mm
• Provides good resistance to water and chloride penetration
• Good mechanical strength
• Excellent workability characteristics
Table 11  Technical information about material A²⁷.

<table>
<thead>
<tr>
<th>Mix ratio</th>
<th>3.4 – 4 litres of water per 25kg of powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot life (23°C)</td>
<td>30 – 50 minutes</td>
</tr>
<tr>
<td>Density</td>
<td>1.65 kg/litres of fresh mortar</td>
</tr>
</tbody>
</table>

Strengths (28 days, 23°C, 50% RH)
- Compressive 35-45 N/mm²
- Flexural 5-7 N/mm²
- Adhesion Tensile 1.5-2.5 N/mm²

Thermal expansion coefficient 11×10⁻⁶°C
E - modulus (static) 13,000 N/mm²

8.3. Material B (bonding bridge)
Material B is a cementitious, polymer-modified one-component bonding slurry and primer with active corrosion inhibitors.

This product can be used for the following:
- Protection of reinforcement against corrosion
- Bonding bridge between concrete and repair mortars

A brush is used to apply this material to the affected reinforcement or the concrete substrate.

The manufacturer claimed that the product has the following advantages:
- Only needs mixing water (one component mix)
- Excellent adhesion to concrete and steel. (1.5-2.5N/mm²)
- Provides good resistance to water and chloride penetration
- Moisture insensitive
Table 12  Technical information about material B²⁷.

<table>
<thead>
<tr>
<th>Mix ratio</th>
<th>5,0 – 5,5 litres of water per 25kg of powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot life (23°C)</td>
<td>90 – 120 minutes</td>
</tr>
<tr>
<td>Density</td>
<td>1,8 kg/litres of fresh mortar</td>
</tr>
<tr>
<td>Strengths (28 days, 23°C, 50% RH)</td>
<td></td>
</tr>
<tr>
<td>• Compressive</td>
<td>30-35 N/mm²</td>
</tr>
<tr>
<td>• Flexural</td>
<td>5,5-7,5 N/mm²</td>
</tr>
<tr>
<td>• Adhesion tensile</td>
<td>1,5-2,5 N/mm² (concrete failure)</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>1,5 × 10⁻⁶ m/m/°C</td>
</tr>
<tr>
<td>E – modulus (static)</td>
<td>20,000 N/mm²</td>
</tr>
<tr>
<td>Chloride corrosion protection value</td>
<td>&lt; 0,1mm penetration</td>
</tr>
</tbody>
</table>

8.4. Material C (repair mortar)

Material C is a quick-setting, polymer-modified, low-permeability cementitious mortar containing synthetic fiber reinforcement and corrosion inhibitors. In general, material C can be used on concrete, mortar and masonry substrates. It is particularly suited for hand-placed quick repairs. The material can be overcoated within two hours after placement. The material is also suitable for fast-track projects. The material can be used with or without a bonding bridge.

The manufacturer claimed that the product has the following advantages:
- One component, shrinkage compensating material
- Easy to apply
- Good freeze/thaw resistance
- Good resistance to the penetration of chlorides and water
- Excellent slump resistance
Table 13  Technical information about material C²⁸.

<table>
<thead>
<tr>
<th>Mix ratio</th>
<th>2.75-3.25 litres of water per 25 kg of powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot life (20°C)</td>
<td>20 minutes</td>
</tr>
<tr>
<td>Density</td>
<td>2.1 kg/litres of fresh mortar</td>
</tr>
<tr>
<td>Strengths (28 days, 23°C, 50% RH)</td>
<td></td>
</tr>
<tr>
<td>• Compressive</td>
<td>10 N/mm² @ 1 day</td>
</tr>
<tr>
<td></td>
<td>35 N/mm² @ 28 days</td>
</tr>
<tr>
<td>• Flexural</td>
<td>7 N/mm² @ 28 days</td>
</tr>
<tr>
<td>• Adhesive tensile</td>
<td>1.5-2.5 N/mm² @ 28 days</td>
</tr>
<tr>
<td></td>
<td>(Failure plane in the concrete)</td>
</tr>
</tbody>
</table>

8.5. Material used as a concrete substrate

In order to assure that the concrete substrate has the same properties throughout the research work done, standard driveway blocks (300*300*100 thick) were used as supplied by a precast manufacturer. The driveway blocks are made of CEM 1 42.5 cement, 6mm stone and crusher sand, in the ratio: 3:7:5. The compressive strength of the blocks is 30 MPa.
CHAPTER 9
EXPERIMENTAL WORK:
EFFECT OF THE REMOVAL OF DAMAGED CONCRETE
ON THE BOND STRENGTH

9.1. Goal of the experiment

It must be remembered that new and advanced technology will not always work under South African conditions. The low level of skills of the workforce used in the construction industry is a reason for this limitation. Because of restricted budgets, low cost and unskilled labour is often used on construction sites resulting in ineffective operations and the inadequate or non-existent use of machinery that requires technical skills.

Difficult and complex repair techniques cannot be used, because the failure of the repair can almost be guaranteed when such systems are specified. Therefore, affordable removal techniques are a must for South Africa. Currently, removal is mostly done by the so-called mechanical methods i.e. grinder, jackhammer or chisel. These are easy and affordable techniques, but they have drawbacks, for example, the formation of micro-cracks, resulting in low bond strengths.

If we accept that these removal techniques will be used by the industry, what is the best method to apply these removal techniques? How are the detrimental affects, for example, micro-cracks, minimized?

9.2. Experimental procedure

The concrete driveway blocks were used as the concrete substrate. The 300*300*150 blocks were cut into 300*150*150 blocks, prepared and placed in standard 750x150x150 steel beam moulds. The underside of the driveway blocks was used for preparation and application of the repair materials. A 1000-Watt jackhammer was used and the first 10 to 15mm of the concrete substrate was removed
The following surface preparation techniques were used:

- Jackhammer only
- Jackhammer and sandblasting
- Jackhammer and hydro-jetting (150, 250 MPa)
- Jackhammer and steelbrush

After the preparation of the substrate, the tensile strengths of the different concrete substrates was determined by using the Dyna Pull-off Tester. The purpose is to determine what affect the removal technique has on the concrete substrate. The results obtained can be seen in table 14.

After the placement of the concrete blocks into the steel moulds, all loose material and dust were removed by high-pressure oil free air. The concrete substrate was saturated with water for a period of one hour, after which all the surface water was removed. Material B was applied by brush, and left for ten minutes as specified by the manufacturer. Material A was applied by hand. The repair material was thoroughly worked to assure proper compaction. The temperature on the particular day of application was 23°C with no wind. After the initial set, the surface was finished by using a steel trowel. The samples were placed in a curing room and cured for 28 days at 24°C at 85% relative humidity.

After 28 days, the samples were removed from the curing room. The adhesion between the repair material and concrete substrate was determined by doing pull-off tests. The results obtained can be seen in table 15. The equipment used is described in the following section.
9.3. Testing equipment used


Determining the bond strength of overlays and other surface-bonded materials can be accomplished through in situ testing. The pull-off test measures the bond between two layers. A core is made through the surface layer into the second layer. The tester then generates a tensile force on the core until tensile failure occurs.

There are three types of possible tensile failure:

- Failure in the substrate layer
- Separation at the interface between the substrate and the surface layer
- Failure in the surface layer

The testing device can also record the force required to cause failure, which, if divided by the surface area of the specimen, will give tensile strength\(^1\).

The device used during this study is the Dyna Pull-off Tester. This device can be used to measure the following:

- Surface strength of the concrete
- The adhesive strength of all types of applied coatings

The measuring procedure for the adhesive strength of coatings is as follows:

- The measuring surface on the coating is defined by making a circular incision down to the substrate using a 50mm-dia. core drill.
- A test disc is glued to this measuring location by using a standard commercial epoxy based rapid adhesive.
- The test disc is then pulled off by using the DYNA pull-off tester. Direct indication in N/mm\(^2\) is read off from the dial. Between five and seven pull-off tests were done per sample. The pull-off tests were done at random positions on the samples.

The measuring procedure for the surface strength of concrete is as follows:

- The measuring surface on the concrete surface is defined by making a circular incision by using a 50mm-dia. core drill.
- A test disc is glued to this measuring location by using a standard commercial epoxy based rapid adhesive.

90
The test disc is then pulled off by using the DYNA pull-off tester. Direct indication in N/mm² is read off from the dial. Between five and seven pull-off tests were done per sample. The pull-off tests were done at random positions on the samples.

Material D was used as the adhesive. After application, 45 minutes were allowed for the adhesive to set.

9.4. Results obtained

Table 14 Average tensile strength of prepared concrete substrates.

<table>
<thead>
<tr>
<th>SUBSTRATE PREPARATION METHODS</th>
<th>AVERAGE TENSILE STRENGTHS OF CONCRETE SUBSTRATE'S</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGHTWEIGHT JACKHAMMER</td>
<td></td>
</tr>
<tr>
<td>Pull-off test</td>
<td>TENSILE STRENGTH</td>
</tr>
<tr>
<td>Number</td>
<td>(MPa)</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>1.9</td>
</tr>
<tr>
<td>AVERAGE TENSILE STRENGTH:</td>
<td>0.98 N/mm²</td>
</tr>
<tr>
<td>σ = 0.49</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIGHTWEIGHT JACKHAMMER AND STEELBRUSH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull-off test</td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>AVERAGE TENSILE STRENGTH:</td>
</tr>
<tr>
<td>σ = 0.13</td>
</tr>
<tr>
<td>Pull-off test</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

AVERAGE TENSILE STRENGTH: 1.12 N/mm²
σ = 0.23

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>TENSILE STRENGTH (MPa)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>Plain of fracture 5mm into substrate</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>Plain of fracture 1mm into substrate</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>Plain of fracture 3mm into substrate</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>Plain of fracture 1mm into substrate</td>
</tr>
<tr>
<td>5</td>
<td>1.6</td>
<td>Plain of fracture 1mm into substrate</td>
</tr>
</tbody>
</table>

AVERAGE TENSILE STRENGTH: 1.56 N/mm²
σ = 0.41

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>TENSILE STRENGTH (MPa)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>Plain of fracture 1mm into substrate</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>Plain of fracture 3mm into substrate</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
<td>Plain of fracture 25mm into substrate</td>
</tr>
<tr>
<td>4</td>
<td>1.7</td>
<td>Plain of fracture 4mm into substrate</td>
</tr>
<tr>
<td>5</td>
<td>1.8</td>
<td>Plain of fracture 2mm into substrate</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>Plain of fracture 5mm into substrate</td>
</tr>
<tr>
<td>7</td>
<td>4.6</td>
<td>Plain of fracture 2mm into substrate</td>
</tr>
<tr>
<td>8</td>
<td>3.7</td>
<td>Plain of fracture 2mm into substrate</td>
</tr>
</tbody>
</table>

AVERAGE TENSILE STRENGTH: 2.46 N/mm²
σ = 1.04
Table 15  Pull-off test results, 28 days after the repair material was placed on the concrete substrates prepared with different removal techniques

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
<td>Concrete substrate</td>
</tr>
</tbody>
</table>

**LIGHTWEIGHT JACKHAMMER**

**AVERAGE TENSILE STRENGTH:** 0.7N/mm²  \[ \sigma = 0.21 \]

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>4</td>
<td>1.1</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>Concrete substrate</td>
</tr>
</tbody>
</table>

**LIGHTWEIGHT JACKHAMMER AND STEELBRUSH**

**AVERAGE TENSILE STRENGTH:** 1.0N/mm²  \[ \sigma = 0.18 \]

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td>Concrete substrate</td>
</tr>
</tbody>
</table>

**LIGHTWEIGHT JACKHAMMER AND WATERJET (150MPa)**

**AVERAGE TENSILE STRENGTH:** 1.0N/mm²  \[ \sigma = 0.24 \]

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>Concrete substrate</td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td>Concrete substrate</td>
</tr>
</tbody>
</table>
## 9.5. Discussion of results

### 9.5.1. The tensile strength of different concrete substrates before the application of repair materials

The average tensile strength of concrete substrates prepared with different preparation methods before the application of repair materials.

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
<th>AVERAGE TENSILE STRENGTH: 1.2N/mm²</th>
<th>σ = 0.19</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.3</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pull-off test number</th>
<th>Tensile strength (MPa)</th>
<th>Plain of fracture</th>
<th>AVERAGE TENSILE STRENGTH: 0.7N/mm²</th>
<th>σ = 0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.7</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
<td>Concrete substrate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 33**: The average tensile strength of concrete substrates prepared with different preparation methods before the application of repair materials.
Before the results shown in Figure 33 are discussed, it is important to note that a tensile strength of more than 1.5MPa is used as the norm of acceptance by the industry. The concrete substrate must have a tensile strength of at least 1.5MPa. From the results, it is clear that only jackhammer and sandblasting, and jackhammer and waterjet (250MPa) yielded acceptable results. The other three methods did not yield results that would be accepted by the industry. The concrete substrate prepared by jackhammer did not even reach a tensile strength of 1MPa. This could be because of the formation of micro-cracks in the first few millimetres of the concrete substrate. The use of a steelbrush is not recommended because not enough of the damaged concrete is removed. Even waterjetting at a low pressure will not yield the desired results. A pressure of more than 250MPa are recommended. Of all the methods used, the best results were obtained by using the jackhammer in combination with sandblasting or waterjetting (250MPa).

9.5.2. The tensile strength of different concrete substrates after the application of repair materials

![Graph showing comparison of tensile strengths before and after the application of concrete repair materials](image)

**Figure 34** Comparison of tensile strengths before and after the application of concrete repair materials
From table 15 it is clear that failure was in the concrete substrate. It is concrete substrate tensile failure, rather than bond strength failure between the repair material and the concrete substrate. From figure 34 it is clear that the tensile strength after the application of repair materials are of the same magnitude as before the application of repair materials. The difference between the results obtained before and after application can be ascribed only to the fact that more torsion forces are applied to the concrete surface in the samples that have repair materials on the concrete substrate. The torsion forces weaken the bond between the cores and the in situ concrete substrate. When cores are drilled in the sample before application, the torsion forces are applied for a very short period. The bond strength between the repair material and the concrete substrate must be of a higher magnitude than the tensile failure that took place.

9.6. Conclusion

The method of removal that gave the best tensile strength failure results, both before and after the application of repair materials, is a lightweight electrical jackhammer with sandblasting to remove the concrete that is bruised by the jackhammer. Removal of concrete by jackhammer and waterjetting at pressures in excess of 250MPa also yielded acceptable tensile failure results. In all cases the bond strength between the repair material and the concrete substrate was in excess of the tensile strength obtained.
CHAPTER 10
EXPERIMENTAL WORK:
APPLICATION OF REPAIR MATERIALS

10.1. Goal of the experiment
It is a fact that most of the concrete repairs done in South Africa are done by hand. It is a fairly cheap method of application and does not require the use of expensive equipment. Hand application has some clear-cut drawbacks, for example, poor compaction, feather edging and poor bonding to the concrete substrate. If applications are done by hand, how could the best results be obtained?

The following application methods were used:
- Vibrating table
- Hand and hammer
- Application in one layer moving from the inside outwards
- Application in one layer moving from the outside inwards
- Application in two layers moving from the inside outwards
- Application in two layers moving from the outside inwards

10.2. Experimental procedure
The concrete driveway blocks supplied by a local precast concrete manufacturer were used as the concrete substrate. The top 5-10mm of the concrete substrate was removed by using a jackhammer and sandblasting. The blocks were placed into the standard 750x150x150 steel moulds as described in chapter 9. All debris and dust were removed by high-pressure air. The surface of the concrete substrate was saturated for one hour, after which all the surface water was removed by high-pressure oil free air. The bonding coat, material B, was applied by brush to the concrete substrate and left for a period of ten minutes. Material A was mixed to the specifications of the manufacturer, after which the different application methods followed.

The following application methods were used:
- Mould placed on vibrating table and concrete repair material placed by hand, and vibrated thoroughly for two minutes.
- Application done by hand in one layer. A hammer and a small piece of wood were used to compact the repair material.

- Application of repair material by hand in one layer. All hand movements were in an outward direction, thus compacting the material in the direction of the mould.

- Application of repair material by hand in two layers. The first layer was about 35mm thick. After the initial set as described by the manufacturer, the second 35mm thick application was done by hand. All hand movements were in an outward direction towards the mould.

- Application of repair material by hand in one layer. All hand movements were in an inward direction, thus compacting the material to the centre of the mould.

- Application of repair material by hand in two layers. The first layer was about 35mm thick. After the initial set as described by the manufacturer, the second 35mm thick application was done by hand. All hand movements were in an inward direction towards the centre of the mould.

After the initial set, all the samples were finished by using a steel float. The sample was cured in a curing room for 28 days at a temperature of 24°C and at a relative humidity of 85%. After 28 days the bond strength of the different samples was determined by using the Dyne pull-off tester. The results are presented in Table 16.

### 10.3. Results obtained

**Table 16**  Pull-off test results obtained by using different application methods.

<table>
<thead>
<tr>
<th>Application by hand and hammer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pull-off test</strong></td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

**Application by hand in two layers moving outwards**

<table>
<thead>
<tr>
<th>Number</th>
<th>Tensile strength</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>No binding at all</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>Between two layers of repair material</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>Between two layers of repair material</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
<td>Between concrete and repair material</td>
</tr>
</tbody>
</table>

**Application by hand in two layers moving inwards**

<table>
<thead>
<tr>
<th>Number</th>
<th>Tensile strength</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>Between two layers of repair material</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>Between two layers of repair material</td>
</tr>
</tbody>
</table>
### Application by hand in one layer moving outwards

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>MPa</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>In repair material</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>In repair material</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>In repair material</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>In concrete</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>In concrete</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
<td>In concrete</td>
</tr>
</tbody>
</table>

### Application by hand in one layer moving inwards

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>MPa</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>In concrete</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>In concrete</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>In concrete</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>In concrete repair material</td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
<td>In concrete</td>
</tr>
</tbody>
</table>

#### 10.4. Discussion of results

All six samples of the application done by hand and compacted by wood and hammer have a failure plane in the concrete repair material. The cause of this can be the smooth surface formed by the small piece of wood. It is difficult for the newly placed repair material to bond properly to the smooth surface. This application method is not recommended, as the result is unsatisfactory. The bond strength between the concrete substrate and the repair material must be in excess of 0.5 MPa.

The plane of fracture for the samples compacted on the vibrating table was all in the concrete repair material itself. The mixing water moving to the surface of the samples because of over vibration can cause the weak plane in the repair material. A weak laitance layer is formed on the surface. This application method is not recommended. The bond strength between the concrete substrate and the repair material must be in excess of 1 MPa.
Of the six samples placed in two layers with hand movements in the outward direction:

- One sample had no bonding at all.
- Two samples had failure between the two layers of repair material
- Three samples had failure between the concrete substrate and the repair material

The failure between two layers of repair material is because of the lack of bond between the two layers. If the surface of the first layer of repair material is to smooth, proper bond will not take place. The three samples where failure was between the repair material and the concrete substrate gave an average bond strength of 0.4 MPa.

Of the six samples placed in two layers with hand movements in the inward direction:

- Two samples had failure between the two layers of repair material
- Four samples had failure between the concrete substrate and the repair material

The failure between two layers of repair material is because of the lack of bond between the two layers as discussed above. The four samples where failure was between the repair material and the concrete substrate gave an average bond strength of 0.7 MPa.

Of the six samples placed in one layer with hand movements in the outward direction:

- Three samples had failure in the repair material
- Three samples had failure in the concrete substrate

The average bond strength between the concrete substrate and the repair material must be in excess of 1 MPa.

Of the six samples placed in one layer with hand movements in the inward direction:

- One sample had failure in the repair material
- Four samples had failure in the concrete substrate
- One sample had failure between the concrete substrate and the repair material.
The average bond strength between the concrete substrate and the repair material must be in excess of 1.28 MPa.

10.5. Conclusion

Table 17 Estimated bond strengths for different application methods

<table>
<thead>
<tr>
<th>Application method</th>
<th>Estimated bond strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>By hand in two layers moving outwards</td>
<td>0.4</td>
</tr>
<tr>
<td>By hand and hammer</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td>By hand in two layers moving inwards</td>
<td>0.7</td>
</tr>
<tr>
<td>On vibrator table</td>
<td>&gt;1</td>
</tr>
<tr>
<td>By hand in one layer moving outwards</td>
<td>&gt;1</td>
</tr>
<tr>
<td>By hand in one layer moving inwards</td>
<td>&gt;1.28</td>
</tr>
</tbody>
</table>

If possible, applications should be done in one layer with all hand movements to the inside. Applications can also be done in one layer with hand movements to the outside. Applications in two layers should be avoided. If applications must be done in two layers, the bonding coat must be used or the surface must be grooved with a sharp object to increase the mechanical interlock. Smooth surfaces between two layers of concrete repair material must be avoided. The optimum layer thickness is dependent on the type of material used.
CHAPTER 11
EXPERIMENTAL WORK:
CURING

11.1. Goal of the experiment
In Europe, scaffolding covers the entire building under repair. Plastic sheeting then covers the scaffolding. Afterwards, sprinkler systems are put up for curing purposes. This means that repair work is done under almost ideal situations. Again, the cost of such an operation is immense. In South Africa, contractors usually cut down on these costs. This means that mostly curing agents, plastic sheets with no curing or plastic sheets with wetting at intervals of two days are used for curing. In general, curing is the most important neglected part of construction. In Switzerland, repair work is done only in the shade. The construction workers move with the sun during the day. The South African construction industry does not have the money or are ignorant to follow a good construction practice, but there must be an acceptable solution.

The following curing methods were investigated:

- No curing
- Repair covered for 28 days with plastic sheets
- Curing at 85% humidity for 1 day
- Curing at 85% humidity for 3 days
- Curing at 85% humidity for 7 days
- Curing at 85% humidity for 28 days

11.2. Experimental procedures
The concrete driveway blocks supplied by the precast manufacturer were used as the concrete substrate for the experiment. The top 5-10mm of the concrete blocks were removed by jackhammer and sandblasted. This is done to remove surface laitance and to assure that bonding will be to sound concrete. The blocks were placed in standard 750*100*100 steel moulds. All dust and debris were removed by high-pressure air. The surface of the concrete substrate was saturated for one hour with water, after which all the standing water was removed. Material B was applied to the surface by brush as a bonding bridge and left for ten minutes, as specified by the
manufacturer. Material A was mixed to the specifications of the manufacturer and placed on the vibrating table. By vibrating the moulds properly, the compaction and the bond will be achieved. After the initial set, the samples were finished by using a steel trowel. Some of the samples were left outside with no curing at all, and others were covered by plastic sheets for 28 days. The rest of the samples were placed in the curing room at a temperature of 24°C and a relative humidity of 85%. After twenty-four hours, some of the samples were removed and placed in a room with no further curing at all. The same was done after three and seven days. The rest of the samples were cured for 28 days in the curing room. The bond strengths were determined by using the Dyna pull-off tester. The plane of fracture was determined visually.

11.3. Results obtained

<table>
<thead>
<tr>
<th>Table 18</th>
<th>Pull-off test results obtained by using different curing techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No curing</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Number</strong></td>
<td><strong>Tensile strength</strong></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

| **Repairs covered by plastic for 28 days** | |
| **Number** | **Tensile strength** | **Plane of fracture** |
| 1 | 1.4 | In concrete |
| 2 | 0.8 | In concrete |
| 3 | 0.9 | In repair material |
| 4 | 0.8 | In concrete |
| 5 | 1 | In concrete |
| 6 | 1.1 | In concrete |

104
### Curing at 85% humidity for 28 days

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength (MPa)</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.1</td>
<td>In concrete</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>In concrete</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>Between concrete and repair material</td>
</tr>
</tbody>
</table>

### Curing at 85% humidity for 1 day

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength (MPa)</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>Between concrete and repair material</td>
</tr>
<tr>
<td>2</td>
<td>1.7</td>
<td>In concrete</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>In the repair material</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>In concrete</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>In the repair material</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>In the repair material</td>
</tr>
</tbody>
</table>

### Curing at 85% humidity for 3 days

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength (MPa)</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.3</td>
<td>In the repair material</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>In the repair material</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>In the repair material</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>In concrete</td>
</tr>
<tr>
<td>5</td>
<td>1.3</td>
<td>In concrete</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>In concrete</td>
</tr>
<tr>
<td>7</td>
<td>1.4</td>
<td>In concrete</td>
</tr>
</tbody>
</table>
Curing at 85% humidity for 7 days

<table>
<thead>
<tr>
<th>Pull-off test</th>
<th>Tensile strength</th>
<th>Plane of fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>MPa</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.3</td>
<td>In concrete</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>In the repair material</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>In concrete</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>In concrete</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>In the repair material</td>
</tr>
<tr>
<td>6</td>
<td>1.3</td>
<td>In concrete</td>
</tr>
</tbody>
</table>

11.4. Discussion of results

Of the six samples that received no curing at all:

- Three samples had failure in the concrete substrate
- Three samples had failure between the concrete substrate and the repair material

The three samples where failure took place between the concrete substrate and the concrete repair material gave an average bond strength of 0.87 MPa. For the three samples where failure took place in the concrete substrate the bond strength must be in excess of 0.7 MPa.

Of the six samples that was covered with plastic sheets for 28 days:

- Five samples had failure in the concrete substrate
- One sample had failure in the repair material

The bond strength between the concrete substrate and the repair material must be in excess of 1 MPa.

Of the six samples that was cured at 85% relative humidity for 28 days:

- Two samples had failure in the concrete substrate
- Four samples had failure between the concrete substrate and the repair material
The bond strength between the concrete substrate and the repair material is 0.8MPa.

Of the six samples that received curing at 85% relative humidity for one day:
- Two samples had failure in the concrete substrate
- One sample had failure between the concrete substrate and the repair material
- Three samples had failure in the repair material

The bond strength between the concrete substrate and the repair material must be in excess of 1.17MPa.

Of the seven samples that received curing at 85% relative humidity for three days:
- Four samples had failure in the concrete substrate
- Three samples had failure in the repair material

The bond strength between the concrete substrate and the repair material must be in excess of 1.21MPa.

Of the six samples that received curing at 85% relative humidity for seven days:
- Four samples had failure in the concrete substrate
- Two samples had failure in the repair material

The bond strength between the concrete substrate and the repair material must be in excess of 1.25MPa.

Of the 37 pull-off tests, 54% of the cores broke in the concrete substrate and 24% in the repair material itself. The fact that the cores failed in the repair material means that the concrete substrate and bonding bridge are of sufficient strength. Of all the cores, 22% broke on the plane between the concrete substrate and the repair material. This could be due to the failure of the bonding bridge to create a bond of sufficient strength between the old and the new concrete.
The fact that the samples cured at 85% relative humidity for 28 days yielded such low results can be ascribed to the following:

- Four of the six samples of the plane of fracture were between the concrete substrate and the concrete repair material. This indicates that the bond between the old substrate and the new material was insufficient.
- There may be some deficiencies in the application of the repair material.
- After pre-wetting, was all the standing water removed?
- Was the repair material mixed in the right proportions?

The fact is that a problem occurred somewhere that caused the low results. These low results for curing at 85% relative humidity for 28 days cannot be used to make any assumptions.

11.5. Conclusion

Table 19  Estimated bond strengths obtained by using different curing methods.

<table>
<thead>
<tr>
<th>Curing method</th>
<th>Estimated bond strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>No curing</td>
<td>0.87</td>
</tr>
<tr>
<td>Plastic sheets</td>
<td>&gt;1.00</td>
</tr>
<tr>
<td>1 day at 85% RH</td>
<td>&gt;1.17</td>
</tr>
<tr>
<td>3 days at 85% RH</td>
<td>&gt;1.21</td>
</tr>
<tr>
<td>7 days at 85% RH</td>
<td>&gt;1.25</td>
</tr>
</tbody>
</table>

What is clear from the results is that curing for seven days at a relative humidity of 85% yielded the best estimated bond strength results. It is interesting to note that the difference between one day and three days of curing at a relative humidity of 85% in estimated bond strength is only 0.04N/mm². This difference is so small that it is almost negligible. It seems that proper curing for one day will also yield acceptable bond strength results.
CHAPTER 12
IN SITU TESTING OF CONCRETE REPAIR MATERIALS

12.1. Goal of the in situ testing
There are current problems with the concrete structure at RAU. The structure was built in the early 1970s, almost 30 years ago. Portions of the concrete facades are spalling due to improper construction methods. The cover to steel was specified as per SABS 0100-2:1992 for various exposure conditions. In practice, this specification was not followed. The result was that the average cover of the reinforcement to the surface was very low in the concrete facades. The reinforcement began to corrode, because of inadequate cover. The corrosion caused spalling. The spalling was aesthetically unacceptable and accelerated the deterioration process of the structure.

Some companies were given the responsibility of doing the repairs on certain parts of the building. The repairs done did not perform very well. In general, problems were experienced with unacceptable cracking and delamination of the concrete repair patches from the concrete substrate. Because of the nature of the problem, RAU implemented an in-house repair programme. Currently the search for a suitable repair material and repair system is on. As a pilot project, with the main purpose of training and finding a suitable repair system, a section on the RAU building was selected for repair. The section is outside the foyer at the auditorium near the steps leading to the inner court.

As part of the search for an acceptable repair system, a project was undertaken under the supervision of Mr Heinz Banziger of Sika AG, Switzerland. He visited South Africa with the sole purpose of evaluating his company’s different repair systems at the RAU and identifying the best repair system for the in situ conditions experienced at the RAU. Mr Banziger brought a new product from Switzerland for this project, which will be called material C. He was interested in the performance of the new product under South African conditions.
12.2. The section under repair

The section chosen for repair was badly deteriorated and required urgent maintenance. The section faces east and was divided into seven sections. Different repair systems were used on each section. The sections are referred to as sections A to G.

Figure 35  The section under repair.

Spalling of the surface concrete was the biggest problem. The reinforcement expands and the increase in volume causes the spalling of the surface concrete. A typical example of the corroded reinforcement can be seen in figures 36 and 37. The corrosion is a direct symptom of the process of carbonation. Because of the inadequate cover to the reinforcement the carbonation front passed the reinforcement and the process of corrosion began.

The thermal movement and stresses developed in the structure caused some of the cracks in the section. Because the section faces east, the sun bakes the outside of the surface in the morning and early afternoon. The inside surface of the section is cool because it faces the inside of the building and is therefore never exposed to direct sunlight. A temperature gradient exists between the outside and the inside surface. As soon as the stresses caused by the temperature gradient are greater than the internal stresses of the concrete, cracks start to form. The situation is further aggravated by
the late afternoon thundershowers experienced in Johannesburg in the summer. The rainwater cools the outside surface of the concrete section and increases the temperature gradient.

Figure 36  The spalling of surface concrete.

Figure 37  Corroded reinforcement.
12.3. Preparation of the section

The proposed sections for repair were marked by using chalk. The marked sections were kept as small as possible and only the concrete in the vicinity of cracks was removed. The shape of the sections was kept rectangular to keep the edge distance as small as possible. The edges of the sections were cut about 10mm deep with an angle grinder to prevent the formation of featheredging. All damaged concrete was removed by small hand-held jackhammers.

Figure 38  Cutting of edge with grinder.

Figure 39  Removal of damaged concrete by hand-held jackhammers.
Steelbrushes were used to clean the reinforcement to a bright steel colour. All the dust and debris were removed by high-pressure waterjet. Plastic sheets to protect the surface from wind and direct sunlight covered the entire concrete section. A sprinkler system was installed to pre-wet the surface for 24 hours prior to the application of the concrete repair system.

Figure 40 Sprinkler system.

Figure 41 Sections covered by plastic sheets.

Figure 42 Sprinklers on and sections protected by plastic sheets.
Figure 43  Section A after surface preparation.

Figure 44  Section B after surface preparation.

Figure 45  Section C (left) and D (right) after surface preparation.
Figure 46  Section E after surface preparation.

Figure 47  Section F after surface preparation.
12.4. Repair materials used

Table 20 Repair materials used.

<table>
<thead>
<tr>
<th>System/Section</th>
<th>Bonding bridge</th>
<th>Repair material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/A</td>
<td>Material B</td>
<td>Material A</td>
</tr>
<tr>
<td>2/B</td>
<td>Material B</td>
<td>Material C</td>
</tr>
<tr>
<td>3/C</td>
<td>Material B</td>
<td>Material A</td>
</tr>
<tr>
<td>4/D</td>
<td>Material B</td>
<td>Material C</td>
</tr>
<tr>
<td>5/E</td>
<td>Material B</td>
<td>Material A</td>
</tr>
<tr>
<td>6/F</td>
<td>No bonding bridge</td>
<td>Material C</td>
</tr>
<tr>
<td>7/G</td>
<td>No bonding bridge</td>
<td>Material C</td>
</tr>
</tbody>
</table>

12.5. Application of repair materials

The bonding bridge was applied by brush to the reinforcement and the concrete surface. The repair materials were applied by hand and finished by using a steel trowel.

**System 1/Section A**
- Material B as bonding bridge
- Material A as repair material
- Surface finished direct after application by steel trowel

![Figure 48](image-url)  
Section A after the application of system 1.
**System 2/Section B:**
- Material B as bonding bridge
- Material C as repair material
- Surface finished by steel trowel directly after application

![Figure 49](image)

**Section B after the application of system 2.**

**System 3/Section C**
- Material B as bonding bridge.
- Material A as repair material. The section is filled, but the last 5mm are left for application the next day.
- The last 5mm are filled and finished by steel trowel on day 2.

![Figure 50](image)

**Figure 50**  Repair material applied on section C and last 5mm left for application the next day.
System 4/ section D

- Material B as bonding bridge.
- Material C as repair material. The section is filled, but the last 5mm are left for application the next day.
- The last 5mm are filled and finished by steel trowel on day 2.
Figure 53  Application of material C to section D, and last 5mm left for application the next day.

System 5/Section E
- Material B as bonding bridge
- Material A in a layer of 3cm
- Material A in a layer of 2.5cm on day two
- Finish last 5mm of repair on day three by steel trowel

Figure 54  Application of bonding coat to section E by brush.
Figure 55  Section E after the application of the first 30mm thick layer of material A.

Figure 56  Application of 2.5cm layer of material A on the second day to section E.
System 6/Section F

- No bonding bridge
- Material C as repair material
- Surface finished by steel trowel after application

Figure 57  Section F after the application of system 6.

System 7/Section G

- No bonding bridge
- Material C as repair material
- Surface finished by steel trowel after application

12.6. Curing

Plastic sheets covered sections A to F. Sections A-F were cured by wetting the surfaces at regular intervals of no more than one hour. Section G had no curing at all and was not even covered with plastic sheets.

12.7. Experimental procedure

All the sections were evaluated after 28 days in the following manner:

- Visually for cracks
- Sounding with hammer to pick up delaminations
12.8. Results obtained

Table 21 Results obtained through visual inspection and sounding after 28 days.

<table>
<thead>
<tr>
<th>System/section</th>
<th>Visual inspection</th>
<th>Sounding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/A</td>
<td>Section cracked</td>
<td>No hollow sound</td>
</tr>
<tr>
<td>2/B</td>
<td>No cracks</td>
<td>No hollow sound</td>
</tr>
<tr>
<td>3/C</td>
<td>Section cracked</td>
<td>Hollow sound</td>
</tr>
<tr>
<td>4/D</td>
<td>No cracks</td>
<td>No hollow sound</td>
</tr>
<tr>
<td>5/E</td>
<td>Very fine cracks</td>
<td>Hollow sound</td>
</tr>
<tr>
<td>6/F</td>
<td>No cracks</td>
<td>No hollow sounds</td>
</tr>
<tr>
<td>7/G</td>
<td>Cracks along edges of repair</td>
<td>Hollow sound</td>
</tr>
</tbody>
</table>

12.9. Discussion of results

Table 22 The suitability of different repair systems for the RAU

<table>
<thead>
<tr>
<th>System/section</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/A</td>
<td>Not suitable for RAU (Section cracked)</td>
</tr>
<tr>
<td>2/B</td>
<td>Suitable for RAU</td>
</tr>
<tr>
<td>3/C</td>
<td>Not suitable, the thin layer dries out too quickly under South African conditions</td>
</tr>
<tr>
<td>4/D</td>
<td>Not suitable, the thin layer dries out too quickly under South African conditions</td>
</tr>
<tr>
<td>5/E</td>
<td>Not suitable for RAU</td>
</tr>
<tr>
<td>6/F</td>
<td>Suitable, but the use of a bonding bridge should be considered</td>
</tr>
<tr>
<td>7/G</td>
<td>Not suitable for RAU, but with proper curing, the system will work</td>
</tr>
</tbody>
</table>

Material C preformed very well under the conditions and could be used as a suitable concrete repair material for RAU. Material C should be used with material B as a bonding bridge. The only problem with material C is the high cost of the product. Material A is too crack sensitive to guarantee long-term success and the durability of the repairs.
### Conclusion

The following repair system is recommended for RAU:

#### Table 23  Repair system recommended for RAU\(^{29}\).

<table>
<thead>
<tr>
<th>Material</th>
<th>Purpose</th>
<th>Application</th>
<th>Curing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material B</td>
<td>Bonding bridge</td>
<td>• By brush</td>
<td>- Curing must start as soon as possible and continued for at least two days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Apply as much as can be covered by repair mortar in 20 minutes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Apply wet to wet</td>
<td></td>
</tr>
<tr>
<td>Material C</td>
<td>Repair mortar</td>
<td>• Apply by hand</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Maximum layer thickness 3-4cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• If layer thickness is more than 4cm, apply in two or more layers</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Finish repair from centre to the edges</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water to powder ratio as small as possible</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 13
QUESTIONNAIRE

13.1. Goal of the questionnaire

The preceding chapters identified seven factors that influence the success of a concrete repair project, namely:

- The diagnostic process
- The removal of damaged concrete
- The cleaning of reinforcements
- The protection of the reinforcements
- The repair material
- Application methods
- Curing
- Workmanship

A survey was conducted to determine the relevance of the above-mentioned factors among stakeholders in South Africa. The aim of the survey is threefold. The first aim is to determine which of the above-mentioned factors are important to the success of concrete repair projects as identified by the role-players and the decision-makers in the construction industry. During the literature study, the removal of damaged concrete, application methods, and curing were identified as the three main causes of concrete repair failure. The second aim of the questionnaire involves the gathering of relevant information about the respondents' viewpoints on how these three factors influence the success of concrete repair projects. The third aim of the questionnaire is to determine the attitude of the respondents to the training of their staff.

The first part of the chapter explains the methodology and provides a profile of the respondents. The second part of the chapter consists of an analysis of the response to each of the questions completed in the questionnaire.
13.2. Methodology
The relevant data used to fulfil the above-mentioned aims was collected by means of questionnaires. Questionnaires were used because of the effectiveness and ease with which the data could be collected. It is important to note that questionnaires provide only a quantitative perspective, but for this study, the quantitative perspective is judged to be sufficient. The questionnaire was constructed in such a way to ensure that it could be completed easily and quickly.

Over a period of about six months, questionnaires were distributed to role-players and decision-makers in the concrete repair industry in the following manner:

- By fax
- By e-mail
- Handed out at the International Workshop on Concrete Repair and the Fourth South African Conference on Polymers in Concrete held in the Kruger National Park from 20 to 23 June 2000
- Handed out at a Seminar on Concrete Repair held at the CCI in Midrand on 18 April 2001

A total of 300 questionnaires were distributed, 50 of which were returned and deemed acceptable for inclusion in the study. A response rate of 16% was thus achieved.

13.3. Profile of the respondents
The respondents consisted of role-players and decision-makers from the construction, consulting, manufacturing and academic sections of the repair industry in South Africa. The reason for using only South African respondents is clear from the title of this thesis. Some of the academic respondents indicated that they did mainly consulting work. For this reason, it was decided to add the academic respondents to the consulting respondents. The profile of the respondents as determined by Question 1 is displayed in figure 58. Eighteen (36%) of the respondents were from the construction industry, whereas twenty-three (46%) of the respondents were from the consulting industry. Only nine (18%) of the respondents completing the questionnaire were from the manufacturing industry.
13.4. The success of concrete repair projects

The purpose of question 2 was to obtain the respondents' perception of the success rate of concrete repair projects in South Africa. From figure 59, it is clear that 61% of the respondents were of the opinion that 75% to 100% of repair projects undertaken were successful.

13.5. The influence of different factors on concrete repair systems

Different factors affecting the success of concrete repair systems were identified during the literature study. The respondents were asked to indicate three of the main causes of concrete repair failure. The obtained results can be seen in Table 24. The causes are arranged from most to less important as indicated by the respondents.
Table 24  The main causes of concrete repair failure.

<table>
<thead>
<tr>
<th>The cause</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workmanship in general</td>
<td>37</td>
<td>74</td>
</tr>
<tr>
<td>Application methods</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>Inadequate curing</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>The diagnostic process</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>The removal of damaged concrete</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Repair material failure</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>The cleaning of reinforcements</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>The protection of reinforcements</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Source: Question 3

The main cause of concrete repair failure as indicated by the respondents was workmanship. Application methods, inadequate curing and the diagnostic process followed workmanship as the most important causes of concrete repair failure.

The respondents noted the following causes under “other”:
- Not using specialist contractors and suppliers
- Budget constraints
- Ignorance of latest developments
- Inadequate manufacturer specifications
- Poor understanding of materials and the effect of ambient conditions on concrete

The respondents were requested in question 4 to rate the importance of the concrete repair steps for the success of a concrete repair project on a five-point scale where:

1 = Very important
2 = Relatively important
3 = Unsure
4 = Relatively unimportant
5 = Unimportant
Table 25  The importance of different concrete repair steps as rated on a five-point scale.

<table>
<thead>
<tr>
<th>Statement</th>
<th>1 (%)</th>
<th>2 (%)</th>
<th>3 (%)</th>
<th>4 (%)</th>
<th>5 (%)</th>
<th>Average rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal of damaged concrete</td>
<td>76</td>
<td>18</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2.8</td>
</tr>
<tr>
<td>Application of repair material</td>
<td>78</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>2.84</td>
</tr>
<tr>
<td>Diagnosis of current concrete substrate</td>
<td>72</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2.92</td>
</tr>
<tr>
<td>Selection of a suitable concrete repair material</td>
<td>68</td>
<td>22</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Curing</td>
<td>66</td>
<td>20</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>3.2</td>
</tr>
<tr>
<td>Cleaning of reinforcements</td>
<td>44</td>
<td>44</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>3.64</td>
</tr>
<tr>
<td>Protection of reinforcements</td>
<td>36</td>
<td>46</td>
<td>12</td>
<td>4</td>
<td>2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Source: Question 4

From table 25, it is clear that more than two thirds of the respondents felt that the following steps were very important by marking scale 1:

- Application of repair materials (78%)
- Removal of damaged concrete (76%)
- Diagnosis of the current concrete substrate (72%)
- Selection of a suitable concrete repair material (68%)
- Curing (66%)

The fact that the average rating ranges from 2.8 to 3.8 indicates that all seven steps were seen as important to the success of a concrete repair project, although the effect of cleaning and protecting the reinforcement was seen as less important to the success of concrete repair projects.

13.6. The removal of damaged concrete

In the previous section the removal of damaged concrete was identified as one of the crucial steps that could cause the failure of concrete repair projects. The purpose of questions 5 to 9 was to get an indication of how concrete is generally removed in South Africa.
From Figure 60 it is clear that mechanical methods such as jackhammer (72%) and hammer and chisel (56%) were used the most in South Africa followed by hydro-jetting (30%) and scablers (30%). Because of the formation of micro-cracks in the concrete substrate, it is important to use sandblasting or hydro-jetting to remove the top 3-5mm of concrete. This fact necessitated the question: Are combinations of the above-mentioned removal techniques used? Fifty percent (source: Question 6) of the respondents indicated that combinations were used in general. Of the fifty percent of the respondents who responded positively to question six, fifty-two percent indicated that they used a mechanical method in combination with sandblasting. The remaining 48% used hydro-jetting.
Figure 62  Methods used to clean the reinforcement.

From Figure 62, it is clear that the reinforcement was cleaned by means of sandblasting (74%) in the majority of circumstances, followed by hydro-jetting (26%). The following methods were noted by the respondents as "Other methods":

- Sandpaper
- Steelbrush
- Scablers
- Wires
- Abrasive tape
- Needle gun
- Angle grinders

It is also important to determine the respondents’ perception of an adequate depth of removal. The response can be seen in Figure 63. It is important to note that only 60% of the respondents answered this question.
From Figure 63, it is clear that the adequate depth of removal seems to be between 51-100mm (63%). The respondents made the following comments:

- Depth of removal must be 20mm behind the reinforcement
- Depth of removal depends on the type and depth of damage
- All damaged concrete must be removed

From the comments it is clear that the circumstances of a particular project determine the depth of removal.

Sixty percent of the respondents indicated that the entire cracked area must be removed whereas forty percent indicated that only the damaged concrete in the vicinity of the cracks must be removed (See Figure 64). Only 70% of the respondents
answered this question. Again, it becomes clear that the particular circumstances of a repair project determine the magnitude of concrete removal.

13.7. The application of repair materials

The goal of questions 10 to 19 was to get an indication of how the application of concrete repair materials is generally done in South Africa. The first important question to address is the issue of whether the substrate should be pre-wet or not?

![Figure 65: Do you pre-wet the concrete substrate?](source)

From Figure 65, it is clear that the majority (87%) of the respondents were of the opinion that the pre-wetting of the concrete substrate was necessary. The second important question is for what duration the substrate should be pre-wet? The respondents' answer to this question can be seen in Figure 66. It is clear that the respondents did not have a particular preference when it came to the duration of pre-wetting.
Figure 66  Period of pre-wetting.

Figure 67  Are pre-wet surfaces allowed to dry partially before application?

From figure 67, it is clear that more than 40% of the respondents mainly allowed for the substrates to dry out partially before beginning the application of the repair materials. Of all the respondents, 27% always allowed the substrate to dry out. Thirty % of the respondents never or seldom allowed the concrete substrate to dry out.
Figure 68  Are applications of repair materials done in the shade?

Only 9% of repairs were always done in the shade, whereas 50% were mainly done in the shade. Forty-one percent of the respondents never or seldom did repairs in the shade. This means that almost half of the repairs done in South Africa are done in direct sunlight, which increases the rate of evaporation and the drying of the concrete repair materials. The results can be seen in Figure 68.

Figure 69  How are repair materials applied in general?

From figure 69 it is clear that the majority (74%) of concrete repair applications in South Africa are done by hand.
Eighty percent of concrete repair applications are done in layers in South Africa. The respondents gave the following comments:

- Depends on the materials used
- Depends on the thickness of the repair
- If depth of repair exceeds 30mm, the repair is done in layers

The next important question to ask is that if applications are done in layers, how many layers are used in general? Eighty percent of the respondents indicated that they used more than one layer whereas 20% used two layers (Source: Question 16). An important comment made by some of the respondents was that the depth of repair and repair material used determine the amount of layers used.
Forty-seven percent of the respondents used a layer thicknesses of between 31mm and 50mm. A layer thicknesses of less than 30mm was used by 35% of the respondents. A layer thicknesses of more than 51mm was used by only 18% of the respondents. Again the respondents stated that the type of material used to do the repair determined the actual layer thickness.

![Bar chart](image)

Source: Question 18

**Figure 72** Is the floating of the final surface by using water as a wetting agent allowed?

From figure 72, it is clear that 48% of the respondents never float the final concrete surface by using water. Thirty-five percent of the respondents' seldom float the final concrete surface. It is clear that the finishing of concrete repair surfaces by floating is not a general practice in the South African industry.

![Pie chart](image)

Source: Question 19

**Figure 73** Does your company have any fixed specifications regarding the placement of concrete repair materials?
Fifty-nine percent of the respondents' employers had standard specifications for the placement of concrete repair materials. But forty-one percent of the employers had no specifications in place.

13.8. Curing
The purpose of questions 20 to 24 was to get a better idea of how the vital step of curing was performed in the context of the South African construction industry.

Of all the respondents, 52% indicated that they always protected concrete repair sections from wind and sunlight. This is followed by 36% of the respondents who mainly protected the repair sections. In general, it seems that concrete repair sections are well protected.

The purpose of the next question was to get an indication of what types of protection were used. The results are shown in table 26. Plastic sheets (47%) are the most popular protection method, followed by curing compounds (41%). It is debatable whether curing compounds and mist spray could be seen as proper protection of concrete repair sections against wind and sunlight. Hessian (31%) is also a common protection product used by the industry.
Table 26  What protection is used against wind and sunlight?

<table>
<thead>
<tr>
<th>Protection type</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic sheets</td>
<td>47</td>
</tr>
<tr>
<td>Curing compounds</td>
<td>41</td>
</tr>
<tr>
<td>Hessian</td>
<td>31</td>
</tr>
<tr>
<td>Mist spray</td>
<td>19</td>
</tr>
<tr>
<td>Windscreens</td>
<td>16</td>
</tr>
<tr>
<td>Shade cloth</td>
<td>9</td>
</tr>
<tr>
<td>Shutter boards</td>
<td>3</td>
</tr>
</tbody>
</table>

Source: Question 21

Table 27  Curing methods used.

<table>
<thead>
<tr>
<th>Method</th>
<th>Always</th>
<th>Mainly</th>
<th>Seldom</th>
<th>Never</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Curing compounds</td>
<td>17</td>
<td>48</td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td>Plastic sheets</td>
<td>9</td>
<td>46</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>Water</td>
<td>7</td>
<td>43</td>
<td>43</td>
<td>7</td>
</tr>
</tbody>
</table>

From table 27, it is clear that curing compounds were the most commonly used curing method in South Africa, followed by plastic sheets and water. The respondents also had the opportunity to indicate what other methods were used in general. The following methods were mentioned:

- Wet hessian
- Cover repair by a layer of sand
- Leave shutters in place
Figure 75  How is water applied to the surface of a concrete repair?

It is clear from figure 75 that the majority of water curing is applied by sprinkler systems (46%) to the surface of concrete repairs. It is also apparent that a hosepipe is used in 32% of the instances where water is used as a curing agent. The duration of water curing plays an important role in the attainment of acceptable strengths of the concrete repair material.

Figure 76  Duration of application of water if used as a curing agent.

Forty-three percent of the respondents indicated that they generally undertook curing for seven days. It is necessary to note that literature states that seven days is the preferable duration of curing. Twenty-eight percent of the respondents preferred to do
curing for three days, followed by twenty-four percent of the respondents who only undertook curing for between one and twenty-four hours.

13.9. Training and skill levels

The purpose of questions 25 to 28 was to get an idea of the skill level of the applicators of repair materials. It is important for the applicators to have the necessary skills because they are working with high technologically advanced materials. It was also important to get an indication that if the applicators were trained and what training was available.

From figure 77 it is clear that 40% of the applicators have primary education and 38% have secondary education. It is interesting to note that 18% of the applicators have no education at all. Only 4% of the applicators received any training at tertiary education level.
Only 53% of the respondents sent their workers for training before the workers started doing concrete repair projects. The following training institutions were mentioned by the respondents:

- ASCC certification
- City & Guildes
- In-house training
- Construction skills certification scheme (UK)
- The product supplier

Work was done under the supervision of a superior 86% of the time.
Fifty percent of the superiors doing supervision over the applicators had secondary education, followed by forty percent having tertiary education.

13.10. Conclusions

Although the response rate was only 16%, the questionnaire definitely achieved its goal, which was to obtain information about the South African concrete repair industry. It is not possible simply to superimpose overseas working ethics onto South African conditions. The circumstances under which concrete repair is done in South Africa differ too much from those experienced overseas. After the analysis of the questionnaire, a clear picture was formed about the South African repair industry.

The majority of the respondents were from the consulting industry. The response rate of the construction industry was also acceptable, but the response of the manufacturing industry was dismal. It is also clear that the majority of the respondents thought that a high success rate exists for repair projects in South Africa. In fact, 61% of the respondents thought that 75% or more of repair projects undertaken were a success.

The following three factors were identified as the main causes of concrete repair failure:

- Workmanship in general
- Application methods
Inadequate curing

All seven concrete repair steps are seen as crucial to the success of concrete repair.

The following three steps were rated as the most important:

- Removal of damaged concrete
- Application methods
- Inadequate curing

It is important to note that all the factors mentioned basically tie back to workmanship. Workmanship is one of the biggest problems in the South African concrete repair industry.

Mechanical methods are used to do the majority of the removal of damaged concrete. Seventy-two percent of removal is done with a jackhammer and fifty-six percent with a hammer and chisel. The problem with mechanical methods is the formation of micro-cracks in the first two to five millimetres of the concrete substrate. It is alarming to note that only 50% of the respondents used hydro-jetting or sandblasting to remove the first few millimetres. Of the 50% who do remove the first few millimetres almost half used hydro-jetting and the other half used sandblasting. Sandblasting (74%) was in most instances used to clean the reinforcement.

The following factors play an important role in the depth and magnitude of concrete removal:

- Type of damage
- Depth of damage
- Budgetary constraints
- Availability of technology

Most of the applicators of concrete repair materials pre-wet (87%) the concrete substrate before they begin to do the actual repair. A great deal of discussion and difference in opinion about the duration of pre-wetting exists in South Africa.
Twenty-five percent of the respondents indicated that they pre-wet for a period of one to two hours. Thirty percent pre-wet for a duration of between three and twelve hours, whereas twenty-eight percent pre-wet for a duration of between thirteen and twenty-four hours. Most of the concrete repair sections are left to dry out partially, although thirty percent of the respondents seldom or never allow the partial drying of the concrete substrate. Almost 60% of concrete repairs are done mainly or always in the shade.

Concrete repair materials are applied by hand (74%) in most instances in South Africa. The application is mostly done in two layers with a thickness of between thirty-one and fifty millimetres.

It is important to note that the thickness of a layer is determined by the following factors:
- The material used
- The overall thickness of the repair

In general, water is not used as a wetting agent to float the final surface of the concrete repair. Almost sixty percent of companies have set specifications for concrete repair.

Eighty-eight percent of the time, concrete repair projects are protected from sunlight or wind. Plastic sheets, curing compounds and wet hessian are the most common materials used to protect concrete repair sections. Curing compounds followed by plastic sheets and water are the most popular curing methods used. Sprinkler systems are used 48% of the time, followed by the more common hosepipe as an application method of water as a curing compound. Most of the respondents preferred to do curing for a period of at least seven days (43%). Twenty-eight percent of the respondents indicated that at least three days of curing was enough followed by twenty-four percent who thought that between one and twenty-four hours was enough.
In general, the applicators who do concrete repairs have a Primary education (40%) or even secondary education (38%). What needs further attention is the fact that 18% of the people who do applications have no education at all. Totally unskilled people do one fifth of all applications. Only half of the applicators are sent on training programmes. This percentage needs to be higher to guarantee that the standard of workmanship is better in the future. A factor that plays an important role in the quality of workmanship is supervision. Eighty-six percent of repair work is done under the supervision of a superior. Workmanship is still seen as one of the major problem areas in the South African concrete repair industry. Could the problem be that supervision is not done for the duration of the concrete repair project? The education level of the supervisors is sufficient (Secondary education - 50%, Tertiary education - 40%). Another problem could be that information is not readily available and conveyed to the man who is actually doing the concrete repair.

It is apparent from the questionnaire that the South African repair industry is on the right path. New knowledge is slowly starting to be used in the practical field. Although the industry has problems with some failures of concrete repairs, the majority of projects can be seen as successful. A few general misconceptions need to be addressed in the next few years, and then South Africa could truly regard themselves as experts in the concrete repair field.
CHAPTER 14
CONCLUSIONS

14.1. Introduction
From previous research and personal experience, it became clear that many inadequacies exist in the current concrete repair system used by the repair industry. However, it must be noted that according to the questionnaire, the majority of repair projects undertaken are successful in South Africa. In the unsuccessful projects, the inadequacies are easy to correct because basic mistakes are made due to the lack of knowledge or proper training.

The basic repair steps could be summarized as follows:
1. Diagnosis of the current substrate
2. Removal of the damaged concrete
3. Cleaning of the reinforcement
4. Application of the reinforcement
5. Curing and protection of the repaired section
6. Quality and durability checks over the lifetime of the repaired section

The following five factors were identified as the main contributors to the failure of concrete repair projects:
• Workmanship in general
• Application methods
• Inadequate curing
• The diagnostic process
• The removal of damaged concrete

A factor that plays a very important role in South Africa is the client. In many situations, the client is his own biggest enemy. The client wants the best solution at the lowest price. In practice, the cheap solution will result in low durability and a short life span. The old saying of "Penny wise, pound foolish" is very true of the South African repair industry. The obsession of clients to fast track projects simply further increases the possibility of poor workmanship and the loss of durability and the effectiveness of concrete repair solutions.
The following three steps were investigated:

- Removal of damaged concrete
- Application of repair materials
- Curing

14.2. The causes and symptoms of concrete deterioration

It is very important to know the symptoms and causes of concrete deterioration. The difference between the cause and symptom of concrete deterioration must be clearly understood. It will not help to treat the symptom alone. The cause of concrete deterioration must be eliminated, otherwise the problem will simply recur. Without this knowledge, it is impossible to undertake an adequate diagnosis of a structure. To make an applicable and correct recommendation to a client, it is necessary to understand the entire repair process and all the factors that could lead to the success and failure of a repair.

The following are symptoms of concrete deterioration:

- Cracks
- Concrete wear
- Discoloration
- Pop-outs
- Cavitation
- Efflorescence
- Spalling
- Seepage
- Distortion
- Delamination

The following are causes of concrete deterioration:

- Bleeding
- Corrosion
- Honeycombing
- Cold joints
- Segregation
- Aggressive chemical exposure
- Temperature gradients
• Faulty workmanship
• Shrinkage

14.3. The concrete repair process
The concrete repair process could be summarised as follows:
1. Evaluate the existing concrete structure
2. What is the effect?
3. What caused the effect?
4. Is repair required?
5. If the answer is “No”, evaluate the structure again in a few years
6. If the answer is “Yes”, do a condition survey
7. Do a repair analysis
8. Prepare the repair strategy
9. Do the actual repair

14.4. The removal of damaged concrete
Surface preparation is the process of conditioning the existing concrete to receive concrete repair materials. To ensure a good bond between the concrete and the repair material, all the damaged concrete must be removed. Only sound good-quality concrete should be left after the removal of the damaged concrete. The concrete patch layout must be made as simple as possible. The aim is to keep the boundary edge length to a minimum. The choice between the removal of all damaged concrete and simply removing the concrete that affects the serviceability of the structure must be made. Budget constraints will determine the magnitude of the removal in most instances. The concrete should be removed to a depth of around 10mm behind the reinforcement.

The different removal techniques that could be used are:
• Blasting
• Shotblasting
• Sandblasting
• Acid etching
• Cutting
• Impacting
• Milling
• Presplitting
• Abrading

Mechanical methods such as jackhammers (72%) and the hammer and chisel (56%) are used the most in South Africa. The problem with the use of mechanical methods is the formation of micro-cracks in the first few millimetres of the concrete substrate being prepared. Mechanical methods must never be used on their own, as the required tensile strength of 1.5N/mm² will never be reached. The first few millimetres must be removed by either hydro-jetting or sandblasting. The removal of damaged concrete done with a combination of mechanical methods and sandblasting or hydro-jetting accounts for only 50% of the repair projects undertaken. The reinforcement must be cleaned properly with either sandblasting or hydro-jetting. The majority of the reinforcement (74%) is cleaned by sandblasting. If the reinforcement is not properly cleaned, the bond between the reinforcement and the repair material will be weak.

The proper removal of damaged or contaminated concrete is essential for the long-term success of a concrete repair project.

14.5. Application of concrete repair materials

The bond between the concrete repair material and concrete substrate must be of sufficient strength to transfer the stresses developed. For a proper bond, the concrete substrate must be clean, the profile must be rough, an open pore structure is needed and the repair material must be applied with enough pressure.

The placement technique must deliver the repair material to the concrete substrate. An adequate force must be applied to the repair material to ensure intimate contact with the concrete substrate.

The following placement methods could be used:
  • Dry pack
  • Form and cast-in-place
  • Grouted pre-placed aggregate
  • Full-depth repair
  • Form and pump
  • Shotcrete (dry)
  • Shotcrete (wet)
• Hand-applied

Most of the applications done in South Africa are done by hand (74%). Applications by hand could cause bonding and compaction problems, especially in the vicinity of the reinforcement. From the experimental results obtained, it is clear that adequate tensile results could be obtained if the applications were done by hand in one layer and all the movements must be in the inward direction. Applications done in one layer will yield better results than applications done in two layers. If applications are done in two layers, a bonding coat must be used and the surface of the first layer roughened to ensure a good mechanical interlock. Although hand applications are not the most reliable application technique, with proper attention and workmanship good results could be obtained. Surfaces must be pre-wet before the application and, if possible, the application must be done in the shade. All this will stop the rapid evaporation of moisture from the concrete repair.

14.6. Curing

The purpose of curing is to prevent the loss of moisture from concrete. The moisture is needed to keep the hydration process going. The evaporation of moisture is affected by the relative humidity of the atmosphere, the temperature and the wind velocity. The worst case of evaporation is when the relative humidity is low and the temperature and wind velocity is high. It is important to note that only the first 30-50mm of cover concrete is really affected by curing.

The properties that are affected by curing are:
• Permeability
• Resistance to carbonation
• Resistance to weathering
• Resistance to corrosion
• Resistance to abrasion

Two methods of curing could be used: wet curing or membrane curing. For wet curing the concrete surface should be kept moist for a specified period. Membranes prevent the loss of water from the concrete surface. Curing compounds are very sensitive to the time of application and must be used with care. Literature generally recommends a curing period of no less than seven days.
Curing compounds and plastic sheets are the most used curing techniques in South Africa. From the results obtained, it is clear that seven days of curing will yield the best tensile strength results. On site wet curing should be done for at least one full day. The difference in the results obtained for one and seven days of curing is almost negligible. It is important to note that on 76% of the repair projects, wet curing is done for a period of longer than 24 hours. It is also important to protect freshly placed concrete repair materials against evaporation. Only 52% of repair projects are protected against the environment.

14.7. Final conclusion

What is very encouraging for the South African concrete repair industry is that the majority of concrete repair projects seem to be a success. Those projects that are not a success can be attributed to elimination mistakes made in the concrete repair process. With only little adjustments to the process and the attitude of the applicators, the success rate could become almost 90%.

The obstacles in the way of a 90% success rate that need to be addressed are the following:

- The client
- The applicator
- The diagnostic process
- The original designer / contractor
- Quality assurance and maintenance over the life span of a structure

In most instances, the client is the greatest contributor to concrete deterioration and the concrete repair project failure. Budgetary and time constraints implemented by the client in many instances cause the reduced life span of a structure and problems with durability. It is almost impossible to construct durable structures if the time and funds are not available. Even after durability problems are experienced, clients still neglect routine maintenance to keep a structure in an acceptable state of serviceability. The irony of the situation is that the longer the period of no maintenance, the higher the actual cost of refurbishment. Spending the funds up front would mean large savings in the future.

It became clear that workmanship is a big problem in South Africa. The only way to address this problem is through proper supervision and training. It is alarming that only half of the applicators are sent on training programmes. Without proper knowledge about concrete repair a durable repair, is almost impossible. The applicator must understand the importance
of each step in the concrete repair process to ensure that the step is done to acceptable standards. The civil engineer and structural designer also have a role to play to ensure that structures are durable and usable to future generations. Design faults and poor supervision on site cannot be repaired. The problem can be cured only for a short period. With a proper design, detailing and supervision problems experienced with durability later on in the lifetime of a structure could be eliminated.
REFERENCES


6. American Concrete Institute, 1996, Committee 209, Prediction of creep, shrinkage and temperature effect in concrete structures, (ACI 209R-82).


