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Critical Literature Review on Concrete Crack Repairs

Dissertation presented for the Degree of Master of Engineering in Civil Infrastructure

Management & Maintenance

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Abstract

This dissertation focuses on an in-depth review of literature on concrete crack repairs. Deterioration of concrete affects both the aesthetics and the integrity of structures. As a result, there is need to repair such defects in order to restore the aesthetics and the integrity of concrete structures. This research discusses concrete crack repairs taking into consideration the mechanisms resulting in concrete cracking, techniques to determine concrete cracking, practices for prevention of concrete cracking and concrete crack repair techniques. Causes of cracking include alkali silica reactions (ASR), steel reinforcement corrosion, shrinkage, thermal variations, foundation movements, soil settlement, vegetation effects and cracking related to earthquake effects. Non-destructive and destructive techniques to determine concrete cracking shall be discussed. Destructive techniques usually involve core drilling of samples whilst non-destructive techniques include visual inspections, ultrasonic pulse velocity test, acoustic emission, spectral analysis of surface waves, modal analysis, petrographic analysis and infrared thermography.

Several concrete crack repair techniques are to be discussed such as epoxy injection, routing and sealing, near surface reinforcement, additional reinforcement, gravity filling, grouting, dry packing, crack arrest, polymer impregnation, overlay and surface treatments, crack filling, crack sealing, blanketing, stitching and external stressing. These techniques are applied differently depending on the nature and cause of the concrete cracks.

Further discussions will be on various case studies around the world on concrete crack repair which demonstrate the application of various concrete crack repair techniques to different types of concrete cracking scenarios. The case studies also highlight recent developments in technology, repair materials, application fields for various techniques and limitations to concrete crack repair. Some of the case studies discussed include concrete crack repair due to ASR damage on transport infrastructure in USA, ASR effects and crack repairs on a two storey building in California (USA), ASR effects and crack repairs to concrete structures in Hokuriku District in Japan, ASR effects and crack repairs to a gravity dam in India, crack repairs at Buttermarket Shopping Center due to shrinkage cracking and concrete crack repairs in Cheshire due to thermal effects.

LIST OF ACRONYMS

AASHTO – American Association of State Highways and Transport Officials

AAR – Alkali Aggregate Reactions

ACI – American Concrete Institute

ACRA - Australian Concrete Repair Association

ASR – Alkali Silica Reactions

ASTM – American Society for Testing Materials

ASTM - American Society for Testing and Materials

BS – British Standards

CRM – Concrete Repair Manual

DRI - Damage Rating Index

FHWA - Federal Highway Administration

TRJET – International Research Journal of Engineering and Technology

NDT – Non Destructive Testing

SEM - Scanning Electron Microscope

SDT - Stiffness Damage Test

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CHAPTER 1: INTRODUCTION

1.1 Background

This dissertation provides an analysis of the various causes of concrete cracking, the testing methods available to detect cracking in concrete, concrete crack repair techniques and the materials used to repair concrete cracks. Concrete cracking is defined as the separation of concrete completely or incompletely into two or more parts caused by breaking and fracturing. The study of concrete crack repair is vital in the field of civil engineering since concrete cracking can result in structural failure which may have negative effects on the safety of users. This research will identify from literature the recent trends in concrete crack repair techniques and materials including the evaluation of how these are applied in practice.

Wager (2016) stipulates that cracking in concrete is an inherent feature which cannot be completely eliminated or prevented, but can only be minimised or controlled through consideration of the design criteria or through using adequate materials and techniques of construction. Structures are designed to carry loads taking into consideration that cracking can occur. Concrete cracking should be allowed to a certain degree that does not impair the serviceability or aesthetics of the structure. Concrete cracks are not always detrimental, sometimes they are beneficial depending on their nature and location. For instance, hairline cracks give signals and warnings of defects and deterioration requiring intervention. In other cases, cracks contribute to relieving stresses from structural members (Wager, 2016).

Cracks start to develop in concrete once tensile stresses or strains exceed the tensile capacity of concrete (Martin, 2008). According to Croxton (2000), the crack width should not exceed 0.3 mm in members where cracking does not have adverse effects upon the preservation of reinforcing steel or the durability of the structure. An upper limit of 0.2 mm is recommended as the maximum crack width in members where cracking in the tensile zone is harmful either because members are exposed to moisture or in contact with soil. For aggressive environments, the suggested maximum crack width is 0.1 mm. Cracking is influenced by many factors and is a variable phenomenon, hence absolute limits to the widths of cracks cannot be stipulated and the requirements given in the design codes merely provide an acceptable probability of the limiting widths not being exceeded (Martin, 1997).

Causes of concrete cracking should be investigated through observing the size, shape, depth, location and behavior of the cracks. Jaya (2014) categorises concrete cracking into two main groups namely structural cracks and non-structural cracks. Non-structural cracks may emanate due to chemical action, thermal variations and moisture changes. Non-structural cracks occur due to internally induced stresses in concrete and normally do not endanger the safety of the structure. Examples of non-structural cracks include ASR cracks, shrinkage cracks and corrosion-induced cracks. Structural cracks are caused by applied forces such as foundation settlement, dead, live, seismic and wind loads. Structural cracks may be difficult to rectify and may endanger the stability of concrete structures. Examples of structural cracks are the cracks appearing on abutment walls, columns, beams and slabs. These cracks may emanate due to various reasons such as incorrect design, soil overloading and overloading of structural elements (Jaya, 2014).

(Wager, 2016) outlines the causes of non-structural cracks such as cracking due to shrinkage effects, alkali-silica reactions, thermal variations and reinforcement corrosion. Moisture variations occur as a result of moisture loss from the cement paste, a phenomenon known as shrinkage (Wager, 2016). Shrinkage is a physical cause of concrete cracking. There are different categories of concrete shrinkage such as plastic shrinkage, drying shrinkage and carbonation shrinkage (Martin, 2008).

Chemical reactions result in concrete cracking due to the expansive reactions between aggregates containing active silica and the hydroxides derived from the cement hydration. The reactions between the alkali and the silica may result in the formation of a swelling gel that causes local expansion in concrete, thus resulting in the formation of cracks. Thermal variations cause cracking in concrete due to the expansion of material on heating and contraction on cooling. Corrosion induced cracking occurs as a result of deleterious substances penetrating through the concrete cover to the steel reinforcement bars. The products of corrosion result in volume increase within the concrete causing cracking and spalling (Wager, 2016).

There are other factors that create conditions conducive for structural cracking such as faulty construction and poor workmanship often due to lack of quality control, incorrect or defective design and detailing of steel reinforcement or joints, incorrect assessment of foundations and soil bearing capacities, incorrect load assumptions and overloading. Poor workmanship and design

may lead to the production of poor quality concrete with inadequate density and permeability, allowing penetration of various aggressive agents that facilitate steel reinforcement corrosion. Vegetation may result in concrete cracking due to the expansive action of tree roots growing under foundations. Earthquakes also cause cracking in concrete due to the sudden shift in lower layers of the earth resulting in forced movement of structural elements such as foundations walls, beams and columns. Poor maintenance of structures can further allow condition necessary for concrete cracking and depending on the quality of design, some structures need consistent maintenance whilst some can sustain themselves very well for many years (Jaya, 2014).

Cracking and causes of cracking in concrete can be detected through destructive and non-destructive testing methods. Destructive testing is done through the drilling of concrete cores to detect the presence or possibility of alkali-aggregate reaction from reactive aggregates. Some of the tests that can be conducted on core samples include the aggregate reactivity test, petrographical examinations, and mineral analysis such as X-ray diffraction and microscopic analysis. There are several non-destructive testing methods used to detect cracking and causes of cracking in concrete structures such as visual inspections, ultrasonic pulse velocity test, acoustic emission, impact echo, modal analysis and infrared thermography. Destructive testing techniques can also be used to detect cracking or causes of cracking in concrete structures (Martin, 2008).

There are several concrete crack repair methods and materials used in practice around the world. Some of the methods and standards for repairs are outlined in various codes of practice such as the American Concrete Institute ACI 224.1R-07 (2008), the HB 84 (2006) - Guide to Concrete Repair and Protection which is a joint publication of Australian Concrete Repair Association ACRA (2006) and Standards Australia Limited (2006) and the Commonwealth Scientific and Industrial Research Organisation CSIRO (2010).

Before repairing cracks in concrete structures, it is imperative to identify the cause of the cracking. Unless the cause is addressed, it is most likely that cracking will reappear. Repair or treatment of concrete cracks should be based on the identification of crack types and considerations on how harmful the cracks are in relation to the use of the structure (Wager, 2016). The aim of these repairs should be established before selecting any repair methodology or repair materials. There are various reasons for concrete crack repairs such as improving the aesthetics of the concrete surface,

restoring strength of cracked components, prevention of liquid penetration, restoring the stiffness of cracked components, improving durability of the concrete and improving the functional performance of the structural elements (Jaya, 2014).

Repair of structural cracks often involves some urgency to ensure the restoration of lost strength or durability. High accuracy is required when repairing concrete cracks. Some of the concrete crack repair methods include epoxy injection, dry packing, routing and sealing, gravity filling, grouting, crack arrest, polymer impregnation, overlay and patch repairs, crack filling, crack sealing, drilling and plugging, blanketing, concrete jacketing and stitching. These methods are applied differently depending on the nature of cracks, type of structure being repaired and the climatic conditions (Martin, 2008).

In this research, case studies shall be presented from literature to identify recent trends in concrete repair techniques and materials and evaluate how these are applied. Case studies presented on Chapter 5 of this dissertation outline the most common and recently used concrete crack repair methods. These have been identified being crack injection, crack sealing, patch repairs, surface coatings and dry packing. These methods can be used to repair both structural and non-structural cracks. There are various materials that can be used to repair concrete cracks depending on the nature of cracks and the purpose of repair. Crack injections can be done using epoxy adhesives, polysulphide sealants, silane compounds and lithium products. Crack sealing can be done using various products. Latest developments include the use of silane products such as 40% water based silane, 100% silane, 20% silane in water, 20% silane in isopropyl alcohol, 40% silane in isopropyl alcohol, sodium silicate and silane siloxane. The most common lithium products include lithium silicate and lithium nitrate. Repair materials used for surface coating include epoxy resins, acrylic and urethane sealants. Patch repairs are usually done using polymer-modified cementitious mortars. Dry packing methods are carried out using rapid repair mortars, re-profiling mortars, polyurethane sealants, polymer-modified repair mortars and low epoxy resins.

1.2 Aims of the Research

This research aims at providing in depth analysis on concrete cracking based on literature review, focusing on the following aspects:

- Causes of concrete cracking, crack evaluation methods, crack repair techniques and crack repair materials
- Application of crack repair techniques in practice
- Recent trends in concrete crack repair techniques and materials

1.3 Scope and Limitations of the Research

This research will focus on concrete crack repairs taking into consideration how cracks originate, mechanisms involved and ways to repair them. Gathering latest information on concrete crack repair case studies was a challenge hence the case studies to be presented will give an indicative view of latest repair information. Conversely, the research does not aim at developing any new methods of concrete crack repairs. Furthermore, it will focus on concrete crack repair only and ignore concrete rehabilitation and retrofitting.

1.4 Outline of the Dissertation

This section highlights the outline of the dissertation, which consists of six chapters.

Chapter 1

This is an introductory chapter to the research and gives a brief background on the causes of concrete cracking, methods for detecting concrete cracking and various concrete crack repair techniques and materials. It further outlines the aims of the research, scope of the dissertation and limitations to the research.

Chapter 2

This chapter outlines the causes of cracking in concrete structures. It gives in depth understanding more on structural and non-structural cracks and how they originate.

Chapter 3

This chapter discusses the destructive and non-destructive methods to detect cracking and causes of cracking in concrete structures. Non-destructive techniques include visual inspections, ultrasonic pulse velocity test, acoustic emission, impact echo, modal analysis and infra-red

thermography. Destructive techniques include the drilling of concrete cores to detect the presence of cracking or possibility of reactive products which may result in concrete cracking.

Chapter 4

This chapter outlines the methods of concrete crack repairs. It describes concrete crack repair methods such as epoxy injection, dry packing, routing and sealing, gravity filling, grouting, crack arrest, polymer impregnation, overlay and surface treatments, crack filling, crack sealing, drilling and plugging, blanketing and stitching.

Chapter 5

This chapter focuses on concrete crack repair case studies. Emphasis shall be on the application of concrete crack repair methods and materials highlighting the recent trends and developments.

Chapter 6

This chapter concludes the findings from literature on concrete crack repair and indicates the recent developments on concrete crack repair methods and materials with reference to various case studies.

CHAPTER 2: CAUSES OF CRACKING IN CONCRETE STRUCTURES

As mentioned previously, concrete cracking can be divided into two main categories namely non-structural cracks and structural cracks. Examples of non-structural cracks include cracking due to moisture variations, thermal variations and chemical action. Structural cracking examples include cracks emanating from various reasons such as incorrect design, soil overloading, over-loading of structural element, earthquakes and vegetation effects. The main objective of this chapter is to discuss in detail the causes of cracking in concrete structures taking into consideration the mechanisms involved.

2.1 Non-Structural Cracking

There are various sources which explain non-structural cracking and the Concrete Society (UK) Technical Report 4th edition of 2010 is one of the sources indicating that non-structural cracks are mainly due to plastic, early thermal and long term drying shrinkage. It further outlines other causes of non-structural cracking such as ASR, steel reinforcement corrosion and crazing. Fulton 9th edition of 2009 and the American Concrete Institute Proceedings volume 42 are among the common sources indicating the above mentioned causes of cracking in concrete. It is also imperative that in some cases the effects of non-structural cracks may have structural consequences.

2.1.1 Alkali Silica Reaction (ASR)

Alkali-Silica Reaction is one of the chemical causes of concrete cracking. ASR is a phenomenon that was first discovered in 1940 by Stanton in North America and from then, many countries have been acknowledging this effect. Many studies and research have been going on since the Stanton discovery. ASR is a phenomenon whereby aggregates react with the alkali hydroxides which are in concrete, causing swelling or expansions leading to the development of the cracks. The swelling causes tensile stress and the moment the swelling pressure becomes more than the tensile strength of the concrete, cracking starts to develop (Stark, 1994).

ASR result in concrete cracks due to the reactions between silica and alkali from cement paste (Addis, 2009). The reactions involving the metastable silica minerals such as tridymite, opal, volcanic glasses and cristobalite are more specifically referred to as alkali-silica reactions whilst

alkali quartz bearing or alkali siliceous rock reaction are the reactions between the alkalis and rocks such as greywacke, granite gneiss, hornfels, quartzite, granodiorite and granite which contain cryptocrystalline quartz, chert, microcrystalline quartz, chalcedony and strained quartz (Oberholtzer, 1984).

2.1.1.1 ASR Effects in South Africa

Wood (2009) discussed about the effects of ASR in South Africa. There were reports in 1960 on deteriorations in the Western Cape at the Steenbras Dam due to ASR. In 1971 and 1972, there were signs of the same type of deterioration in the Cape Peninsula. Types of the aggregates in the Western Cape are the Table Mountain group quartzite and quaternary river gravels. The reactions affected many concrete structures such as culverts, dams, earth retaining walls, bridges, reservoirs, conductor mast foundations and concrete roads. By 1976, it was finally concluded this was a result of the reactions between high alkali cement and Malmesbury group aggregates. This led to further conclusions that the alkali expansion of such rocks is due to the reaction with the reactive silica (Wood, 2009).

In the Eastern Cape Umtata area, the effects of ASR have been observed in concrete structures such as dams, bridges and electric mast foundations. In Gauteng, there are signs of deterioration due to ASR especially in the Heidelberg region which is located in the eastern side of Gauteng. The type of aggregates used are the Witwatersrand quartzite (Schutte, 1982). Blight and Alexander (2001) have reported the effects of ASR on several structures in South Africa. They have monitored in service a bridge pier affected by ASR. After their investigations, they were of the view that full-scale load testing must be regarded as the ultimate criterion of the serviceability of an ASR-affected structure and state that “If the structure behaves predictably and in accordance with the design requirements and if strains and deformations are of reasonable magnitude and recoverability, there can be little doubt that the structural adequacy has been preserved”. Mitigation of ASR can be achieved through reducing the reactive silica amounts in concrete aggregates, minimising the external alkalis and reducing the alkali content in cement. ASR cracks are usually associated with map pattern cracks as indicated on Figure 1 below.



Figure 1 ASR wider and spreading map pattern cracks (Wood, 2009)

2.1.2 Reinforcement Corrosion

Chloride and carbonation effects are the two main causes for steel reinforcement corrosion in concrete (Martin, 2008). In South Africa, many structures have been affected by corrosion both in coastal and inland areas. Research has proven that corrosion in overseas countries in the Northern Hemisphere is largely related to chloride-induced corrosion due to the use of de-icing salt in winter (Martin, 2008). In South Africa and other coastal areas, the problem emanates from the wind-borne salts carried inland as a result of on shore prevailing winds or from direct contact with sea water from splash and spray zones. Corrosion can be detected by noticing the brown stain on the concrete surface and associated defects such as cracking, delamination and spalling. Carbonation induced corrosion is experienced mainly in interior areas away from the oceanic environment due to carbon dioxide. Corrosion of concrete structures happen if there is enough oxygen and moisture required to initiate the process (Clear, 1976).

Martin (2008) stipulates that corrosion of steel reinforcement in concrete occurs when the chloride concentration exceeds the required minimum threshold values or when carbonation depth exceeds the concrete cover. The main effects of corrosion include rust staining, cracking, spalling and delaminations. Corrosion of steel bars embedded in reinforced concrete structures reduces the

service life and durability. This can cause early failure of the structure resulting in cost increases through inspections and related maintenance (Martin, 2008).

For corrosion to occur, it requires an electrolyte, a cathode and an anode. The electrolyte enables easy ionic movements. The metal anode oxidises to form soluble ions and on the other hand, the cathode acts as reducible metal providing hydroxyl ions. Corrosion occurs at lower pH values. At higher pH values around 12.5, the steel reinforcement in concrete will be in a passive state and at lower pH values, the gamma ferric oxide layer is eliminated thereby initiating the corrosion process. Monitoring reinforcement corrosion is of significant importance to prevent premature failure of structures (Clear, 1976). Corrosion effects can be controlled during the design stage through designing for durability to achieve quality concrete that does not allow easy penetration of deleterious substance. Design considerations such as increased cover to reinforcement depth and coating of reinforcement bars with corrosion inhibiting products assist in mitigating corrosion effects (Martin, 2008).

2.1.2 1 Steel Reinforcement Corrosion Effects in South Africa

Steel reinforcement corrosion has been experienced in South Africa. Concrete structures located in coastal areas such as Durban, East London, Port Elizabeth and Cape Town are the most affected due to chloride induced corrosion. The corrosion effects are common due to the shallow cover to reinforcement. As a case study carried out by the author, the SABS building in Durban will be utilised as an example. On the structure, significant signs of corrosion were detected in 2014 and the effects were found to compromise the structural integrity of the building (Figure 2) below. Chloride and carbonation tests were carried out and corrosion was detected to be a result of chloride effects and this was mostly likely because the structure is located close to the Indian Ocean. However, corrosion effects are also being experienced on inland structures mainly due to carbonation effects. In Pretoria, the former Public Works Tshwane Building a 14 storey suffered reinforcement steel corrosion and the occupants have been relocated to another structure since the structural integrity has been compromised. A team of professionals has been appointed to conduct condition assessments and develop a detailed maintenance plan to repair the building and restore its structural integrity.



Figure 2: Cracking, spalling and delaminations at the SABS building due to corrosion effects

2.1.3 Moisture Variations and Shrinkage

Shrinkage effects on concrete are mainly due to moisture variations. Shrinkage cracking can be classified as a physical cause of concrete cracking. The American Concrete Institute ACI, 224.1R (2008) defines shrinkage as a phenomenon whereby concrete loses its moisture. Martin (2008) identifies the four main physical causes of concrete cracking namely plastic shrinkage, drying shrinkage, autogenous shrinkage and carbonation shrinkage. Concrete shrinks once exposed to certain conditions especially drying environment. The degree or extent of shrinkage depends on many factors such as temperature, time of exposure to the drying environment, material and relative humidity (Addis, 2009).

2.1.3.1 Plastic Shrinkage

Bloom (1995) articulates that plastic shrinkage cracking is caused by adverse hot weather conditions on fresh concrete. Plastic shrinkage cracking occurs as a result of restrained stresses and strains exceeding the capacity of concrete. Plastic shrinkage cracks usually appear on horizontal surfaces and develop as the water sheen disappears from the concrete surface. Shrinkage

can also be a result of the hydration process which removes free water or a result of drying due to inadequate protection (Witman, 1976). Martin (2008) describes plastic shrinkage cracks in concrete being a result of restraint provided by the concrete below the drying surface, resulting in tensile stresses developing in the weak stiffening plastic concrete. The result is cracks forming in different polygon random patterns of shallow depths parallel to each other as shown on Figure 3 below.



Figure 3: Plastic shrinkage cracks at Unilever Ice Cream Plant in Midrand, Johannesburg

Martin (2008) further describes the process and initially if water is added to the cement, there is a reduction in the volume due to a certain amount of the cement entering into the solution. Absorption of moisture on the cement surface results in the closer packing of the water molecules. Aggregates which are porous can absorb more water leading to further decrease in volume. The changes in volume usually happen when the concrete is still in its plastic state. Cohen (1991) et al., state that the higher surface area of silica fume particles increase the capillary pressure and consequently make concrete more vulnerable to plastic shrinkage cracking. Berhane (1984) describes plastic shrinkage as usually happening before curing commences when the surfaces are exposed to quick loss of moisture due to external effects such as the wind, high temperature, low humidity and bleeding characteristics of concrete. This usually occurs when the rate of moisture

evaporation is faster than the bleeding rate. Since plastic shrinkage is related to the bleeding rate, both the environmental conditions and the concrete composition play a significant role. Fog spray, water proofing and thorough mixture proportioning are some of the measures that can be implemented to control plastic shrinkage (Almusallam et.al., 1997).

2.1.3.2 Plastic Shrinkage Effects in South Africa

The author has some hands on experience among some concrete construction projects completed in South Africa. There is a project which was completed in February 2016 and the author was actively involved as part of the design and supervision team. The project was for the Unilever Ice Cream Manufacturing Plant in Midrand, Johannesburg along Allandale road towards Kempton Park. The project scope involved the construction of a massive production plant of steel structures on concrete bases as well as a large concrete parking area where delivery trucks would use during loading and offloading ice cream products. The concrete hardstand parking area was constructed using 40 MPa reinforced concrete, 250 mm thick with concrete joints at 3 m intervals. Lafarge was the supplier of the concrete and trucks were used for delivery. Curing was to be done as specified in the designs and plastic shrinkage was experienced due to high temperatures and high moisture evaporation rate during the windy spring and summer periods. The construction team managed to control the effects to a minimum to avoid severe damages.

2.1.3.3 Drying Shrinkage

Hamanaga (2004) defines drying shrinkage as the contracting of concrete as a result of the loss of capillary water. Pietro (2006) articulates drying shrinkage cracks as being formed due to volume changes caused by loss of excess water. According to Martin (2008), drying shrinkage is a process which happens when the net outflow of moisture from the concrete to the environment results in volume decrease. The rate of moisture flow from the concrete is usually very slow and as a result, the strain responses are time dependent.

Kraai (1985) describes the drying shrinkage process being a result of moisture loss from the cement paste which can shrink as much as 0.01% of the unit length. Concrete does not crack if shrinkage of concrete takes place without any restraint. Water content and aggregate type are the main factors influencing drying shrinkage. Using a significant amount of aggregates can reduce the drying shrinkage (Kraai, 1985). Martin (2008) stipulates that the higher the water content, the more the

drying shrinkage and the stiffer the aggregates the more effective in reducing the shrinkage of concrete. Drying shrinkage can be controlled through proper steel detailing and construction of properly spaced joints.

2.1.3.4 Drying Shrinkage Effects in South Africa

The author has been recently involved in another project in Gauteng. The project was for Peri, the company provides scaffolding for concrete works around South Africa. The company secured a larger area for their operations and they had to build an office block, concrete parking area and a warehouse. The parking area was constructed of reinforced concrete 200 mm thick, 30MPa and concrete joints at 2 m intervals. Concrete cracking due to drying shrinkage was experienced at the Peri scaffolding delivery yard concrete pavement in Centurion, South Africa in March 2017. The author was involved in providing repair solutions to the concrete yard, which was approximately 10 000 m² in size. Figure 4 below shows concrete cracking due to drying shrinkage.

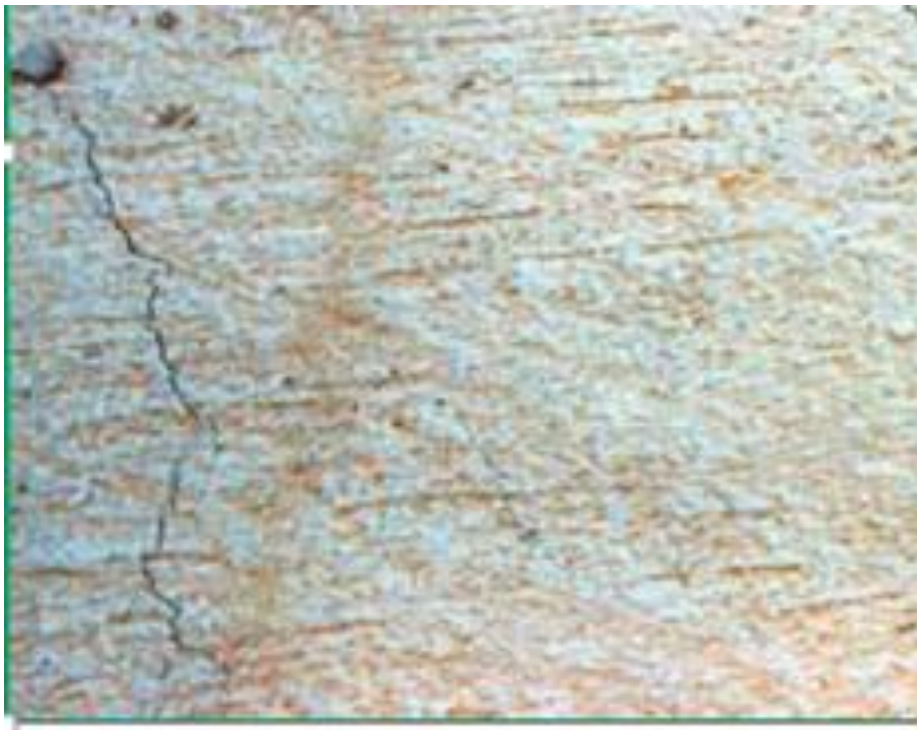


Figure 4: Drying shrinkage cracking on a concrete slab (Peri Scaffolding in Centurion, South Africa)

2.1.3.5 Autogenous Shrinkage

Autogenous shrinkage occurs as a result of the formation of hydration products with lesser volume compared to the total volume of the original components considered individually (Martin, 2008). The absorption of moisture during the hydration process can also cause autogenous shrinkage especially in cases where there is a shortage of water during the mixing process. Volume changes due to autogenous shrinkage are not as significant when compared to carbonation and drying shrinkage (Swamy, 1979).

2.1.3.6 Carbonation Shrinkage

Carbonation shrinkage develops when concrete is exposed to the atmosphere containing carbon dioxide (Martin, 2008). The shrinkage process occurs in cases where the hardened concrete is exposed to air containing carbon dioxide and as a result, the weight increases and the concrete undergo irreversible carbonation shrinkage. This results in a reduction of volume and the process occur over a long period of time. Carbonation can occur at low carbon dioxide concentrations and can convert the hydrated cement paste to alumina, silica, ferric oxide and calcium carbonate. Carbonation shrinkage is susceptible when carbonation happens subsequent to drying and can be reduced at either higher or lower humidity (Swenson, 1998).

2.1.4 Thermal Variations

Thermal variations result in concrete cracking due to the expansions and contractions which occur as a result of changes in temperature conditions in effective of the cross-sectional area. Concrete does expand when heated up and contracts upon cooling (Wager, 2016). In South Africa, these effects are common in concrete structures located in areas such as Queenstown in the Eastern Cape where there is a wide range in temperature changes. For instance, the highest temperature during the day can be 35°C and drop at night to -2°C. Thermal movements can be prevented through the introduction of expansion joints, slip joints, construction joints and control joints (Martin, 2008).

2.2 Structural Cracking

According to Addis (2009), structural cracks emanate from various reasons such as incorrect design, soil overloading, overloading of structural elements, vegetation effects and earthquakes. Structural cracks can be as wide as 10 mm and usually requires immediate action for repairs as

they affect the integrity of the structure. Examples of structural cracks are the foundation wall cracks, continuous horizontal cracks along the walls, cracks on beam foundation slab, stair step cracks, cracking developing to the top level of the structure, corners of the walls showing signs of angled cracks and wider cracks developing on walls vertically. Figure 5 below is an example of structural cracking (Addis, 2009).

Failure to address structural cracks imminently may pose safety risks to the users as there can be negative effects such as structural collapsing which may cause injuries or fatalities. Structural cracks are usually accompanied by other signs of foundation issues such as sloping floors, sticking windows and doors, cracks in porches and slanted doors. It is recommended to attend to structural cracks the moment they start developing so as to maintain the safety of the structure and avoid extensive future repair costs (Addis, 2009).



Figure 5: Structural cracks (Edwin, 2017)

2.2.1 Foundation Movement and Soil Settlement

Differential settlement of foundations may lead to the development of shear cracks in concrete structures. Uniform settlement up to some tolerance levels does not cause structural problems. Foundation settlement can be a result of changes in moisture content of the soil below the foundation, decay of organic matter in the subsoil or overloading of the super structure (Jaya,

2014). Design consequences such as using the minimum factors of safety in foundation designs may result in shear cracks. Soil overloading can cause shear cracks especially on instances where bearing strength of the soil is exceeded by the structural loads. Shear cracks can also be a result of unequal bearing pressure under different parts of the structure. Cracking due to foundation movement or soil settlement can be controlled through the creation of slip joints under the support of concrete slabs. Shear cracks can be controlled through the provision of movement joints between the top of brick panels and reinforced concrete beams or slabs (Martin, 2008).

2.2.1.1 Structural Cracking Effects in South Africa

The author's experience on structural cracking was the cracking due to foundation movements at a school built in the Free State, South Africa in 2015. Phephetso Secondary School located in Kroonstad was constructed through the Development Bank of Southern Africa (DBSA), Accelerated Schools Infrastructure Delivery Initiative Programme (ASIDI) in 2015. A year after construction, the classroom blocks started to develop structural cracks in areas above the windows and doors as shown on Figure 6 below. The conclusion was foundation movements due to heaving effects of the clay soil below the foundation during the rainy season.



Figure 6: Structural cracks at Phephetso Secondary School classrooms

2.2.2 Cracking Related to Earthquakes

Geological factors can result in earth movements. Earthquakes can result in structural cracks due to the sudden shift in the lower layers of the earth. Movements of the earth do result in the forced movement in structural elements such as walls, beams, slabs and foundations resulting in crack development. Cracking due to earthquakes can be avoided by constructing structures on a firm ground. Another solution is to tie the structure with connecting beams at different levels such as foundation level, door level and roof level (Wager, 2016).

Structural cracking due to earthquakes was experienced at a parking garage in Los Angeles, USA due to the 1994 Northridge earthquake. Investigations were carried via a Response Spectrum Analysis of a coarsely meshed finite element model and confirmed that the cracks were due to the earthquake. Shear cracks were observed in the basement and ground floor post tensioned slabs and cast-in-place shear walls (Paret et.al, 1998).

2.2.3 Cracking Resulting from Vegetation Effects

Vegetation such as trees can cause cracking in concrete elements due to the expansive action of roots growing under the foundations. The expansive action causes the upward movement of structural elements such as the foundations, walls and columns resulting in crack development. The cracks may occur in clay soil as a result of moisture effects in the roots. In order to minimise cracking due to vegetation, it is imperative to remove any sapling of trees the moment they start growing near the walls (Wager, 2016).

2.3 Conclusion

This chapter discussed the causes of concrete cracking. It is important to understand the cause of concrete cracking as this determines the level of urgency and techniques required to repair the cracks. The two major categories of concrete cracking can be classified as the structural and non-structural cracks. Structural and non-structural cracks usually differ on appearance especially on features such as the widths of the cracks and their patterns. Structural cracks affect the integrity of the structure and they need to be attended as soon as possible in order to protect the users from effects such as structural collapse.

To some extent non-structural cracks have effects on the integrity of the structure and they need to be attended to in order to avoid further damages. Non-structural cracks emanate due to ASR, corrosion effects, shrinkage effects and thermal variations. ASR effects are due to the reactions between silica and alkali. The effects of ASR have been experienced in South Africa and world at large. In order to minimise ASR, it is imperative to consider use of low alkali cements and selection of aggregates with less silica containing minerals. ASR at its early stages does not pose structural threats however, if the effects are not addressed promptly may result in further widening of the cracks which allows the penetration of deleterious substances resulting in steel reinforcement corrosion.

Reinforcement corrosion may result in concrete cracking, spalling and delaminations and these usually affect the aesthetics of the structure at early stages. Chloride and carbonation-induced reinforcement corrosion are the two common types experienced in concrete structures. Corrosion does not pose structural threats at its early stages. However, if not controlled it may affect the original design dimensions of the steel reinforcement bars and the design strength which may affect the structural integrity. Corrosion effects can be prevented as early as at design stage through considerations such as increased cover to reinforcement, specification of suitable cementitious binder types and concrete mixes and coating of reinforcement bars with corrosion inhibiting products.

In South Africa, shrinkage effects are very common as a result of adverse weather conditions experienced especially during the summer season where temperatures are very high with low humidity values. Shrinkage effects on concrete are mainly due to moisture variations. Plastic shrinkage and drying shrinkage are the common types of shrinkage experienced in construction. However, there are other types of shrinkage such autogenous and carbonation shrinkage. The amount of shrinkage depends on many factors such as temperature, time of exposure to the drying environment, material and relative humidity. Fog spray, water proofing and thorough mixture proportioning are some of the measures that can be implemented to control plastic shrinkage. Water content and aggregate type are the main factors influencing drying shrinkage.

Thermal variations result in concrete cracking due to the expansions and contraction, which occur as a result of changes in temperature conditions. Concrete does expand when heated up and

contracts upon cooling. The effects are common usually in areas experiencing high variations in temperature ranges. Structural cracks emanate from various reasons such as incorrect design, soil overloading, overloading of structural elements, vegetation effects and earthquakes. The effects usually affect the integrity of the structure. Structural cracks can be a result of poor workmanship due to some companies trying to cut costs on resources leading to poor quality control and supervision, use of unqualified and non-technical personnel on sites with limited knowledge on correct construction practices.

Even-though cracking is expected in concrete, it is important to investigate the causes of cracking immediately the cracks start to appear. Due to lack of knowledge within the construction industry, many people do not consider concrete cracking as a priority towards maintenance of structures especially if the cracks appear narrow. Early signs of cracks can actually warn individuals at early stages to consider preventative measures to stop the cracks from manifesting. Causes of cracks should be investigated once the warnings of cracking are observed so that correct preventative measures and repair techniques can be applied. Once the causes are identified and correct repair methods applied, it saves a lot in the long run in terms of maintenance costs.

CHAPTER 3: EVALUATION, DETERMINATION OF LOCATION AND EXTENT OF CRACKING

This chapter focuses on testing techniques used to determine the location and extent of cracking in concrete structures. These techniques can be classified into destructive and non-destructive testing methods. Destructive testing involves the damage of specimen during testing whilst non-destructive testing does not involve damaging of the specimen. Destructive and non-destructive testing techniques are used to detect concrete crack location, width and depth. They are also used to determine concrete strength predictions, structural and general conditions of concrete, foundation condition, reinforcement steel location, cover depths and corrosion assessment (Martin, 2008).

Examples of non-destructive techniques include visual inspections, ultrasonic pulse velocity, acoustic emission, spectral analysis of surface waves, modal analysis, and infrared thermography. Destructive methods include core drilling for tests such as compression testing, tensile testing, impact testing, bending testing and petrographic analysis. Other methods that assist in the identification of cracks in concrete structures include drawings, construction and maintenance records (Croxtton, 2012).

3.1 Non-Destructive Testing Methods

3.1.1 Visual Inspections

Visual inspection is the most common and oldest method used in condition assessment of concrete structures. This method classifies and documents the appearance of distress on the surfaces of concrete. It is widely used to assess deterioration such as concrete cracking, scaling, spalling, construction defects and erosion (Martin, 2008). Crack features such as rounded or sharp edges can be identified through visual examination with a naked eye or magnifying glasses. Visual assessments require essential accessories such as notebooks, photographs, videos, marking pens, chalk and pro-forma sheets (Kurt, 2006). Visual assessment can determine the severity of cracking through recognition of cracking characteristics such as width, depth and crack direction. Cracks can be vertical, transverse, longitudinal, diagonal and random (Martin, 2008).

Visual assessments are used to identify effects of cracking in concrete such as map cracking, localised cracking, hairline cracking, offset cracking and diagonal corner cracking. Crack width is one of the features that can be used to determine the cause and effects of cracking. Although there are many sophisticated ways to determine crack width, a plastic crack comparator is a common simple equipment that can be used to determine crack width. Map cracking and hairline cracking usually occur due to non-structural effects and the crack widths are small. Offset and diagonal cracking usually emanate due to structural effects and the crack widths are relatively large. Map cracking or crazing can be identified by a naked eye and they often do not pose any structural issues due to the fact that they are usually shallow and limited to the concrete surface. Crazing cracks or map cracking are often related to plastic shrinkage and commonly regular in appearance (Allam, 2012). Figure 7 below shows an image of map cracking.



Figure 7: Map pattern cracks (CRM1-279, 2012)

The American Concrete Institute Guidelines ACI, 116R (2008) define hairline cracks as narrow cracks usually formed on exposed concrete surfaces. Hairline cracking occurs in both hard and

fresh concrete. It is characterised by very thin, shallow features and allow for more serious cracking once the concrete has hardened. An example of hairline cracking is indicated on Figure 8 below and they are usually less than 0.08 mm in width. Hairline cracks originate from various reasons such as concrete settlement after placing and shrinkage effects. However, recent literature does not show any method of determining crack depth based on crack width. Hairline cracks due to thermal variations are observed during the initial stages of cracking and they act as early warning signs to cracking effects. However, if they are not addressed immediately they may widen to values greater than 0.08 mm. Crack widths due to foundation movements can be as wide as 5 mm (Martin, 2008).

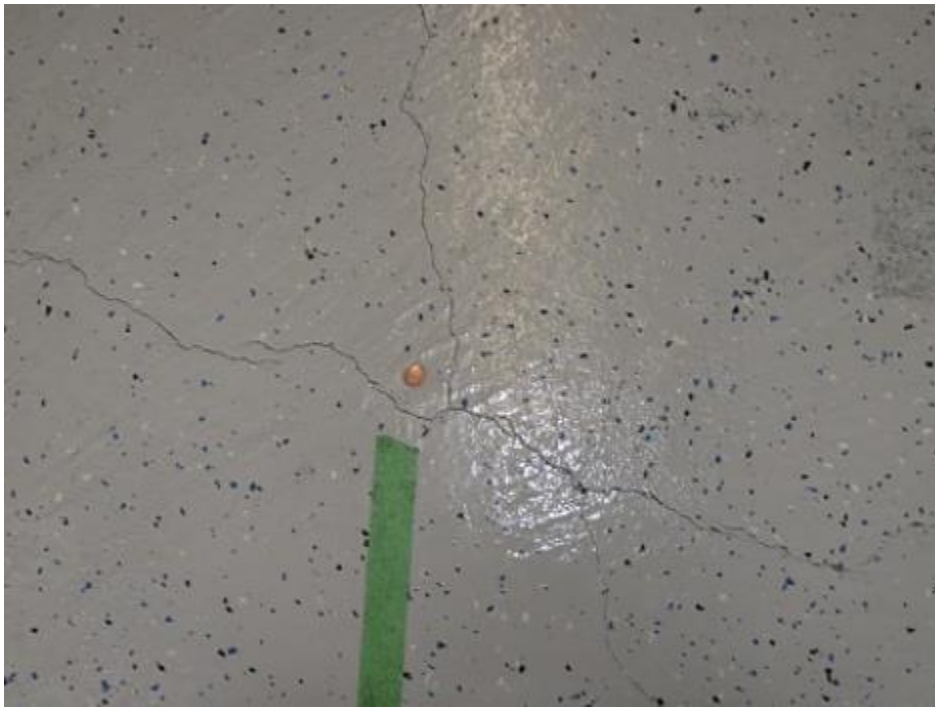


Figure 8: Hairline cracks (Allam, 2012)

Offset cracks occur due to uneven surfaces below the concrete surface. They are characterised by an elevation differential across the crack. The cause can be due to various reasons such as subgrade settlement, external pressure due to tree root action, poorly consolidated base beneath the concrete and expansive soils. These cracks need to be addressed immediately once they start appearing as they pose safety concerns to the structure. Offset cracks can be as wide as 5 mm if not addressed immediately and Figure 9 below is an example of an offset crack (Addis, 2009).



Figure 9: Offset cracking (CRM1-279, 2012)

Diagonal corner cracking occurs when a crack runs from one joint to its perpendicular joint at the corner of a concrete slab. Diagonal cracks are observed at the corners of slabs or at a joint intersection caused by warping, curling or by overloading of the slab. The crack widths can be greater than 2 mm in many cases. Warping is caused as a result of moisture differential whereas curling is caused by temperature differences between the bottom of the slab and the surface. An example of overloading is a vehicle driving over the curled corner with no support resulting in the breaking of the concrete as indicated on Figure 10 below (Allam, 2012).

Another type of cracking rarely experienced in concrete structures is the D-crack. This type of cracking is a terminal condition or progressive scenario and does not have a cure. The D-cracks are usually observed as a series of cracks parallel to a joint as indicated on Figure 11 below. Technically, the cracks are a result of moisture infiltration through the joint to the concrete aggregates that will crack under the freezing and thaw conditions. D-cracks can be as wide as 1mm and due to the fact that the concrete near the joint is usually saturated, freezing begins to crack the aggregates and the concrete. These types of cracks are usually experienced in areas where there are high variations of extreme temperatures (Martin, 2008).



Figure 10: Diagonal cracking (Kumar, 2000)



Figure 11: D-cracking near a concrete joint (ACI, 116R)

Visual observations of salt deposits on the concrete surface due to the leaching of lime compounds is also an indication of concrete cracking. Cracks in concrete allow corrosion products such as

lepidocrocite, goethite and magnetite to be leached to the surface of concrete by aqueous solutions. Visual observations of brown staining on the concrete surface due to corrosion indicates the existence of cracking in concrete. Calcium compounds are the most common corrosion products which are leached out through concrete cracks and are visible by a naked eye (Kumar, 2000).

The major advantages of visual inspection as compared to other non-destructive testing techniques is that it is cheaper, gives immediate results and requires less preparation. However, it is imperative to take cognisance of the fact that before one can conduct visual assessments, training is required for one to be able to identify the cause of cracking. There is a need to consider possible structural effects which requires the understanding structural engineering. This requires knowledge of materials, deterioration mechanisms, flow of stresses, assessment of the environment etc. On the other hand, the human eye is sophisticated and can easily be tricked and as a result, visual inspection has its own shortfalls such as imprecision and unreliability. Optical illusion makes visual inspections unreliable and hence visual inspection should not be the only method used for inspections (Allam, 2012).

3.1.2 Ultrasonic Pulse Velocity Test

This method is used to determine cracking in concrete and most effectively crack depths. Concrete crack depths can be determined through measuring the time of a pulse of ultrasonic waves through a known path (ASTM C597, 2005). This method is useful for determining the homogeneity and quality of concrete (BS1881 Part 303, 1983). The HB84 (2006) outlines that UPV measurements determine the uniformity of concrete, concrete quality and other qualitative measurements such as the concrete cracks, honeycombing, voids and delaminations. The UPV signals dictate density discontinuities in acoustic impedances arising from deformations such as concrete cracks, voids and delaminations (HB84, 2006).

The equipment used for ultrasonic pulse velocity comes as a set comprising of an electrical pulse generator, transducer, amplifier and electronic timing devices. The set-up is shown on Figure 12 below. The principle of ultrasonic velocity involves the production of a longitudinal stress wave energy by an electro-acoustical transmitting transducer that is coupled to concrete. After transversing through the concrete, the pulse is received and converted into an electrical signal by a second receiving transducer located at a distance L . The period of transmission T between the

two transducers is measured electronically. The pulse velocity V is obtained by dividing L by T (Komolos, 1995).



Figure 12: Ultrasonic pulse velocity test (HB84, 2006)

The transmission of an ultrasonic pulse is related to the elastic properties and the density of the concrete. The advantages of ultrasonic pulse velocity is that it provides faster and more accurate results without causing destruction or damages to the concrete elements. Some of the challenges for using this method are that it requires manual operations, which require high accuracy and experience (Maierhofer, 2003). Recently, the ultrasonic pulse velocity methods have been used in the UK for dams that were showing significant signs of concrete cracking due to alkali-silica reactions and did provide some guidance on the state of concrete deterioration conditions (Hammersley, 2008).

3.1.3 Acoustic Emission and Impact-Echo

This method is used to determine cracking in concrete. When the concrete cracks, it results in the release of stored strain energy, which generates mechanical wave pulses known as acoustic emissions, which are recorded by an array of sensors identifying the origin of the mechanical stress wave events (CRM1, 2015). It involves the monitoring of spontaneous ultrasonic signals produced

by internal changes in a structure which can be used to infer its condition. Cracks under cyclical load or propagating cracks can also be expected to produce emissions, hence it may be possible to use acoustic emissions to locate alkali-silica reaction cracks (Woodward, 1993).

Acoustic emission has been widely used to determine the location and rate of concrete cracking and to determine the location of the snapping of post-tensioned strands through triangularisation from multiple sensors (ACI 228.2R, 2008). This can be used as a short-term snap shot or as a permanent device on monitoring concrete structures. Acoustic emissions for bridges have been used in the past and one major problem encountered is related to signals from the background noise and the separation of multiple emission sources (Woodward, 1993).

The Impact-echo testing methods is a common non-destructive testing technique of concrete used to determine cracking in concrete. It was invented and diverse applications were developed through research groups such as Cornell University and the US National Bureau of Standards. A setup of the equipment is shown on figure 13 below. This method can be used to detect honeycombing, voids, debonding and delaminations in concrete structures. It functions through propagation of sound waves through concrete which are then reflected by internal flaws and external surfaces



Figure 13: Impact Echo demonstrations (CRM1-279, 2012)

3.1.4 Spectral Analysis of Surface Waves

The spectral analysis of surface waves is used to determine cracks in concrete through the use of the frequency based phase analysis. This method involves impacting the concrete surface to generate surface waves and monitor their propagation with at least two receivers. The two receivers monitor the surface motion and the signal analysis allows determination of wave speed as a function of wavelength. The slower velocities indicate weaker portions of concrete such as concrete cracks and faster velocities indicate stronger concrete (CRM1, 2015: 297).

Wave propagation characteristics are influenced by the severity of internal defects such as cracking, delaminations, voids and honeycombing. The properties of mechanical waves such as the amount of wave energy or wave velocity reflected from an interface between two distinct media are a function of the mass density of the solid material or the elastic properties. For instance, the velocity of these waves propagating through a material are controlled by the density of the material and elastic moduli i.e. Shear Modulus, Young's Modulus and the Poisson's ratio (Algernon, 2008).



Figure 14: Spectral Analysis of Surface Waves (CRM1, 2015)

The equipment required to do the test include wave detection sensors, wave source, data acquisition and analysis system. The wave source is typically provided by a local impact event such as the impact of a hammer on the surface of concrete or a steel sphere. The impactor size

controls the frequency content usually up to 15 kHz. Detectors of the waves are mounted sensors usually accelerometers or geophones. Surface motion caused by the wave propagation is measured by the sensors and they provide an analog voltage output which is collected over some time to give a time domain signal. Computer systems using commercially available platforms can be used to perform the analysis in either frequency or time domain and where needed, performs the inversion and matching process (Shayea, 1996). This method was used effectively in 1996 in Denmark to determine the cracking in a reinforced concrete deck of a railway bridge. The bridge was showing cracking due to ASR in a 1 m thick deck. The tests managed to detect horizontal cracks at mid depth over the entire span and the bridge was judged to be unsafe and was demolished (Sansalome, 1998).

3.1.5 Modal Analysis

This is another method of determining concrete cracks through forcibly vibrating the whole structure or use of large vibrators under normal loading while monitoring the frequencies of the structure consistently. The natural frequencies of the structures are determined and compared to the natural frequencies of the built-in models. Faults and damages on the structure result in the reduction of frequencies of the structure. The determination of cracks can be through Hilbert-Huang Transform method or through computer models (CRM1, 2015).

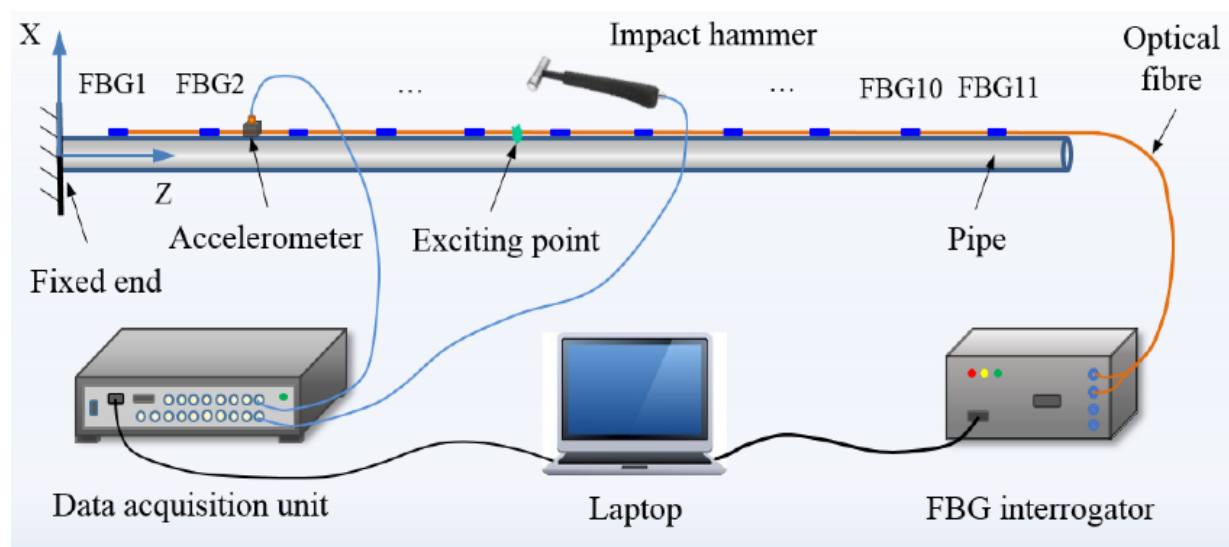


Figure 15: Demonstration of Modal Analysis (CRM1, 2015)

Several studies have been done to detect cracks in concrete beams using modal analysis. A crack in a beam element introduces local flexibility of which the dimensions depend upon a number of degrees of freedom considered which would have been expressed by a local flexibility matrix. The flexibility matrix of cracked elements has been concluded using an approach based linear fracture mechanics theory. Numerical studies are performed by considering a simply supported beam with single and multiple cracks at different locations with different crack depths (CRM1, 2015).

3.1.6 Petrographic Analysis

This method can be argued that it is not a crack detection technique but it is used for determining the cause of cracking. However, other sources such as the HB84 (2006) describes petrographic analysis as a method that can be used for detecting the possible causes of damages such as crack locations, concrete homogeneity, air content proportion of aggregates and the concrete ingredients. It can also detect the effects of ASR and it needs an experienced person to do the tests. The test can be used in conjunction with other physical or chemical analysis. Petrography can frequently determine the relative age of cracks and can identify secondary deposits of fractured surfaces which have an influence on repair methods. It can also identify other factors that may be related to cracking such as the relative paste volume, water to cement ratio and distribution of concrete components (HB84, 2006).

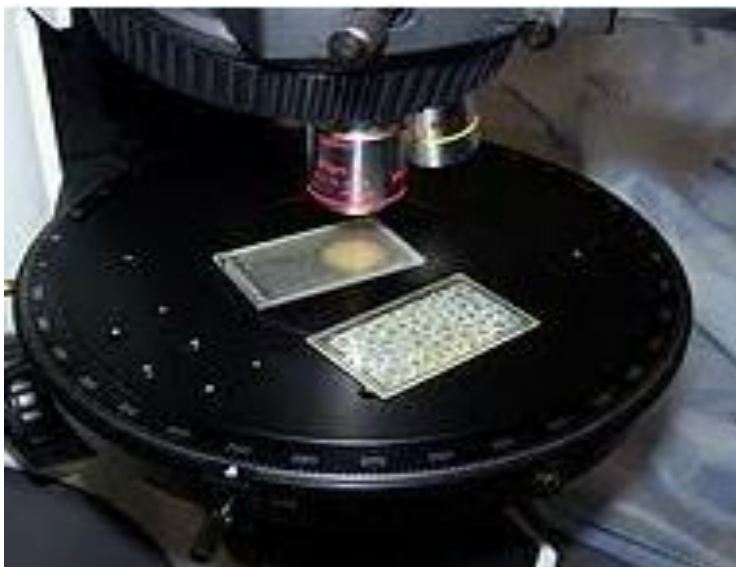


Figure 16: Demonstration of petrographic analysis (HB84, 2006)

3.1.7 Infrared Thermography

Infrared thermography is the science of measuring and mapping surface temperatures. Infrared thermography is used to detect geometrical defects in concrete specimens using thermal imaging. Concrete cracking is detected using the heat flow phenomenon in a conductive medium of specific geometry which is intended to model predetermined boundary conditions. The infrared camera detects the material discontinuities that influence the propagation of the heat flow. The infrared camera captures the surface temperature distribution which then determines the position of the crack, delamination or any other geometrical imperfection.

Infrared thermography has emerged as an effective, convenient and economical method to detect the propagation of cracks and determining their width with the substrate structure of the composite system. This method is used to detect crack growth internally within the concrete and is effective in situations where the temperature differential between the surfaces is too high. It has some important qualities such as being repeatable, economical and does not inconvenience the public (Inagaki, 1999).

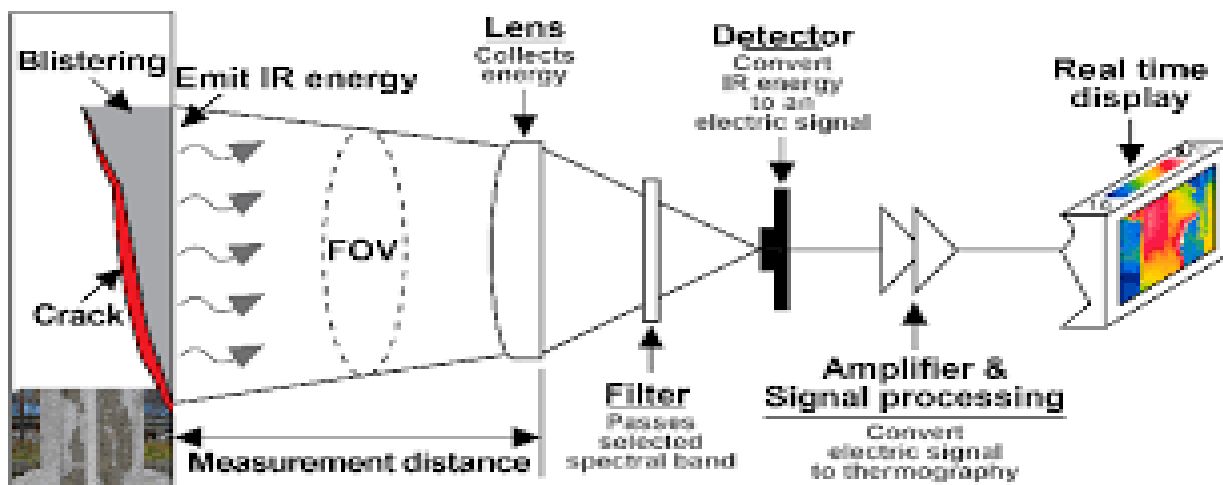


Figure 17: Demonstration of infrared thermography (Inagaki, 1999)

3.2 Destructive Methods (Core Samples)

Core samples can be taken from the concrete structure to investigate the characteristics of concrete and the possible causes of cracking in concrete. ASR is one of the most common causes of cracking in concrete and the following tests can be done to determine the possible effects of ASR;

- Petrographic examinations – these tests are performed on concrete aggregates to fully characterise the aggregate source and quantify the various rock and mineral constituents present. These can be done in accordance with the ASTM C295 guidelines.
- Mineral analysis i.e. X-ray diffraction and microscopic analysis - these are done to investigate the presence of minerals known to be detrimental to concrete. The interference or diffraction phenomenon of X-ray identifies the materials and is also capable of distinguishing between different crystalline forms of the same material (Arthur, 1979).

3.3 Conclusion

This chapter discussed destructive and non-destructive testing techniques used to determine the location and extent of cracking in concrete structures. These techniques are used to detect concrete crack location, width, depth, cover depths, strength predictions and reinforcement steel location. Non-destructive techniques were discussed and visual inspection is the most useful tool used to identify the cause and extent of cracking. Through visual inspections, one can relate crack widths and patterns to various causes of cracking. The main advantage of visual inspection is that it is cheap, requires less preparation and gives immediate results. Rust staining and leached salt deposits on the surface of concrete are signs of possible concrete cracking. Cracking can be identified in various forms depending on the depth and direction of cracking.

Ultrasonic pulse velocity test is used to detect cracking in concrete and most effectively crack depths. This method is generally able to determine the homogeneity and quality of concrete. Acoustic emission is another method widely used to determine the location and rate of concrete cracking. This method is not easy to use and obtain accurate results, experience and extensive preparation is required to obtain accurate results. However, there are other methods used to detect cracking in concrete such as spectral analysis of surface waves, modal analysis, petrographic analysis and infrared thermography. These methods are effective depending on how they are intended to be used. It is imperative to take cognisance of the fact that these methods require experience, preparation and the related costs are higher as compared to visual inspections. In most cases the results are not immediate, calculations and analysis of the data obtained is required.

Destructive testing is usually done through core drilling of samples that are taken to the laboratory for further investigations. Core drilling is usually done for further investigations and testing to

detect the characteristics of concrete such as cracking, strength, honey combing and voids. Some of the tests that can be conducted from the core drilled samples include compression testing, tensile testing, impact testing, aggregate reactivity tests, mineral analysis and petrographic examinations. Lastly, there are other techniques that assist in the identification of cracks in concrete structures such as drawings, construction and maintenance records.

CHAPTER 4: METHODS FOR CONCRETE CRACK REPAIR

This chapter presents various methods of concrete crack repair, repair materials and their applications. There are several methods that can be used to repair concrete cracks such as crack sealing, routing and sealing, near surface reinforcement, additional reinforcement, drilling and plugging, gravity filling, grouting, dry packing, crack arrest, polymer impregnation, overlay and surface treatments, crack filling, blanketing, stitching and external stressing. Cracks need urgent repair if they compromise the strength, stiffness or durability of the structure to an unacceptable level or if the function of the structure is seriously impaired (Trout, 1997).

The selection of a concrete crack repair method is dependent on the objectives the repair needs to achieve. Such objectives include among others, restoring or increasing stiffness, improving durability, increasing strength, improving the appearance of the concrete, providing water tightness, preventing the development of a corrosive environment and improving the functional performance of the concrete structure. Crack width has a considerable influence on the materials and methods to be applied for the repairs. Crack injection is the most common method used to repair narrow and wide cracks (Jaya, 2014).

Smith (2014) mentions that live cracks can be repaired through the use of flexible materials such as polysulphides or polyurethanes. Wider cracks can be repaired effectively using polymer modified cementitious grouts of acrylic, styrene-acrylic and styrene-butadiene. In some instances, polymer mortars may also be used to repair wide cracks. Dormant cracks can be repaired by enlarging the crack along the external face followed by filling or sealing with a joint sealer. Dormant cracks can be repaired using epoxies, polymer mortars, silicones, asphaltic materials, urethanes and polysulphides. Preparations should be done before application of repair materials. Dry or moist crack edges must be wetted thoroughly wherever a cementitious material is used (Smith, 2014).

4.1 Repair of Cracks in Concrete Structures

The objective of any repair should be to return the concrete structure to a satisfactory condition in terms of durability, structural adequacy and appearance at a cost commensurate with the benefit derived (Waddell, 1986). In order to execute the repairs efficiently, it is imperative to develop a

concrete crack repair program. A concrete crack repair program consists of six discrete steps namely diagnosis, prognosis, scheduling, selection of a repair method, preparation and application.

The Concrete Repair Program

Step 1: Diagnosis

Diagnosis starts with the identification and classification of the damage. It also provides a general evaluation of the extent of the distress and identifies the nature of failure. Preliminary investigations enable the examiner to determine the causes of the damage thereby allowing the development of a detailed survey such as;

- Performance of the onsite tests such as the pulse velocity test and resonant frequency tests
- Taking of samples for laboratory testing and examinations
- Document review pertaining to the structure. This includes information such as drawings (preliminary and as-built), construction and inspection reports, soil reports, laboratory analysis of materials and concrete, specifications and weather reports.
- Interviews with material suppliers, architects, engineers, contractors, the owner and workmen who were employed on the job (Waddell, 1986).

Step 2: Prognosis

After diagnosis, the next step is the process of prognosis which answers whether it is possible to execute the repairs? And is it worthwhile? There might be doubts that the repairs will last long and be permanent or the structure cannot be repaired at a reasonable cost. If the answer is positive, then scheduling can be done (Waddell, 1986).

Step 3: Scheduling

Scheduling involves the need to get the structure into a serviceable condition whilst considering priorities based on weather and work progress. Concrete crack repairs take on the characteristics similar to a major construction job that requires a detailed flow diagram to co-ordinate all aspects of material requirements, equipment, personnel and work assignments to fit seasonal weather conditions and service demands of the structure (Waddell, 1986).

Step 4: Selection of a repair method

Selection of a repair method depends on various factors such as the adaptability of a proposed method, the nature of distress, desired appearance, environment, cost, availability of materials and whether the repair is to be a permanent restoration or temporary expedient. Various repair methods shall be discussed and their application shall be discussed under the case studies to follow in Chapter 5.

Step 5: Preparation

Preparation of the concrete surface can be as simple as cleaning loose material or can be as complex as major preparation of dam beams, pilings and spillways beneath the water line. Cleaning the concrete surface can generally be accomplished using water, compressed air or water jets (Waddell, 1986).

Step 6: Application

This involves the proportioning of the fill material and selection of the equipment and tools necessary for the proper and expeditious completion of the repairs. Application and placing of the fill can be done in accordance with the construction practices. The materials should comply and adhere to the manufacturer's instructions. If the procedures are followed according to the repair guidelines and standards, the builder will be able to select an appropriate repair procedure and be able to apply it in a manner that will produce strong, durable and aesthetically satisfying repairs (Waddell, 1986).

4.2 Selecting a Repair Method

Before repairing a concrete crack, it is imperative to identify the cause of cracking or else there may be a risk of the crack reappearing if the cause is not addressed. A repair method to be used depends on various reasons such as;

- What is the main aim of repair? Is rehabilitation and retrofitting required to restore strength? Is it to restore the aesthetics of the structure? Does the methods require to address leakage problems?
- What is the magnitude and direction of predicted future movements?
- Are the cracks dormant or active?
- Whether or not sealing against pressure is required?

- The width or depth of the crack?
- Where are the cracks originating from? and can they be classified as patterns cracks or isolated defects? (ACI, 2008).

4.3 Concrete Crack Repair Methods and Guidelines

Concrete crack repairs are done according to different codes of concrete crack repair guidelines. However, it is imperative to appreciate the recent developments on concrete crack repair trends as well as the repair materials. There are several guidelines that can be used as reference to various concrete crack repair methods such as the, the American Concrete Institute (ACI 224.1R-07) – Causes, Evaluation and Repair of Cracks in Concrete Structures, the International Standard Organisation (ISO/TC 71/SC 7) – Maintenance and Repair of Concrete Structures, the Eurocode (1504-9) – Guideline to Protection and Repair of Concrete and the (HB 84–2006) - Guide to Concrete Repair and Protection which is a joint publication of Australian Concrete Repair Association (ACRA), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Standards Australia Limited 2006.

4.3.1 Crack Filling or Injection

Whiting (1992) describes this method of concrete crack repair as being economical and effective when repairing non-moving cracks in concrete walls, slabs, piers and columns. It is closely related to epoxy injection which is a known concrete crack repairs technique. This method has been in use since the 1940s and is capable of restoring the concrete to its pre-cracking condition without increasing its strength. This is one of the most common method used recently to repair cracking in concrete structures and can repair narrow cracks close to 0.05 mm (Gaul, 1993). The repair materials must constitute certain properties to ensure durability. Some of the properties include low viscosity, good workability, mix stability, aging resistance, compatibility of the substrate material and strength. Figure 18 below presents crack injection using epoxy resins (HB 84, 2006).



Figure 18: Crack injections using epoxy resins (Nomura, 2013)

ASTM C 881 Type 4 outlines the repair materials and techniques used for epoxy injections. Figure 19 below shows crack sealing using polyurethane products.



Figure 19: Crack sealing using polyurethane products (Aoyama, 2013)

Crack sealing is a common concrete crack repair methods used to repair fine pattern cracks or isolated defects using epoxy products or compounds. It does not work effectively when repairing

cracks subjected to hydrostatic pressure or when repairing active cracks. The repair steps include cleaning the cracking surface, widening of the concrete cracks and sealing the cracks using epoxy, polyurethane products etc. (HB 84, 2006).

It is important to determine the cause of cracking before executing any injections. On the other hand, other sources such as the ACI 503R (2008) describes the main steps used during epoxy injection as involving the creation of entry and venting ports along the crack, sealing the crack and injecting the epoxy under pressure. The epoxy bond to the concrete substrate is usually stronger than the concrete's tensile strength. Stratton and McCollum (1994) confirm this repair method to be working efficiently on cracks that are not active or where there are no water leakages or where cracks are not in large numbers.

4.3.2 Routing and Sealing

This method has been in use since the 1940s. This method involves enlarging the crack along its exposed surface, filling and sealing with a suitable joint sealant. Sealants can be asphaltic materials, urethanes, polymer mortars, epoxies, polysulphides and silicones. This method is closely related to crack sealing but the main difference is that it can be used to repair water leaking surfaces under hydrostatic pressure. Routing and sealing reduces the ability of moisture to reach the reinforcing steel. It is considered to be less easy to apply compared to epoxy injection and is considered effective on scenarios not involving structural cracking such as flat surfaces like floors and pavements (Trout, 1997). The main steps used during the repairs include preparation of a groove usually 6 mm to 25 mm, cleaning the groove using water, air or sand blasting then filling the groove using high viscosity rigid epoxy (ACI 224.1R-07, 2007).

4.3.3 Additional Reinforcement

Stratton (1980) mentions that the method of placing steel reinforcement bars using epoxy to bond them can be used to effectively repair concrete cracking on various structures and this was evident during the repairs of several bridge girders in the USA. It is recommended that the materials used on these repairs should be in line with the ASTM C881 type 4 (ACI 224.1R-07, 2007).

4.3.4 Gravity Filling

Rodler (1989) articulates that gravity filling is a concrete crack repair method which can be used to repair cracks as narrow as 0.03 mm to 2 mm through the use of low viscosity resins or monomers such as urethanes and epoxies. The steps used during the repairs include cleaning the concrete surface through sand, air and water blasting. The cleaned surface is left to dry and the resins are applied using brooms or rollers. The cracks should be cleaned thoroughly since the sealant performs better on clean surfaces without silt, contaminants or moisture (Fulton, 2009).

4.3.5 Cementitious Grouting

Grouting is used widely to repair concrete cracking ranging from narrow cracks such as 0.05mm to relatively wider cracks less than 2mm. It has been used to repair concrete structures since the 1950s and has been proved to be effective. Warner (2004) describes this method as effective in situations where cracks are in a straight line. It is also effective when repairing thick concrete walls and gravity dams using Portland cement grouting. Figure 20 below shows an example of a concrete crack repair using grouting method. It is recommended to repair concrete cracking showing signs of leakages such as water leaks (ACI 224.1R-07, 2007).



Figure 20: Portland cement grouting (Nojimu, 2007)

4.3.6 Dry Packing

This is a concrete crack repair method whereby a bond between the mortar and concrete is achieved through ramming and filling the holes which extend through walls or beams, refer to Figure 21 below. This method is used to repair dormant cracks through the use of slots usually 25 mm wide

and 25 mm deep. The steps involved in executing the repairs include, cleaning the slot, leaving the slot to dry, application of a bond coating and compaction of the blunt (Addis, 2009).



Figure 21: Repair of concrete cracks through dry packing (Kamamoto, 2007)

4.3.7 Crack Arrest

Concrete cracks emanate due to various reasons discussed above and as the cracks develop, arrest of the crack growth is important. When concrete cracking initiates, observations of the crack is carried and the crack growth should be arrested. Cracks can be arrested through drilling of stop holes at the tip of the crack. Drilling of stop holes is effective to stop crack growth because it reduces stress concentrations at the crack tip. This method of crack repair has been used since the 1940s when the discoveries were concluded by the U.S. Army Corps of Engineers in 1945 confirming concrete cracking in huge structures mainly due to surface cooling. Cracking can be minimised through reducing the spacing of reinforcement to suitable scales (ACI 224.1R-07, 2007).

4.3.8 Polymer Impregnation

Webster (1978) confirms polymer impregnation as a concrete crack repair method used in cases where the cracks contain moisture. This method is not suitable for the repair of fine cracks and the repairs are done using low viscosity monomers. The monomers work effectively during the repairs through polymerising into solid thereby filling the concrete cracks. The repair steps include drying

the fracture, encasing the crack with a band of metal that is watertight, soaking the fracture and impregnating with the monomer.

4.3.9 Overlay and Surface Treatments

This method is used to repair disintegrated and spalled concrete surfaces. It is also effective when repairing a large number of cracks where it is difficult to treat each crack independently or when repairing concrete cracks on flat surfaces such as structural slabs and pavements through the use of surface treatments such as bonded and un-bonded overlays. The overlays must be extensible in cases of addressing active cracks through sealing. It has been confirmed that this type of crack repair cannot permanently repair cracks unless designs are done to ensure design loads are handled through the use of sufficiently reinforced overlays (JMCE, 2014).

4.3.10 Blanketing

Blanketing is almost similar to routing and sealing method whereby a crack is repaired through enlarging it along its exposed surface, filling and sealing with a suitable joint sealant. This method of concrete crack repair is expensive and requires good workmanship. It is mostly used to repair both active and dormant cracks. Blanketing does have many applications and types, such as the mortar plugged joint, elastic sealant, type with crimped water bar and type where there is a mastic filled joint (WCSET, 2014). The steps used during repairs include cleaning the concrete surface, dimensioning and shaping the chase, chase preparation, chase filling and anchoring of the mortar cover. After executing the repairs, it is crucial to check the bond between the sealant and the concrete except in rare situations where the crimped water bar is used (Johnson, 1992).

4.3.11 Stitching

This concrete repair method is used in cases where there is need to gain tensile strength. It is closely related to near surface reinforcement considering the fact that both are applicable where there is need to gain tensile strength during the repairs. It is executed in a manner similar to the sewing of a cloth. The strengthening is accentuated by the restraints leading to the concrete cracking and the associated reactive conditions. Before the repairs are done, it is important to investigate the effects of strengthening the cracking areas since the repair effects of strengthening can be transferred to adjacent areas closer to the repaired area and this may lead to the migration of the problems to areas within the vicinity. This repair method is used to repair structural cracks

through the addition of tensile reinforcement at right angle to the cracking plane of the concrete. The main steps involved during the repairs using this method include cutting a slot across the crack, cleaning the cut slot and applying epoxy into the crack which acts as a bonding agent (ACI 224.1R-07, 2007).

It is crucial to realise the fact that stitching itself does not seal the cracks implying that cracks must be sealed to avoid problems such as corrosion especially in cases where there are problems of water leaks (Trout, 1997).

4.3.12 External Stressing

The repair of concrete cracking through crack arrest is a phenomenon whereby the tensile stresses in the concrete crack are arrested through the removal of predominant cracks or through the introduction of compressive forces that are adequate to overcome the tension forces. Pre-stressed rods or wires can be used to induce the compressive forces. External stressing is almost similar to stitching and the major difference is that the stitches are tensioned. Wedging can be used to induce the compressive forces during external stressing. This can be achieved through the use of wedges to open up the cracks then filling them using mortar by jacking or grouting (JMCE, 2014).

4.4 Chapter Summary

Before repairing a concrete crack, it is imperative to identify the cause of cracking or else there may be a risk of the crack reappearing if the cause is not addressed. Various reasons attracting a suitable crack repair methods have been discussed and they should be applied in line with various standards and guidelines of concrete crack repairs. Crack sealing or injection is the most common used concrete crack repair method. Repair methods are depended on various factors such as the cause of the crack, crack width and depth.

Crack sealing or injection is a common concrete crack repair methods used to repair fine pattern cracks, isolated defects and active cracks. This method is limited to repairs that are not subjected to hydrostatic pressure. Grouting is another method widely used to repair cracks which appear in a straight line. It can be used to repair narrow cracks and relatively wider cracks less than 2mm. Crack injection, sealing, filling, routing and grouting usually use the same type of materials during

the repairs and more dependent on factors such as the cause of the crack, width of the crack and climatic conditions.

Blanketing is mostly used to repair both active and dormant cracks. It is an expensive concrete crack repair method and requires good workmanship. Overlay and surface treatments is a method used to repair disintegrated and spalled concrete surfaces. It is also effective when repairing a large number of cracks where it is difficult to treat each crack independently. Materials used for blanketing and overlays are usually the same and their application is mainly dependent on the nature and cause of the cracks and in some instances the weather conditions.

Dry packing as well as drilling and plugging are mostly used to repair dormant cracks. Cementious mortars are used for dry packing repairs. There are other types of concrete crack repairs used in construction even-though they are not commonly used such as near surface reinforcement, additional reinforcement, gravity filling, crack arrest, polymer impregnation and external stressing. Near surface reinforcement, additional reinforcement and external stressing are used on instances where there is need to address strength requirements during the repairs. Crack arrest is more of a preventative measure to concrete cracking whilst polymer impregnation is mostly used in cases where the cracks contain moisture.

CHAPTER 5: CONCRETE CRACK REPAIR CASE STUDIES

This chapter presents an in-depth analysis of various concrete crack repair case studies. The aim of reviewing these case studies is to demonstrate the application of the concrete crack repair techniques (discussed in Chapter 4) to various structures in the real world, which are experiencing signs of deterioration due to concrete cracking. Both recent and older case studies shall be discussed to track the developments that have been established in repair technologies. These case studies shall demonstrate the recent developments in techniques used to determine concrete cracking, concrete crack repair methods as well as the associated repair materials. Furthermore, the effectiveness of various repair methods and their performance under various condition shall also be discussed.

Due to difficulties experienced in gathering the case studies from existing literature, this dissertation shall present case studies from different countries around the world. The case studies to be discussed are a sample obtained from available literature and shall give an indicative view in terms of concrete crack repair methods and materials.

5.1 Concrete Crack Repair Case Studies due to Non-Structural Cracking

5.1.1 Concrete Crack Repair Due to ASR Damage on Transport Infrastructure in USA

This section shall present a sample of case studies which were done across the USA that evaluated concrete crack repair methods to ASR-affected transport infrastructure as part of the United States Department of Transport Federal Highway Administration Concrete Crack Repair Programme. These case studies shall venture into the evaluation of new technologies for the mitigation of reaction and cracking in existing ASR-affected concrete structures (Michael et.al, 2013).

5.1.1.1 Data Collection and Investigation Techniques

These structures were visited among different sites to determine the initial condition survey mainly by visual inspections. After the investigations which included petrographic examinations, the results did indicate the presence of alkali-silica reactions. In some cases, cores were extracted for the stiffness damage testing and the measure of alkali-silica reaction damages was provided using the damage rating index (Michael et.al, 2013).

Following the petrographic examinations and the initial condition survey, the structures were selected for various treatments. The selected sections were instrumented to permit measurements such as the cracking index (CI), length change (expansion) and (RH) the relative humidity. After concluding the length, CI and RH parameters, different treatments were applied such as coatings, sealing and lithium treatment. Several periodic visits were conducted to monitor the changes in CI, RH and length. In most cases, visits would be conducted twice a year and in other instances once a year (Michael et.al, 2013). Length measurements were done using a strain gauge called the DEMEC type as shown on Figure 22 below.



Figure 22: DEMEC type strain gauge measuring length changes (Michael et.al, 2013)



Figure 23: Relative humidity probes inserted into the holes (Michael et.al, 2013)

The Vaisala HM44 Concrete Humidity Measurement System was used to measure internal humidity and temperature as indicated on Figure 23 above (Michael et.al, 2013).

5.1.1.2 Field Sites under Investigations

The field sites under investigations included the Alabama site, Delaware site, Massachusetts site, Texas Houston site and Maine Site. The Alabama site showed ASR-affected concrete arches at the Bibb Graves Bridge in Wetumpka as indicated on Figure 24 below. Technologies evaluated included systems such as the hydrophobic sealers i.e. the water based silanes and epoxy coatings. Built in 1931, the Bibb Grave Bridge comprises of seven parabolic arches.



Figure 24: Bibb Grave Bridge north face (Michael et.al, 2013)

The 5th span was suspected to be showing signs of ASR defects (Figure 25 below) and visits were done in December 2005. Petrographic evaluation of cores confirmed that ASR was caused by the quartzite and chert coarse aggregates resulting in the damage of concrete. The high degree of ASR damages was also indicated by the (Damage Rating Index) DRI values which ranged between 1430

and 1081. Many cracks from the deteriorated arch were found to be filled with large amounts of ettringites (Michael et.al, 2013).



Figure 25: Cracking on top and underside of archway supporting the 5th span (Michael et.al, 2013)

The Delaware site showed ASR-affected concrete pavement near Georgetown. In June 2009, ASR was concluded to be the cause of distress for a 120.8 km section of concrete pavement along the US 113 in Georgetown. Petrographic examinations indicated the extent of damage in concrete being very low to moderate showing heavy signs of ASR both in the fine chert aggregates and coarse gneiss, whilst the DRI values ranged between 65 and 395 (Michael et.al, 2013).

The Massachusetts site had ASR-affected concrete highway barrier walls near Leominster as indicated on Figure 26 below. Petrographic examinations were conducted and they confirmed the presence of ASR and showed signs of map cracking on the barrier walls. The main cause was identified as being the greywacke in the coarse aggregate (Michael et.al, 2013). In 2005, a portion of median concrete barrier wall on State Route 2 near Leominster was treated using a variety of products.

The Texas Houston site had ASR-affected bridge columns. Around 2006, several bridge columns were identified as suffering from ASR-induced cracking. The FHWA Lithium Technology Research Program conducted the initial evaluation and treatment at the site and later the treatment and monitoring were conducted by the FHWA ASR Development and Deployment Programme. After the monitoring of the bridge columns for a period, cores were drilled and taken for petrographic examinations and they confirmed ASR whilst the residual expansion tests showed

the possibility of future expansions. Minor ASR was also found in some of the structural components which had used recycled concrete aggregate (RCA) (Michael et.al, 2013).



Figure 26: Visual contrast between control section on the left and a section treated with water based saline on the right at Massachusetts site (Michael et.al, 2013)



Figure 27: Typical ASR damage on barrier walls treated with elastomeric coating at Massachusetts site (Michael et.al, 2013)

The Maine site showed ASR affected bridge wing walls, abutments and columns in Bangor/Brewer. The symptoms of ASR related distress were noticed in April 2009 on a number of bridge structures along the interstate 395 near Bangor. The symptoms were identified in the wing walls, abutments and columns. A total of 24 cores were drilled i.e. 100mm in diameter and they were extracted from six bridges for further evaluation using petrographic analysis. The tests revealed the presence of ASR and confirmed that concrete in all the six bridges contained reactive argillite/greywacke in the coarse aggregate and the DRI values ranged from 133 to 188 indicating a low to severe degree of ASR damage.

5.1.1.3 Repair Methods and Materials

ASR repairs at the Alabama field site were done using the 40% water based silane and epoxy coat hydrophobic sealers. The treatments were done in November 2010 and monitoring was done over a two and a half years period to determine the effectiveness of the treatments. Monitoring was done on the treated sections as well as the untreated sections and it was concluded that the treatments had little impact on the rate of expansion and relative humidity. The repairs to the Alabama site using 40% water based silane and epoxy coating could not produce effective results. Repairs through coating were ineffective due to the inability of water to escape within the concrete thereby promoting the continuation of ASR

ASR affected pavements at the Delaware site were treated in June 2009 using lithium nitrate 305 solution and monitoring was done over a two year period on length changes, relative humidity and cracking index. In 2011, cores were drilled to investigate the penetration of lithium and the results proved that the use of lithium nitrate products was not an effective ASR mitigation technique for this project. At the same site in 2010, 2011, 2012 and 2013 there were treatments done to the bridge structures using 40% water based silane, 100% silane and an elastomeric coating.

Prior to the treatments, measurements were done to determine length changes, relative humidity, temperature and cracking index. After a three year period of treatments and measurements, the results showed the treatments as not being effective. This was believed to be a result of the moisture supply from the backside of the wing walls and abutments that had masked any beneficial effect of applying the coatings or sealers on the visible above grade surfaces.

The Massachusetts sites concrete barrier walls showing significant signs of deterioration due to ASR were treated using 20% silane in water, 20% silane in isopropyl alcohol, 40% silane in isopropyl alcohol, lithium silicate based penetrating sealer, topical lithium application and elastomeric coating. The same sections were treated and some were left to act as controls and measurements such as length changes, humidity, temperature and cracking index were monitored over a 5 year period. The results indicated that the treated sections showed less expansions and visible cracking as compared to untreated sections.

Repairs to the Texas Houston bridge columns were done using 40% silane in isopropyl alcohol, vacuum impregnation with lithium, sodium silicate applied via vacuum impregnation, electrochemical lithium treatment and silane siloxane blend applied via vacuum impregnation. Silane or silane-siloxane applied by vacuum exhibited lower humidity values whilst the sodium silicate and lithium nitrate exhibited humidity values same as the untreated columns. Several columns at the Maine site were treated using 40% water based silane, 100% silane, elastomeric coating and only one column was wrapped with four layers of fiber reinforced polymer.

5.1.2 ASR Affected Two Storey Building in California (USA)

5.1.2.1 Introduction

This building is a two storey located in California. The building was constructed in 1960 and a maintenance programme was developed to extend its useful life. The structure is part of a propellant manufacturing facility that houses equipment for grinding ammonium perchlorate. During the 17 years of its use, cracks developed on the floor slabs, floor beams and walls. The cause of cracking was mainly the reaction between the aggregate and alkali in cement as well as the expansions due to reinforcement corrosion. Concrete crack repair methods used for the repairs included epoxy injection and crack sealing through pressure injection of epoxy adhesives. Concrete cores were extracted, tested and examined to determine the possible cause of concrete cracking. Some of the tests conducted were as follows;

- Microscopic analysis and aggregate reactivity test
- Standard compression test
- X-ray diffractogram

- Pulse velocity, fundamental frequencies, specific gravity, percent absorption and percent voids.

Photographic records of crack growth were also studied and they have been kept since 1973 (Arthur H, 1979).

5.1.2.2 Condition of the Building

Cracks had developed in the floor slabs, floor beams and walls. Major cracks were located in the second-floor walls and first-floor beams especially in slab areas around the grinder floor opening. The concrete aggregate was the locally available river run non-glaciated sand. The cement used contained sodium oxide with a maximum of 0.6 percent. The history of the repairs indicates that the first-floor was repaired around 1974 using a pressurized epoxy injection applied into the cracks within the 254 mm subgrade walls. The repair methods involved the sealing of crack face whilst ensuring the epoxy ports are spaced at a distance equal to the thickness of the injected concrete. Concrete cores which were drilled indicated sufficient compressive strength (Arthur H, 1979).

5.1.2.3 Building Investigation Programme

Signs of distress became evident during 1973 leading to investigations. Various investigations were conducted including photographing of the developing cracks, visual inspections and testing of concrete cores. Photographs indicating continuous crack development were taken in December 1974, August and April 1975, October and August 1977. Visual inspections were conducted regularly to observe and record changing conditions of the building. Cores were drilled from the first and second-floor walls and the first-floor beams. Some were also drilled from the first and second-floor slabs and these investigations determined the general condition of the concrete and the possible causes of concrete cracking (Arthur H, 1979).

Several tests were conducted such as aggregate reactivity, mineral analysis such as X-ray diffraction and microscopic analysis, sonic tests such as pulse velocities and fundamental frequencies, standard compression tests and specific gravity, percentage of voids and percentage absorption. Pulse velocity test results indicated the condition of the concrete being questionable to good. Test results for the fundamental frequency were unusually high and indicated a uniformity of concrete on all cores tested. The aggregates were slightly alkali silica reactive and the concrete

was questionable to good quality. The compressive strength was satisfactory averaging 24.1 MPa and the void ratio as well as the percent absorption were relatively high.

5.1.2.4 Building Rehabilitation Program

The results of the building investigation indicated that its useful life could be successfully extended and a rehabilitation program was developed and implemented. The main aspects considered during the rehabilitation program included;

- Pressure injection of epoxy adhesives into concrete cracks and sealing the surface of concrete with epoxy to stop moisture intrusion
- Periodic structural inspection
- Installation of structural steel beams to eliminate possible structural distress in the grinder room (Arthur H, 1979).

Weaknesses of the rehabilitation programme used

The rehabilitation programme only used one method of repair which is the pressure injection of the adhesive. Furthermore, there was no scientific measurements or demonstrations done to check if the pressure injection of the epoxy adhesive performs as required considering the causes of concrete cracking. There is a possibility that the ammonium perchlorate stored in the structure reacts with the epoxy adhesive thereby weakening the adhesive characteristics of the epoxy resulting in the failure of repairs.

It would be advisable and of value to consider the use of a variety of concrete crack repair materials so as to establish performance for each material and conclude the best practice that can be applied. As part of the repair programme, it is imperative and recommended to test the performance of repair materials and methods used. Some of the tests that can be done include monitoring the length change measurements, relative humidity and cracking index. This ultimately gives an indication on whether the applied method of repair and materials are performing as required to avoid future expansions and development of further cracking.

5.1.3 ASR Damaged Structures in Hokuriku District in Japan

5.1.3.1 Introduction

Many concrete structures suffered damages due to ASR in the 1980s in Hokuriku district, Japan. Aggregates used were the river sand, river gravel and in other cases some volcanic rock types such as rhyolite, andesite and tuff. Investigations were done to evaluate the residual expansivity due to ASR in accordance with the ASTM C1260 method. ASR deterioration matched the residual expansivity of the cores and most of the cores had expanded by this method and concluded to be having residual expansivity. Surface coatings and crack injections were some of the methods applied to repair the concrete structures since 1988. A few years later after the repairs, cracks and blisters almost occurred on the surface coating being evident that the ASR deterioration and the residual expansivity of the cores did not match. Since 2001, the concrete crack repair techniques used include surface coatings, crack injections and concrete jacketing (Nomura et.al, 2012).

As a result of this discrepancy over the last 15 years, accelerated ASR expansion tests were conducted in accordance with the ASTM C1260 method that supply alkalis from external sources to evaluate the residual expansivity of concrete cores. The ASR deterioration matched the residual expansivity of the cores and most of the cores had expanded by this method and concluded to be having residual expansivity. Since 2001, the common methods which were applied included surface coating, crack injection, concrete jacketing for injury prevention to third parties as a result of concrete exfoliation, section repairs and corrosion inhibition of the reinforcement bars. This study shall examine the applicability of these latest repair methods considering the petrological composition of aggregates, alkali content of concrete and comparing the residual expansivity of the structures according to the ASTM C1260 method before repair and 10 years afterwards (Nomura, M., et.al, 2012).

In Toyama, repairs were done using three types of continuous fiber sheet working as surface coatings namely epoxy, acrylic and urethane types as well as the surface treatments with sodium silicate polymer cement for section repairs with concrete jacketing and shotcrete. Urethane type of continuous fiber sheet performed well in cases of high ASR potential whilst the acrylic fiber sheeting coating proved to be effective in cases of low ASR potential.



Figure 28: Deterioration due to ASR (Nomura, M., et.al, 2012)

However, after a certain period, deterioration reoccurred in cases of concrete jacketing, epoxy surface coating and section repair with polymer cement. As years progressed, it was discovered that ASR had continued following the repairs. From the observations made 21 days before the repairs and 10 years after the repairs, the possibility of re-damage was higher when patch repair was applied as compared to crack injection especially in areas with large number of cracks. The methods and materials used for concrete crack repairs are more depended on the results of expansivity. Ten years after the repairs, ASR was not trending towards convergence in some of the repaired structures and it was concluded that concrete jacketing is not effective for ASR suppression.

5.1.3.2 Survey Results of Surface Treatment Repair Method

During 1995, the structure shown on Figure 28 above was repaired through surface treatment using sodium silicate. A few years later, cracks had occurred as indicated on Figure 29 below.



Figure 29: Cracks occurred on the repaired structure (Nomura et.al, 2012)

Further repairs were done and the repair material consisted of mainly magnesium compounds. The characteristics would enable suppression of ASR progress by densifying the concrete while penetrating into the concrete depths and promoting the formation of new cement crystals that grow in the capillary zone, micro-cracks and transition zone (Nomura et.al, 2012).

5.1.3.3 Survey Results of Patch Repair Methods

Patch repairs using polymer cement were executed after the removal of the concrete cover. The polymer mortars used contained about 1.5 to 2% short fibers in order to avoid cracking of the material. It was discovered that ASR continued after the repairs and cracks with a width less than 0.2 mm had reoccurred as indicated on Figure 30 below (Nomura et.al, 2012).



Figure 30: Cracks occurred on the patch repair in structure F (Nomura, et.al, 2012)

5.1.3.4 Concrete Jacketing

After the removal of the concrete cover, concrete jacketing was done in some structures after placing the reinforcement steel. Crack prevention was achieved through the use of short fibers in the proportion of 0.5% of cement, expansive agents and superplasticiser added as an admixture (Nomura et.al, 2012: 16).



Figure 31: Cracks occurred on the patch repair structure H (Nomura, et.al, 2012)

5.1.4 ASR-Damaged Gravity Dam in India

The dam located in India showed significant signs of ASR cracking by visual observations. The gravity dam was built in 1962 and significant signs of cracking were evident at the intake section of the dam. The penstock gallery structure located at the toe of the concrete gravity dam comprised of six blocks of overflow sections. The blocks were interconnected with beams running parallel to the axis of the dam. Instrumental analysis confirmed the occurrence of alkali silica reactions after almost 25 years of service. The deleterious reactions were believed to be a result of the granite reactions and alkali feldspars used with elements of moderate to high alkali content. The structural stability of the dam was not endangered but the serviceability was affected.

The research and findings were done by the Irrigation Department, Government of Uttar Pradesh, Indian (IDGUPI, 1995). Investigations of the concrete samples using hand magnifying glasses revealed some occurrence of typical white deposits associated with ASR. In most instances, the broken surface of the concrete would be observed as a thin white rim around the aggregate and in few cases a uniform dark band in the peripheral zone of the aggregate would be observed. The Scan Electron Microscope (SEM) was used and aggregates were found to contain a reaction rim altering their borders and sometimes with micro-cracks. The reactive aggregates were further investigated using petrographic examinations and the results indicated the presents of biotites granite, muscovite granite and mica granite (IDGUPI, 1995).

5.1.4.1 The Repairs

The repairs were initially done in the late 1980s. The cracks at the upstream faces were sealed using epoxy grout followed by epoxy painting to minimise the ingress of water. Chemical grouting was done on the mass of the structure to effectively fill up the cracks and restoring the monolithic behavior. As years progressed, some of the repaired sections started to show signs of cracking reappearing. Consultation was done through the American Concrete Institute and other material suppliers to investigate why cracks were reappearing. Recommendations were provided to redo the repairs using the latest repair materials approved according to repair standards (IDGUPI, 1995).

Remedial repairs were done since the late 90s using various repair products. The repairs were done considering the present state of distress as well as the possible aggravation in future. The remedial measures were directed towards minimising the rate of reaction thereby restoring the structural

integrity and accommodating possible future expansions of the concrete. The American Concrete Institute, Detroit, Michigan was consulted to assist with solutions to the repair techniques. The repairs were done using different materials depending on the nature and causes of the cracks. All crack repairs were done using the XPEX concentrate, SealBoss 2400 and the repair mortars. The repairs at the upstream face were executed using a XYPEX concentrate since water proofing was required as part of the repairs. Sealing was done using the SealBoss 2400 in areas with large number of fine cracks concentrated in one area. The SealBoss 2400 performs well when repairing concrete cracks on water retaining structures. The product gives excellent penetrating properties similar to plain water and can easily flow well into the finest cracks and fissures thereby sealing the hairline cracks.

The repair mortar used to seal the cracks was applied as a cementitious slurry to the pre-saturated surface of the existing or newly constructed above and below grade structures. This repair mortar is effective for the repair of water retaining structures such as reservoirs, dams, swimming pools and underground vaults due to the active chemicals which are capable of diffusing into the substrate and react with moisture and the constituent of the hardened concrete to cause a catalytic reaction. The reaction generates a non-soluble crystalline formation through the pores and capillary tracts of the concrete and preventing the penetration of water and other liquids from any direction even under high hydrostatic pressure.

The concentrate is applied using a semi-stiff nylon bristle brush, push broom or specialised spray equipment for large horizontal surfaces. Surface preparation must be done through cleaning the concrete surface from dirt, film, paint coating and other foreign matter. The concrete surface must then be lightly water blasted, sand blasted and etched with muriatic acid. The surface must also have an open capillary system to provide tooth and suction for the treatment. The repair procedure is also different when repairing cracks wider than 0.4mm or for actively leaking cracks. Prior to the application of the coating, chipping of the cracks must be done for faulty construction joints and other cracked areas to a width of 25 mm and depth of 37 mm. The concentrate must not be applied under rainy conditions or when the temperature is less than 4 °C. The repairs using SealBoss 2400 was done through curtain injection or bladder injection or through gel injection directly into porous structures. The injections were done to achieve a water proofing barrier. It is

recommended to inject the SealBoss 2400 from bottom to top beginning at the lowest drill hole. An injection machine called the SealBoss IP2C is usually used for the injection

5.1.5 Repairs at Buttermarket Shopping Centre due to Shrinkage Cracking

The Buttermarket Shopping Centre multi-storey car park is one of the busiest commercial areas in Ipswich, UK, which suffered concrete cracking due to shrinkage cracking as shown in Figure 32 below. The development of the drying concrete shrinkage cracking facilitated the penetration of chlorides, which is a common problem for structures where road traffic is prevalent. As the cracking continued to develop, the building clients required the concrete repairs to be done immediately since the cracking was compromising their safety. The penetration of the chlorides into the concrete surface led to the development of steel reinforcement corrosion. Repair solutions were needed to address the shrinkage cracks as well as eliminating the steel corrosion (Sika, 2016).

5.1.5.1 The Repairs

Dry packing method was used to repair concrete cracking due to drying shrinkage as shown on Figure 32 below. The phenomenon of dry packing can be described as the hand placement of a low water content mortar followed by ramming or tamping of the mortar into place thereby producing intimate contact between the mortar and the existing concrete. The client requested the execution of the repairs within shortest possible time in order to return the car park to full operation, implying that the repair products were supposed to work within the tight timelines. Concrete crack repairs started in September 2016 using the Sika long term, fast curing concrete repair and corrosion management system.

The Sika's repair and management system was essential due the rapid setting characteristics of the products. The Sika Rapid Repair Mortar which is a one component, rapid curing cementitious repair mortar was used to repair all the shrinkage cracking on the surface of the concrete parking floors. The Sika FerroGard-903+ was used to eliminate the risk of reinforcement steel corrosion. This product is a multi-functional liquid corrosion inhibitor and was applied to the chloride contaminated decks. These products have been tested and they do comply with the requirements of Class R4 of BS EN 1504-3. In order to restore the smooth finish of the parking floors, the Sika floor –EB 24 surface resin based finish was applied as shown on Figure 33 below. The repair works were completed within a two months period.



Figure 32: Drying shrinkage cracks within the parking structure (Sika, 2016)



Figure 33: Shrinkage crack repair using dry packing (Sika, 2016)

The Butterworth shopping Centre multi-storey car park case study presented the latest repairs done to a car park showing signs of deterioration due to drying shrinkage and corrosion of steel reinforcement bars. However, the case study could not present in detail the investigations conducted in order to conclude that the cracks discussed were due to shrinkage. It can be argued that the same type of cracks could be due to other factors such as foundation movements and so on. It is imperative to fully understand the causes of cracking before executing the repairs considering the high risk and possibility of the cracks reoccurring.

The repair materials used were deemed compliant to the requirements of Class R4 of BS EN 1504-3. It can further be argued that even though the repair materials are compliant, they may not be the possible best required for the repairs of this nature considering the use of the structure and the climatic conditions of the area. It is recommended to apply a method that has been tested and proved effective to the repairs after considerations to the causes and nature of cracks. The products used for the repairs were the Sika products and these produced a desired finish. These products were recommended to be suitable where aesthetic requirements are needed and on instances where repairs should be complete over a short period of time.

5.1.6 Concrete Crack Repairs in Cheshire due to Thermal Effects

One of the world's renowned centre for radio astronomy, the Jodrell Bank Observatory in Cheshire experienced concrete cracking due to thermal effects at the Mark 11 telescope. The concrete frame was constructed 50 years ago and concrete frame stands are 25 m high supporting the 25 x 38 m diameter telescope dish. The other parts of the concrete portions close to the telescopic dish could not be easily accessed using a fixed scaffolding since the telescope rotates any time of the day or night (Sika, 2016).

5.1.6.1 Investigations

Investigations proved that external seasonal temperature variations caused cracking in the concrete structure. Thicker sections of the concrete supporting the Mark 11 telescope allowed internal temperatures to drop and rise slowly while the surface cools rapidly due to ambient temperatures. The surface contraction due to the cooling was restrained by the hotter interior concrete that doesn't contract as rapidly as the surface and resultant restraints created tensile stresses that cracked the concrete surfaces due to this uncontrolled temperature difference across the concrete

cross section. Thermal cracking occurs at an early stage and there are rare cases where thermal cracking can occur when the concrete surfaces are rapidly exposed to extreme temperatures (Sika, 2016).

5.1.6.2 Recommended Repair Method

The cherry pickers allowed easy access to some of the inaccessible concrete portions closer to the rotating telescopic dish. Dry packing was used to repair concrete cracking. Two components of Sika MonoTop system were used to repair the cracking due to thermal changes and comprised of a bonding primer and a reinforcement coating followed by a concrete repair and reprofiling mortar. To avoid corrosion effects to the repaired cracks, the Sika Ferrogard-903 was used thereby extending the maintenance and service life cycle of the concrete structure. The application of the Sika Ferrogard-903 penetrates the concrete and provide a layer around the steel reinforcement bars. Two coats of Sikagard-675W ElastoColor, a protective and decorative anti-carbonation coating was used to offer further protection and aesthetics to the structure (Sika, 2016).

Flexible repair materials are recommended when executing repairs of this nature due to thermal variations. The elastic properties of such repair materials allow for the contractions and expansions which occur during heating and cooling. Failure to select a proper material may result in cracking or delaminations especially if hard inflexible materials are applied. Length change measurements in concrete can be measured during extreme heating and cooling and the cracking index determined during such extreme variations. Various types of materials can be tested during such conditions and their performance determined (Sika, 2016).



Figure 34: Mark 11 telescope supported by a concrete structure in Cheshire (Sika, 2016)

5.2 Structural Cracking Case Studies

5.2.1 Case Study – High Rise Building (USA)

This building is a double storey structure in USA, North Carolina constructed in 1972. During the early 1990s, the structure showed significant signs of structural cracking in structural elements such as concrete vertical walls, beams, columns (Figure 35 below) and foundation walls. Investigations were done to the causes of the cracking and they were related to the poor soil bearing capacity and swollen soil (Trout, 2006).

The development of these cracks led to the penetration of deleterious substances resulting in the development of steel reinforcement corrosion. The steel reinforcement bars used were predominantly the 16 mm diameter bars and the concrete strength being 30 MPa with a cover to reinforcement of 25 mm. However, the investigations were not conclusive and it was believed that there are other factors which could have facilitated the development of cracks such as overloading, incorrect design and poor construction workmanship. The cracks needed repairs as they created the seepage of water from the underground to the basement area and would also allow further penetration of deleterious substances to the steel reinforcement bars resulting in corrosion (Trout, 2006). Repairs were done starting from 1999 to 2005 whilst close monitoring was done on the effectiveness of the repairs.



Figure 35: Structural cracks starting to appear due to accidental loading (Trout, 2006)

5.2.1.1 Investigations

Investigations were carried on the four faces of the building. It was concluded that the initial causes of concrete cracking was due to the heaving effects of the soil which affected the foundations resulting in the development of structural cracks. However, there was need for further investigation into the effects and amounts of deleterious substances which had penetrated the concrete. The carbonation depths varied between 10 to 15 mm on different faces of the building. The chlorides ranged between 0.1 to 0.15% chlorides by the weight of cement. Cover meter readings were used to determine the cover to reinforcement on all the four faces of the building. The results are shown on the table below (Trout, 2006).

Table 1 below indicates some variations from face to face of the structure showing that up to 10% of the area of the façade or 10% of the reinforcement may be in carbonated concrete due to the low cover. As a result, carbonation was identified as a culprit to the causes of spalling and corrosion of reinforcement.

Table 1: Results from cover meter readings on high rise building

Description	North	South	East	West
Average carbonation depth (mm)	12	14	10	15
Number of tests	40	45	55	40
Average cover (mm)	17	20	18	21
Number of tests with less than average carbonation depth	5	5	5	4
Rebar cover less than the average carbonation (%)	12.5	11	9	10

5.2.1.2 Specifications for Repair

The recommended repair techniques and materials should be able to address the structural cracking problems as well as the corrosion induced cracking. The Flexi-Span foundation crack repair system was recommended to repair wall cracks and foundation cracks. The product is efficient in cases where there is need to address the penetration of moisture through the crack. It was agreed to find all the reinforcement steel with cover less than the average carbonation range and patch

specifications included the crack injection on a number of small cracks to try and ensure that no adequate path for further carbonation exists through the concrete cracks. High-quality anti-carbonation coating was specified to avoid ingress of carbonation and further infection of reinforcing steel bars and to upgrade the appearance of the structure (Trout, 2006).

5.2.1.3 The Repair

The repairs were done using quality-controlled methods through the use of experienced qualified specialists. They investigated the entire façade with cover meters while marking with white chalk all the areas with structural cracks and where reinforcement cover was less than the average of the carbonation depth. Approximately 8% of the steel reinforcement bars were found to be in the low cover range and the results were reasonably accurate.

All the repaired areas were marked on the drawings. Areas with structural cracks were repaired using the polyurethane sealant. The cracks were cleaned through sand blasting followed by pressure injection of a high viscosity polyurethane polymer into the cracks. This product penetrated deep into the crack forming a flexible and durable seal.

Some areas had suffered from concrete cracking and spalling due to the reinforcement steel corrosion. Small scale jack hammers were used to expose the reinforcement bars to a minimum depth of 20mm. These areas were cleaned, reinforcement was coated, the substrate was re-wetted and the bond coatings were applied before the application of the polymer modified repair mortar. Low epoxy resins were used to inject some of the concrete cracks. Lastly, the façade was washed at high pressure before applying the protective coating (Trout, 2006).

5.3 Case Studies Analysis

Case studies presented discussed concrete crack repairs due to structural and non-structural cracking. The analysis below is based on the case studies presented above. It should be noted that if more case studies and information is gathered, the analysis and finding below may not be the same considering comparisons and other details from literature which may be available on concrete crack repairs.

5.3.1 Concrete Crack Repairs due to ASR effects

Concrete crack repairs due to ASR effects were discussed on various case studies above and some of the repairs were effective and some not depending on the methods of application used or the repair materials. Silane based products can be used to treat ASR affected concrete structures. Some of the lessons learnt from the application of silane based products are as follows;

- The application of silane-based products was found to significantly reduce expansion and visible cracking especially on the road concrete barrier walls at the Massachusetts site and this was evident at Leominster, MA. During the course of the seven years field monitoring program, it was found that barrier walls treated with water and solvent based silanes with content from 20 to 40% exhibited a net shrinkage, rather than future expansion. Barrier walls at the twin bridge carrying the Dog River near Montpelier and I-89 over U.S 2/State Street did not show significant signs of expansion reduction.. Berube et al. (2002) and some studies where silanes have been applied do demonstrate that highway barriers are ideal candidates for silane treatment where ASR is deemed to be a concern. Breathable coatings and silanes that reduce the relative humidity content in concrete are also helpful in reducing the ingress of water and deicing salts thereby improving scaling and frost resistance of concrete.
- The application of silanes over the existing paint showed more potential for reducing expansions and relative humidity than in cases where paint was removed prior to the application of the silanes. The explanations to this phenomenon are not yet known but it is believed that during the removal of paint through wet media blasting or sand blasting affects the surface adversely through the creation of micro cracks that allow easier access of moisture. This was evident at Houston Texas site where concrete columns were heavily affected by ASR. It is common in most practices that paint is removed before the application of silanes or similar coatings.
- The research done by Wehrle (2010) were in support of the phenomenon that applying silanes over the existing paint reduces the internal humidity and the potential for future expansions. However, the results included in the reports do not automatically translate to all applications of silanes over paint. It is advantageous to be able to apply sealers or coatings over existing paint since the removal of paint is expensive and requires strict environmental standards in containing the removed paint, dust, debris, liquids and so on. Wehrle (2010) stipulates that

sealers or coatings and the specific combination of the paint should be evaluated first to ensure the underlying paint is breathable thereby allowing the silanes to be able to penetrate sufficiently.

- On the other hand, the efficacy of silane treatment on ASR is difficult to determine especially considering the medium to long-term abrasion resistance of such surface treatment. These treated pavement surfaces are very slippery when wet, so it is important that care should be taken in order to ensure public safety.
- It is recommended that the above products be applied on clean surfaces and treatments done according to the manufacturers recommended rates. The above products also aim at reducing the internal humidity within the concrete due to their hydrophobic properties, hence it is recommended to apply the products on a dry concrete element so as to optimise treatment efficiency and most effectively at least 24 hours of dry weather. Spray nozzles and pressurized handheld containers were proved to be effective when applying silane products in the various field trials used on this study. The elastomeric coating was applied like paint using paint brushes and rollers whilst the silane was sprayed onto the surface of the various structural elements in a left to right to left pattern (Michael et.al, 2013).

Treatments can also be done to ASR affected concrete structures using lithium based surface treatments. Some of the lessons learnt from the use of the chemical treatments using the lithium based admixtures include the following;

- The lithium nitrate applied by either vacuum treatment or topically showed no tangible benefit in terms of reducing cracking or expansions when applied to the highway concrete barrier walls. This was evident at the Massachusetts field trial and the bridge columns at Houston field trial and this can be linked to the overall lack of penetration of lithium nitrate into the concrete. Given the lack of lithium penetration, no beneficial effects of the treatment were observed even if the application is done under vacuum.
- Electrochemical methods were discovered to be performing well in increasing the depth of lithium penetration when applied to bridge columns. Lithium was driven to the depth of reinforcement bars approximately 50mm deep in concentrations believed to be sufficient to suppress ASR induced expansions. Migration of potassium and sodium ions led to the increased alkali concentrations in the vicinity of the reinforcing steel used as cathodic during

the treatment. This was observed in reinforced concrete columns at the Houston field and this was accompanied by an increase in the PH as a result of the cathodic reaction and to maintain electro-neutrality of the concrete pore solution. This phenomenon potentially exacerbates ASR-induced cracking and expansions in this region.

- A lot of effort is required to determine whether lithium electrochemical treatment may result in increased expansions as a result of resaturation that occurs during the multi-week chemical treatment. During the first three years of the monitoring period, lithium-treated columns for the South Parkway Bridge over I-395 Bangor corridor at Maine expanded between 0.21 and 0.23% and similar values were noticed for lithium treated columns at Houston (Michael et.al, 2013).

Crack injection, surface coatings and crack sealing using epoxy products or cementitious repair mortars are some of the most common techniques used to repair ASR affected concrete structures. Some of the lesson learnt from such repairs include the following;

- Epoxy products can be supplied from different companies such as SIKA, SealBoss and Xypex. These materials have been tested and most of them comply with different standards for example the SIKA products are compliant to the Class R4 of BS EN 1504-3. These materials work differently depending on the intended use. SealBoss 2400 Sealer performs very well when repairing water retaining structures. The material is recognized for its characteristics such as its high strength and tolerance for movement. It reacts to form a waterproof, flexible and solid gel with outstanding adhesion to dry and wet mineral surfaces. In cases of alternating dry and wet period, the gel shrinks and swells reversibly. The super low viscosity permits the gel to penetrate into fine pores and fissures of the structure itself.
- The Hokuriko Case study in Japan proved that patch repairs through the use of polymer cement mortar could not suppress ASR induced expansion and the cracks occurred on the surface of the patch. Also the application of patch repair assisted in assessing the trend of residual expansivity on the structures.
- According to the ASR potential of the Hokuriko structures, some surface coatings proved to have performed well. Urethane type of continuous fiber sheet performed well in case of high ASR potential whilst the acrylic fiber sheeting coating proved to be effective in cases of low ASR potential.

Cementitious crystalline repair mortars are effective for repairs of water retaining structures. These are offered by many companies and such as the Xypex. The concrete gravity dam in India which showed significant signs of deterioration due to ASR effects was repaired using the same product and managed to work effectively due to its ability to provide characteristics such as good permeability requirements, ability to effectively seal the cracks, chemical resistance, freeze thaw durability and radiation resistance.

5.3.2 Common Trends on Repair Methods and Materials

The repair methods and materials discussed above were found to be depended on various factors as follows;

- The cause of cracking such as ASR, temperature variations, shrinkage etc.
- How quickly does the repair need to gain full strength?
- Dimensional characteristics of the crack to be repaired
- Are there abrasion requirements to the repairs?
- Are there special requirements to achieve strength?

5.3.2.1 Test Procedures or Investigation Methods

- Visual inspections proved to be the most common method used on most case studies discussed. Visual inspections give an indicative view which usually gives guidance towards the necessary tests required. However, it is imperative to take cognisance that before one can conduct visual assessments, training is required for one to be able to identify the cause of cracking. There is need to consider possible structural effects which requires structural engineering understanding and all other possible causes. This requires knowledge of materials, deterioration mechanisms, flow of stresses, assessment of the environment etc.
- Petrographic examinations as well as the Scan Electron Microscope were the most common methods used for the detection of the possible presence of ASR and reactive aggregates.
- The case studies demonstrated that it is imperative to test the repair products over a certain period of time in order to come to a reasonable conclusion on the effectiveness of the repair material and product applied. Even though most materials may have been manufactured in compliance with various standards, they may not perform as expected depending on the environment and climatic conditions. Very often would the repair material be tested and

monitored over some years and investigation done to check if the repairs are as effective as expected.

5.3.2.2 Repair Methods and Materials

- The most common methods used during the repairs include epoxy injection, crack sealing and surface coatings. These concrete repair methods are implemented using different materials depending on the intended outcome desired from the repairs.
- Crack injections were proved from the case studies above to be done mostly using epoxy products, acrylic, urethane types etc.
- Crack sealing was done commonly using penetrating sealers such as solvent based sealants, acrylic and urethane types
- Surface coatings are commonly done using repair mortars, polymer cements, epoxy products etc.
- There is a trend on the case studies presented on improvements recorded regarding repair materials and methods. Most repairs done in the 80s and 90s proved to be ineffective after some years from the date of repairs. This led to the involvement of bodies such as the ACI to be engaged more through research on how to improve the repair materials and methods. These were accomplished with the assistance of other companies offering concrete crack repair materials such as SIKA, XYPEX and SealBoss. Through the improvements on repair materials as the years progressed, most of the repairs are remaining intact even for a period of more than 10 years after repairs. This has been proved through the effectiveness of repairs presented on the above case studies. Most repairs done in the late 90s and the periods after year 2000 were proved to be effective.
- Most case studies have demonstrated that cleaning is essential for repairs to achieve the desired outcome. Cleaning can be done using sand and water blasting. Rollers, brushes, spray nozzles and pressurized hand containers are some of the equipment commonly used during the repairs

In order to come to a reasonable conclusion regarding the effectiveness of the repairs, it is also crucial to have a control section so that comparisons can be done to the treated and untreated sections. Depending on the nature of repairs, comparisons and investigations may need to be done over some years to allow the repairs to be exposed to various conditions such as weather. However,

the above information and analysis presented is an indicated view of some of the materials and methods being used based on the case studies presented.

5.4 Conclusion

This chapter discussed several concrete crack repair case studies. Case studies elaborated more on concrete crack repair due to structural and non-structural cracking. Non-structural cracking case studies discussed concrete crack repair due to ASR, shrinkage and thermal effects. It was discussed and taken into consideration that in order to execute repairs efficiently, it is imperative to develop a concrete crack repair program. Further discussion was on different causes of concrete cracking and the associated repair techniques and materials.

The FHWA case study presented repairs on ASR affected transport infrastructure such as concrete bridges, concrete pavements and concrete barrier walls. The effectiveness of the materials were tested under several conditions to monitor the humidity, temperatures, length changes and cracking index. Some of the latest repair materials discussed include silanes, epoxy coatings and lithium products. The two storey case study building in California USA suffered significant signs of deterioration due to ASR and repairs were done mainly through pressure injection of epoxy adhesives into concrete cracks and sealing the surface of concrete with epoxy to stop moisture intrusion.

The third case study discussed is the concrete gravity dam in India. The dam showed significant signs of cracking due to ASR. Initially, repairs were done through epoxy injection and crack sealing. The materials used are the products of Xypex and SealBoss. These materials were used differently depending on the causes and nature of cracks such as crack width and concentration of the cracks. Repairs to structures in Hokuriku, Japan case study demonstrated the causes of ASR cracking to the structures through reactive aggregates and high alkali content. Expansivity tests were conducted to monitor the expansive trends of the concrete over a period of 10 years. Different repair methods and materials were used and the effectiveness of the repairs were monitored over a 10 year period. It was concluded that crack injection is a more effective concrete crack repair method due to ASR effects as compared to patch repair.

Repairs due to shrinkage were discussed on the Ipswich parking area case study which had suffered deterioration due to suspected dry shrinkage cracking and corrosion. The Sika Rapid repair mortar

was used to repair all the dry shrinkage cracking on the surface of the concrete parking floors. The Sika FerroGard-903+ was used to eliminate the risk of reinforcement steel corrosion. This product is a multi-functional liquid corrosion inhibitor and was applied to the chloride contaminated decks to eliminate further corrosion due to chloride effects.

Sika concrete crack repair materials were also used to execute repairs at the Jodrell Bank Observatory in Cheshire which experienced concrete cracking due to thermal effects at the Mark 11 telescope. Two components of Sika Mono-Top system were used to repair concrete cracking due to thermal changes and they comprised of a bonding primer and re-profiling mortar. To avoid corrosion effects to the repaired cracks, the Sika FerroGard-903 was used thereby extending the maintenance and service life cycle of the concrete structure. Lastly, structural crack repairs were done to the double storey case study structure in the USA, North Carolina. The structural cracks were related to the poor soil bearing capacity and swollen soil. Repairs were done using the polyurethane sealant, polymer modified repair mortar and low epoxy resins.

CHAPTER 6: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Chapter 1 gives the introduction to the dissertation focusing on the aims of the research, the scope of the dissertation, limitation of the research and outline of the dissertation. Chapter 2 elaborates on the causes of concrete cracking and classifies cracks into structural and non-structural cracks. It further discusses the mechanisms involved and how they lead to concrete cracking. Chapter 3 outlines destructive and non-destructive techniques used to detect cracking in concrete, the location and extent of concrete cracking. The most common non-destructive techniques used to detect concrete cracking include visual assessment, spectral analysis of surface waves (impact echo), ultrasonic pulse velocity test, acoustic emission, modal analysis, petrographic analysis and infrared thermography. Destructive testing techniques were discussed and these involve the drilling of concrete cores to detect the presence or possibility of alkali-aggregate reaction. Some of the main tests conducted from the core samples include aggregate reactivity test, petrographical examinations and mineral analysis such as X-ray diffraction and microscopic analysis.

Chapter 4 ventured into various crack repair methods. These methods are standardised in various codes of practice to ensure the durability of repairs. Different repair materials and their application methods were discussed.

Chapter 5 focused on concrete crack repair case studies. Concrete crack repairs due to ASR effects were discussed on case studies such as the North American Federal Highway Authority concrete crack repair programme, a two-storey building in California, a gravity dam in India and various structures in Hokuriku, Japan. Pressure injection and crack sealing are the common repair methods used to repair ASR damaged structures. These case studies indicated that pressure injection is the most effective way to repair ASR damaged structures as compared to patch repairs. Materials used to repair the ASR damages during the FHWA concrete crack repair programme included silanes, epoxy coatings and lithium products.

Epoxy adhesives were used to repair cracks at the California two-storey building. The urethane type of continuous fiber sheet and the acrylic fiber were used to repair ASR affected structures in Hokuriku, Japan. These repair materials proved to be effective depending on the application

methods and weather conditions. The gravity dam in India was repaired through crack sealing and injections using repair mortars and concentrates of Xypex and SealBoss.

Repairs were also done to a parking area in Ipswich, UK, which experienced significant signs of concrete cracking, as discussed in another case study in Chapter 5. The dry packing method was applied using a rapid repair mortar. Structural cracks observed at a two-storey building in North Carolina, USA were repaired through pressure injections using polyurethane sealant, polymer modified repair mortar and low epoxy resins. However, especially for structural cracks, the right choice of repair method and materials depends on the prevailing conditions with regards to the type and degree of damage, environmental conditions and structural requirements.

It is imperative to take cognisance of the fact that this dissertation reviewed a small sample of case studies. Latest information on concrete crack repair was difficult to source in order to increase the sample of case studies from areas around the world. Hence a sample of case studies selected only gave an indicative view of the latest repair techniques and materials. This dissertation reviewed the literature on concrete crack repair and through the process, several crack repair techniques were presented and how they can be applied to various scenarios which are mainly dependent on the nature of crack, how cracks originate, as well as the environment and location of the structures. Case studies were presented on concrete crack repairs highlighting the latest improvements on repair methods, repair materials and testing methods.

The case studies presented discussed concrete crack repairs on transport infrastructure, water retaining structures and multi-storey buildings. Several materials, repair methods and common trends were analysed to check similarities and differences on the repair methods and materials. Concrete cracking due to shrinkage and thermal effects were also discussed and different repair materials and methods were used depending on the nature of cracks, the environment, intended durability of repairs and the urgency of the repairs.

There are several boards and standards discussed which give guidance to the best practices such as the American Concrete Institute. It should also be taken into consideration that there are several companies that are manufacturing concrete crack repair materials such as Sika, SealBoss and Xypex. These companies have tested their material in line with different guidelines or standards to ensure quality and consistence during the repairs including the application procedures, cleaning

procedures, storage procedures as well as health and safety requirements. Many projects executed in the industry are currently being done using some of the above mentioned products and these are popular depending on the country where repairs are being done, weather conditions, use of the structure, urgency of repairs, and intended durability of the repairs.

6.2 Conclusion

From the discussions above, it can be concluded that concrete cracking is a common trend in concrete structures and cannot be totally eliminated but can be reduced and addressed especially if the signs are recognised at an early stage. These cracks can be detected through various methods depending on the objectives to be achieved. There are various causes of concrete cracking and there are various methods to repair such cracks depending on various factors and requirement. So many developments have been recognised from decades ago to date on repair materials and associated repair methods. Some repairs have been effective and some have failed and research is continuously being developed in order to ensure repairs are functional and durable for the safety of the structures.

6.3 Recommendations

From the findings of this dissertation, it is recommended that further investigations be done on concrete crack repair methods and materials to South African structures encountering the same effects as those discussed on the international case studies. It is also recommended to investigate the effectiveness of latest repair materials discussed on the above case studies and develop a guideline to concrete crack repairs in South Africa taking into consideration the local weather conditions and associated construction standards. Further improvements can be developed to the repair materials and techniques for effective execution of concrete crack repairs to structures showing deterioration due to concrete cracking.

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