A CRITICAL APPRAISAL OF THE DEVELOPMENTS IN DURABILITY DESIGN, SPECIFICATION, CONSTRUCTION AND TESTING OF CONCRETE STRUCTURES IN SOUTH AFRICA

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DECLARATION

I declare that this dissertation is my own unaided work; and that work from external sources has been properly acknowledged. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

The costs associated with the repair of deteriorating concrete structures have been reported to be substantial; however, the costs resulting from poorly designed or executed repairs may be even higher. Therefore, it is important to consider durability of concrete in the design and construction of concrete structures. Concrete durability is the capability of concrete to maintain serviceability over a specified period of time without showing significant deterioration.

The aim of this research was to consolidate knowledge from work done in durability design, specification, construction and testing of concrete structures in South Africa; and investigate the application of this knowledge in practice. The method selected to investigate this was surveys in the form of structured questionnaires issued through electronic mails. The survey samples amongst stakeholders were selected by stratified random sampling which ensured a reduced likelihood of bias.

Survey samples were selected as follows: Consulting Engineers (Sample size - 21, response rate – 86%); Tertiary Institutions (Sample size - 8, response rate – 100%); Contractors (Sample size - 19, response rate – 33%); Readymix Concrete Suppliers (Sample size - 9, response rate – 33%); Cement Suppliers (Sample size - 4, response rate – 75%); and Concrete Admixture Suppliers (Sample size - 4, response rate – 100%). From the data analysis, all stakeholders demonstrated awareness in the subject of durability of concrete as it was found that durability design concepts are incorporated through a careful selection of materials, consideration of the environment to which a structure will be exposed and careful planning of construction processes.

The current methods in practice for design, specification, construction and testing of concrete were found to follow a ‘hybrid’ approach; which is a combination of prescriptive and performance-based approach. In general, the responses from the different stakeholders show similarities in terms of awareness of the need to have

durable concrete, but this awareness is not being implemented by applying measureable durability-related properties of concrete to evaluate its penetrability. With the DI testing methods being incorporated into SANS standards, it is expected that the industry implement these tests in construction projects with the aim of achieving durable concrete. Also, learners in tertiary institutions should be introduced to these test methods as a step towards creating awareness in industry in which they eventually practice.

DEDICATION

I dedicate this dissertation to my mother and my departed father for always supporting me in all my endeavours; and my children who always give me the reason to do better.

ACKNOWLEDGEMENTS

I would like to thank my supervisor and co-supervisor Dr. M. Otieno and Ms J. Kanjee respectively for their guidance and support during the research period at the University Of The Witwatersrand, Johannesburg.

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Chapter 1

1 INTRODUCTION

1.1 Background to Concrete Durability

Ensuring durability of concrete structures is important to the environment as it encourages conservation of natural resources and lowers the demand for the production of new construction materials. The production of some construction materials (such as cement, aggregates, etc.) is damaging to the environment due to carbon emissions which contribute to global warming. In line with preserving our natural resources and the environment, a number of interventions have been proposed in the form of sustainable production of cement and the use of recycled aggregates in the production of concrete.

Durability of concrete can be defined as the capability of maintaining the serviceability over a specified period of time without significant deterioration (Alexander and Beushausen, 2009; Tang, et al, 2015). Durability of concrete results in concrete structures that remain in service for longer periods, even beyond the design service life; which lessens the demand for new concrete materials required to construct new structures or to repair deteriorated structures. This lower demand for new concrete structures will have a positive impact on environmental sustainability as there will be less alteration to our environment. It then follows that durability contributes towards sustainability, on the basis that durability ensures that natural resources are conserved and efficiently used.

1.2 Deterioration of Concrete Structures

Deterioration of reinforced concrete structures is often associated with the ingress of aggressive agents from the exterior resulting in durability problems, and the near-surface concrete quality largely controls durability based on how penetrable it is (Beushausen, et al, 2008). There has been enormous growth in the understanding of the mechanisms and processes of deterioration, the ways to protect concrete against early deterioration and the effective utilisation of concrete-making materials that will enhance durability (Ballim, et al, 2009b). It then follows that durability of concrete is influenced by the environment within which the concrete structure will be exposed and the selection of materials with which the concrete will be produced, and this should be considered in determining the quality of concrete required.

Ballim, et al, 2009a, present an example comparison of two structures A and B to demonstrate the importance of durability, one having acceptable durability (A) and the other showing inadequate durability (B). Structure A with adequate durability shows fair deterioration over time during its service life with minimum required quality at the end of this period. Structure B shows inadequate durability and requires remedial work during its service life as it reaches minimum quality before the end of its service life. These are presented in Figure 1.1.

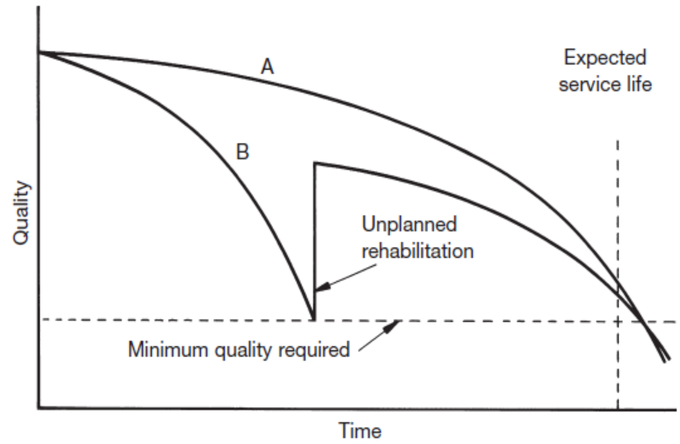

Figure 1.1: Two scenarios of deterioration and rehabilitation of a structure, (Ballim, et al, 2009a)

1.3 Quality of Concrete

The quality of the near-surface concrete or concrete cover is vital as it must provide adequate protection to reinforcing steel to prevent corrosion. Aggressive agents such as chloride ions or carbon dioxide from the surrounding environment ingress concrete structures through concrete cover; therefore, the ability to quantify the quality of the cover layer in terms of engineering parameters is required (Beushausen, et al, 2008). These aggressive agents cause reinforcing steel to corrode resulting in cracking and spalling of concrete, which adversely impacts serviceability of concrete structures (Neville, 1995); and also adversely affect the hardened cement paste resulting in undesirable effects to concrete structures (Beushausen, et al, 2008).

The quality of the concrete cover can be improved by designing and specifying materials that will result in a dense and less penetrable microstructure, testing of as-built concrete to quantify penetrability, and ensuring adequate compaction and curing during construction. The ease with which aggressive agents can penetrate the concrete cover through various transport mechanisms can be estimated using durability index tests, which measure penetrability of the concrete. These durability index tests were developed to give rapid and useful results on the performance of concrete, and they are designed to mimic realistic transport processes through concrete; hence their effectiveness (Alexander, et al, 2008).

Durability index testing may be used to optimise materials and construction processes where specific performance criteria are required (Alexander and Beushausen, 2009); these durability index tests have been developed and are in use in South Africa.

1.4 Durability Design and Specification of Concrete

The design of concrete takes into consideration structural and physical requirements for the structure under consideration. These include but not limited to concrete strength, use of the structure under serviceability, design service life, heat of hydration, durability requirements, etc. Taking these requirements into consideration will result in a specification for the desired concrete properties. It then follows that the selection of materials must ensure that these requirements are met, and for the most part, this study focuses on durability requirements.

The durability design and specification of concrete must ensure that adverse chemical reactions within concrete are mitigated. Furthermore, the final concrete produced should be less penetrable to aggressive agents to prevent pre-mature deterioration. This can be done by proper selection and pairing of concrete ingredients. Durability of concrete is affected by materials selected, production of concrete (supply and construction), and the aggressiveness of the exposure environment (Beushausen, et al, 2008).

The effects of the exposure environment can be categorised into physical attack (erosion, cavitation, etc.) and chemical attack (chemical reactions within concrete, chloride attack, carbonation, etc.) (Ballim, et al, 2009a). In this study, focus will be on ensuring durability of concrete for protection against chemical attack, specifically, chloride attack and carbonation. Some of the chemical reactions and their effects in concrete deterioration are presented in Table 1.1.

Table 1.1: Summary of some of the chemical reactions and their effects in concrete deterioration, (Ballim, et al, 2009a)

<table>
<tr><th colspan="4">Deterioration of concrete by chemical reactions</th></tr>
<tr><th>Reaction</th><th>Outcome</th><th>Result</th><th>Final impact to concrete</th></tr>
<tr><td rowspan="3">Exchange reactions between aggressive fluid and components of hardened cement paste, e.g. acid attack</td><td>Removal of calcium (Ca^{++}) ions as soluble products</td><td rowspan="2">Increase in porosity and permeability</td><td rowspan="2">• Loss of alkalinity
• Loss of mass
• Increase in deterioration process
• Loss of strength and rigidity</td></tr>
<tr><td>Removal of calcium (Ca^{++}) ions as non-expansive insoluble products</td></tr>
<tr><td>Substitution reactions replacing calcium (Ca^{++}) ions in calcium silicate hydrate (CSH)</td><td>-</td><td>• Loss of strength and rigidity</td></tr>
<tr><td>Reactions involving hydrolysis and leaching of the components of hardened cement paste, e.g. soft water attack</td><td>Removal of ions as soluble products</td><td>Increase in porosity and permeability</td><td>• Loss of alkalinity
• Loss of mass
• Increase in deterioration process
• Loss of strength and rigidity</td></tr>
<tr><td>Reactions involving the formation of expansive products e.g. sulphate attack</td><td>-</td><td>Increase in internal stress</td><td>• Loss of strength and rigidity
• Cracking, spalling, popouts
• Deformation</td></tr>
</table>

The result of chemical attack in form of chloride attack or carbonation is the surface ingress through the concrete cover that takes place, and de-passivation of reinforcing steel that is embedded within concrete. The chemical reactions that result from carbonation reduce the pH value of the pore structure which causes de-passivation of reinforcing steel and initiation of corrosion in the presence of moisture and oxygen (Ballim, et al, 2009a). Similarly, chloride attack causes localised de-passivation of the reinforcing steel despite the pH being maintained at a high level (Neville, 1995). Both these forms of attack have similar results when chloride ions or carbon dioxide come into contact with reinforcing steel. It then follows that carbonation exacerbates corrosion initiation when concrete has been penetrated by chloride ions.

Carbonation enhances chloride attack in that a smaller number of chloride ions penetrating the concrete can exacerbate deterioration of concrete (P.C.A., 2002); therefore, a smaller amount of chlorides than anticipated in line with the chloride threshold may cause corrosion initiation. Also, through the pH lowering effect of carbonation, it causes some of the chloride which is chemically bound to the cement to be released within the concrete (Ballim, et al, 2009a), this results in the internal chlorides causing damage and less external chlorides penetrating the concrete. The chemical reactions that take place thereon, in the presence of oxygen and moisture will result in de-passivation of steel and initiation of corrosion. Examples of chemical deterioration are shown in Figures 1.2 – 1.4.

1.5 Construction of Concrete Structures

During the construction process, it is important to ensure that the selection of materials meets the specification and that the concrete produced meets the specified properties (Gjørv, 2011). Transportation, handling and placing of concrete have to be carefully planned and carried out to ensure that concrete is not negatively affected. Testing of concrete in the fresh state prior to placing must be done to ensure that concrete is still suitable for use, e.g. slump test to assess workability. Protection of concrete after placing, also known as curing, has to be maintained to ensure that cement in concrete is hydrated progressively (Ballim, et al, 2009a) and the drying process is not drastic which may be due to weather conditions.

1.6 Testing of Concrete

As part of usual practice, testing of concrete for compressive strength has been done as a quality check for many years. Due to the growing awareness and requirement for durability design, more tests have been developed to assess the ease with which agents can enter the concrete; namely, durability index tests (Alexander and Beushausen, 2009). In this study, it will be evaluated as to how these have been practically applied in real construction projects. With the development of these tests, the uptake by the concrete production/construction industry has to be monitored closely to determine the practicability of application in real projects. Recommendations based on this study will be arrived at.

Figure 1.2: Carbonation induced corrosion, (Source: Sika – Refurbishment Protective Coatings for Concrete)

Figure 1.3: Chloride attack in concrete, (Source: Sika – Refurbishment Protective Coatings for Concrete)

Figure 1.4: Alkali-silica reaction in concrete, (Source: Mapei – The Deterioration of Concrete)

1.7 Flow Chart for the Current Study

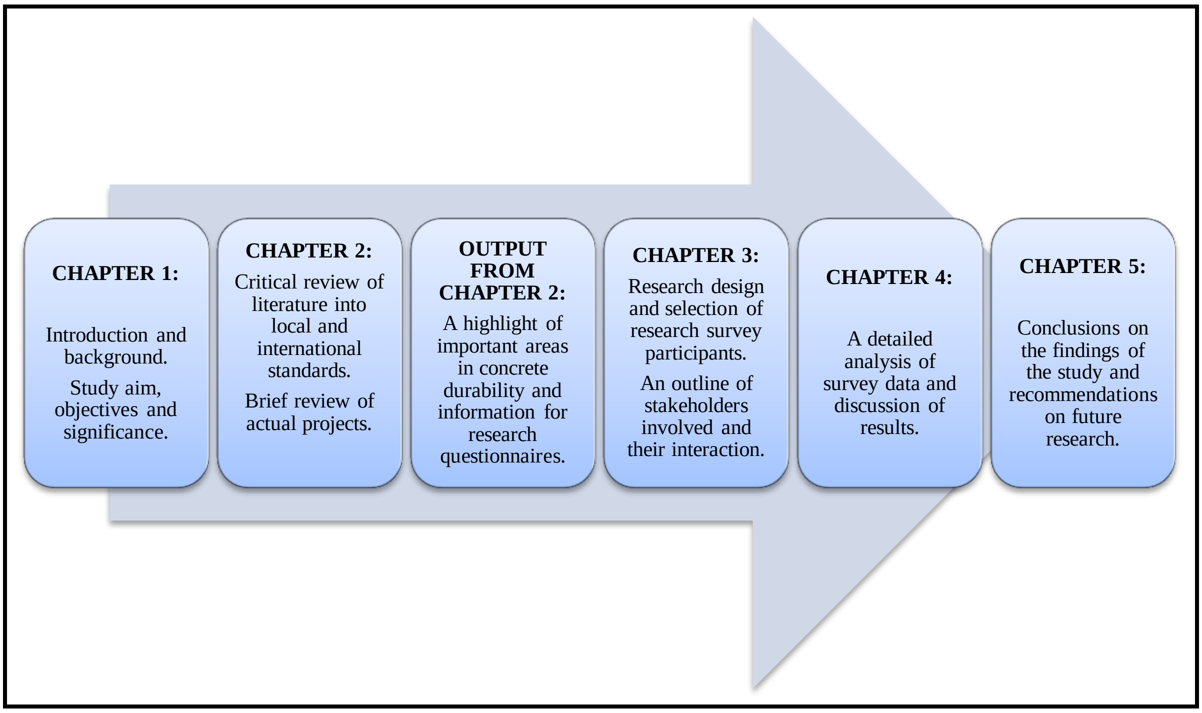

Figure 1.5: Flow chart for the current study

1.8 Problem Statement

Taking durability into consideration when designing, specifying, constructing and testing reinforced concrete structures will ensure that premature deterioration is prevented as it necessitates considerable repair work. Premature deterioration is a major challenge in the industry, as demonstrated in Figure 1.1. The costs associated with the repair of deteriorating concrete structures can be substantial; however, the costs resulting from poorly designed or executed repairs may be even higher (Frankson, 2016). It is therefore imperative that durability of concrete is properly understood and applied when designing and constructing reinforced concrete structures to avert these costs.

It is of great importance for the designer to understand the exposure environment for which the structure is being designed, and the pairing or selection and proportioning of ingredients to prevent adverse chemical reactions. There is an increasing realization that improving the quality of new construction will reduce repair costs over the long term (Alexander, et al, 2008). Internationally, deterioration of concrete infrastructure has emerged as one of the most severe and demanding challenges facing the construction industry (Gjørv, 2011).

Over the years, research studies have been undertaken into the durability of concrete, and various approaches to design for durability have been recommended. At this stage, it is required to collate information of these previous research studies, and further establish how the design approaches are being applied in practice. To this end, a critical appraisal of the durability design, specification, construction and testing of concrete structures in South Africa will be done and it will be determined during this research study as to how improvements can be put in place in this regard.

1.9 Aim

This study focuses on the durability design, specification, construction and testing of concrete structures in South Africa. A brief overview of approaches for durability design, specification, construction and testing of concrete structures from other parts of the world will also be covered. Concepts and approaches that have been developed for durability will be reviewed and discussed. Further, it will be established through industry surveys how practising engineers are approaching the durability design of concrete and also, how durability design has been incorporated into the higher learning education curricula. This study aims to review the general subject of durability design and specification of concrete structures in South Africa.

1.10 Objectives

The objectives of this research are to review work that has been done to develop and implement concepts for durability of concrete structures in South Africa, and these are listed below:

a) to take stock of the work that has been done with regard to durability design, specification, construction and testing of concrete structures in South Africa and around the world; and further provide a critique thereof.
b) to establish the awareness of practicing engineers on the subject of concrete durability design, specification, construction and testing of concrete structures; and how they apply the durability approach.
c) to review the curricula of South African institutions of higher learning in civil engineering to establish how concrete durability has been incorporated therein, if any.
d) to establish the awareness of other stakeholders in the concrete construction industry on the subject of concrete durability approaches.

1.11 Research Significance

This research aims to consolidate knowledge of work done in concrete durability design, specification, construction and testing in South Africa; and investigate the application of this knowledge in practice. This will be in a form of bringing together past research studies into the subject of aforementioned, and recommendations on the way forward in this regard based on research findings. The evaluation of practices of stakeholders in the concrete construction industry to determine how durability has been embraced will be done through industry surveys. It is vital to make an assessment of the uptake of developed interventions to ensure durability of concrete structures.

Further to this, it is imperative that durability design and specification of concrete is included in tertiary studies. To this end, a review of the current civil engineering curricula will be done with a view to understand whether or not durability design and specification has been included; and to what extent if it has. Methods of construction and testing are included in the civil engineering curricula; it needs to be investigated as to how ready the graduates are to apply their minds and make decisions in this regard in the work place.

1.12 Scope and Limitations

This study focuses on the durability of concrete structures in South Africa which cover design, specification, construction and testing thereof. It aims to consolidate knowledge from existing literature on approaches derived for durability of concrete, and does not aim to present any design models and derivations thereof. Through industry surveys, it will be established how these approaches have been implemented on actual projects and how they are incorporated into higher education curricula to date.

A clearer understanding of the current practices and higher education curricula in the country can be reached by extending the study to all South African provinces to practicing engineers, institutions of higher learning and other stakeholders in the concrete construction industry. Due to the time constraints and funding that would be required to carry out a review of this magnitude, this will not be done in this current research. Therefore, this study is limited to the geographical location of the researcher, Johannesburg, in the Gauteng province.

It is foreseen that the results of this study will be representative of the practices in the industry including those in other regions, based on the view that Johannesburg is the economic hub of South Africa where large, innovative and world-class infrastructure projects continue to be developed. It is important to note that this is an assumption made by the researcher on this basis. Examples of prominent projects are listed below:

- Gautrain Rapid Rail project, the first of its kind in South Africa and largest single construction project in Africa in the year 2010 (Du Plessis, 2010), providing a world-class transportation service (Van der Westhuizen, et al, 2013).
- The massive Gauteng Freeway Improvement Project, transforming Gauteng road network to a world-class standard (Robinson, 2015).

- The Mall of Africa located in Waterfall City, Midrand, the largest shopping mall in South Africa and one of the largest single-phase construction projects in the Southern hemisphere (Spottiswoode, 2016).
- The PwC Tower located in Waterfall City, Midrand, the only twisted building in Africa, 24^{th} tallest twisted building in the world (Lawson, et al, 2017).

1.13 Research Report Outline

This report is divided into five chapters as listed below:

Chapter one:	Introduction
Chapter two:	Literature Review
Chapter three:	Research Design and Methodology
Chapter four:	Results and Discussion
Chapter five:	Conclusions and Recommendations

Chapter 2

2 LITERATURE REVIEW

This study focuses on the durability design, specification, construction and testing of concrete structures in South Africa. There are two main approaches for concrete design and specification namely, prescriptive and performance-based approaches. Prescriptive specifications are the norm and have been developed by local experience, but are often conservative as they inhibit innovation since new materials and methods do not fit into the prescriptive approach (Hooton and Bickley, 2014).

Construction of concrete based on prescriptive specifications requires testing for fresh properties and strength of concrete, testing for durability does not form part of these requirements (Beushausen, et el, 2008). During concrete construction, the achieved quality of the concrete placed normally shows a scatter and variability due to a number of factors such as handling and placing, etc. (Gjørv, 2011). This necessitates a performance-based approach to ensure that the achieved quality of concrete will withstand the environmental loads leading to deterioration. The performance-based approach focuses on measurement of relevant properties of the in-situ concrete, in particular transport-related properties for durability (Alexander and Thomas, 2015).

To this end, a framework for use of durability indexes in performance-based design and specification for reinforced concrete structures was developed in South Africa by Alexander, et al, (2008). The framework is the approach developed and implemented in South Africa to improve the quality of the reinforced concrete construction. It presents the durability index tests namely Oxygen Permeability Index, Chloride Conductivity Index and Water Sorptivity Index; and their link to service life models. These can be measured on both laboratory specimens for concrete that was prepared and cured in a laboratory setting and concrete samples obtained by coring as-built structures, which allows for an assessment of both contributions of material and effects of construction processes.

Required performance parameters for a given concrete can be established through environmental exposure conditions, desired service life, concrete material quality and cover thickness. Durability index values can be specified through a deemed-to-satisfy or rigorous approach, and this can be decided on by evaluating the structure in question (Alexander, et al, 2008). Compliance with durability requirements can be evaluated through material potential quality, as-built quality and stipulated project-specific testing frequency. Conformity criteria and acceptance criteria for structures are outlined together with the establishment of acceptance criteria.

2.1 Discussion on Specifications

Durability is a material performance concept for a structure in a given environment; therefore, it cannot be assessed through intrinsic material properties (Alexander and Beushausen, 2009). Although the prescriptive approach may encompass requirements for minimum compressive strength, maximum water/binder (w/b) ratio, minimum supplementary cementitious materials (SCMs – e.g. slag, silica fume, fly ash, etc.) content and cover depth; the desired concrete performance is not described (Kessy, et al, 2015). The specified parameters for durability must also be measureable from an as-built structure, e.g. penetrability by water, etc.

In practice however, an intermediate mixed approach is found to be more useful, termed a ‘hybrid’ approach; whereby a mix of prescriptive and performance requirements are specified with a greater emphasis on the performance criteria (Muigai, et al, 2012; Kessy, et al, 2015). It is important to note that in a full performance approach, specified concrete properties should be measurable in-situ to ensure that as-built quality is achieved, the correct correlation of durability indexes and actual as-built performance must be determined (Kessy, et al, 2015). These Durability Index (DI) tests are briefly discussed in Section 2.4.1.

2.2 Prescriptive Specifications

Most current specifications follow a prescriptive approach to a large extent whereby limits on mix parameters are given such as water/binder ratio, binder content and strength (Alexander and Mackechnie, 2003), based on exposure classes and life span of the structure (Alexander and Beushausen, 2009). Durability issues are not fully appreciated and addressed in this approach as as-built quality of concrete is not assessed and assumed to be as specified (Alexander and Thomas, 2015).

Concrete compressive strength was in the past used as an indicator of durability, but the test for strength did not account for construction processing variables such as placing, compaction and curing; therefore, not an adequate indicator (Beushausen, et al, 2008; Alexander and Mackechnie, 2003). It has been proven that a higher strength value does not necessarily result in better durability; further, the use of high binder contents may result in thermal cracking in concrete and therefore increase its permeability (Nganga, et al, 2013; Angelucci, et al, 2017). Different standards are covered in later sections of this chapter including standards that follow this approach.

2.3 Performance-based Specifications

In the performance-based approach, the design and specification of concrete structures entails two main components: (i) appropriate test method and (ii) appropriate interpretation of test results obtained (Beushausen, et al, 2008; Beushausen and Alexander, 2008). The tests specified monitor the transport mechanisms through the concrete cover to ensure minimal penetrability (Kessy, et al, 2015). In South Africa, DI test methods have been developed for this purpose.

The performance-based approach calls for measuring concrete properties in-situ to ensure that as-built quality is achieved; it is therefore important to specify measurable concrete properties such as measuring penetrability of concrete (Kessy, et al. 2015). Measuring these concrete properties through DI tests will indicate the suitability and resistance of concrete to exposure conditions, and further give an indication on the potential design service life (Alexander and Beushausen, 2009). This approach is discussed in detail below. Different standards are covered in later sections of this chapter including standards that follow this approach.

2.4 Durability Design and Specification in South Africa

In an effort to move away from prescriptive specifications, the DI approach was developed, which permits performance-based specifications for durability of reinforced concrete structures (Muigai, et al, 2012). DI tests are based on measurement of appropriate transport-related properties of the concrete cover layer of laboratory and in-situ concrete, which reflect the dual aspects of material potential and construction quality (Alexander and Beushausen, 2009). This is the measurement of the ease with which aggressive agents can penetrate the concrete cover and eventually cause concrete deterioration over a period of time.

Durability indexes are quantifiable physical or engineering parameters which characterise concrete and are sensitive to material, processing, and environmental factors and can be linked to service-life models (Beushausen, et al, 2008). Test specimens for the DI tests are 70 ± 2 mm in diameter and 30 ± 2 mm thick concrete discs, extracted from the cover zone and have their moisture content standardised before testing by conditioning in an oven at 50 ± 2ºC for seven days (SANS3001-C03-1, 2015). It is important to note that this testing method is limited to concrete with a maximum nominal aggregate size of 26.5mm (SANS3001-C03-1, 2015).

The durability indexes obtained with these test methods have been related empirically to service life prediction models and can be used as the input parameters of service life models together with relevant variables to determine rational design life (Beushausen and Alexander, 2008). These DI test methods are suitable tools for site quality control because they are sensitive to material and constructional effects (Alexander, et al, 2008). This is due to the fact that as-built concrete is also measured in addition to laboratory tests.

It then follows that there are benefits to be realised in moving away from prescriptive to performance-based specifications that significantly assist in improving concrete performance (Beushausen, et al, 2008; Alexander and Thomas, 2015). Ballim, et al, (2009a), describes elements to be developed for the application of performance concepts; limit state criteria, a defined service life, deterioration models, compliance tests, strategy for maintenance and repair, and quality control systems. There is value in the assertion by Kessy et al (2015), that to ensure that the approach is fully performance-based, it should link durability requirements and durability design through service life models in order to estimate the service life of the reinforced concrete structure.

Specifying DI values in performance-based specifications can be either (i) a deemed-to-satisfy approach or (ii) a rigorous approach; however, the former is believed to be adequate for the vast majority of reinforced concrete structures (Alexander, et al, 2008) and produces a more conservative design (Muigai, et al, 2012). If the requirements of the proposed structure are not within the deemed-to-satisfy criteria, the latter may be a suitable approach to use; while this approach is flexible, it requires more expertise on the part of the designer to ensure that the models are being used correctly and the results properly interpreted (Alexander, et al, 2008). The rigorous approach for chloride-induced corrosion is covered in detail by Muigai et al. (2012); this can be reviewed to specify DI values for chloride-induced corrosion where suitability of this approach has been established.

2.4.1 South African Durability Index Tests

As stated above, DI tests are based on measurement of appropriate transport-related properties of the concrete cover layer of laboratory and in-situ concrete, which reflect the dual aspects of material potential and construction quality (Alexander and Beushausen, 2009). This is the measurement of the ease with which aggressive agents can penetrate the concrete cover and eventually cause concrete deterioration over a period of time.

2.4.1.1 Oxygen permeability index test (OPI)

OPI test is used to measure the permeability of concrete and predicting the ease of ingress of carbon dioxide (CO_2) into concrete structures (Beushausen and Alexander, 2008). The test set-up is shown in Figure 2.1. The test set-up is summarised here, an elaborative test set-up is presented in SANS3001-C03-2:2015. The permeability cell shown in Figure 2.1 must be kept in a room where temperature is controlled at 23 ± 2º C, and should have a volume of 5L with a tolerance of ± 5%, warranting no expansion or contraction in the pressure range 0 kPa to 120 kPa. The equipment must be frequently tested for airtightness using impermeable blank specimens, and a drop of 0 kPa in pressure from an initial permeability cell pressure of 100 kPa over a period of 24 hours is required.

The leakage of oxygen is only allowed through the pores of the specimen, this is ensured by the use of compressible rubber collars (free of cracks and tears), that allow a tight fit around the specimen. Additional components of the test equipment are described in the test method in SANS3001-C03-2:2015. Concrete samples as per specimens described in Section 2.4 above are placed in a falling head permeameter with an initial pressure of 100 ± 5 kPa. The test is terminated when the pressure has dropped to 50 ± 2.5 kPa or after 6 hours ± 15 minutes, whichever occurs first; a minimum of 8 readings is required to be recorded at intervals corresponding to a rate of 5 ± 1 kPa.

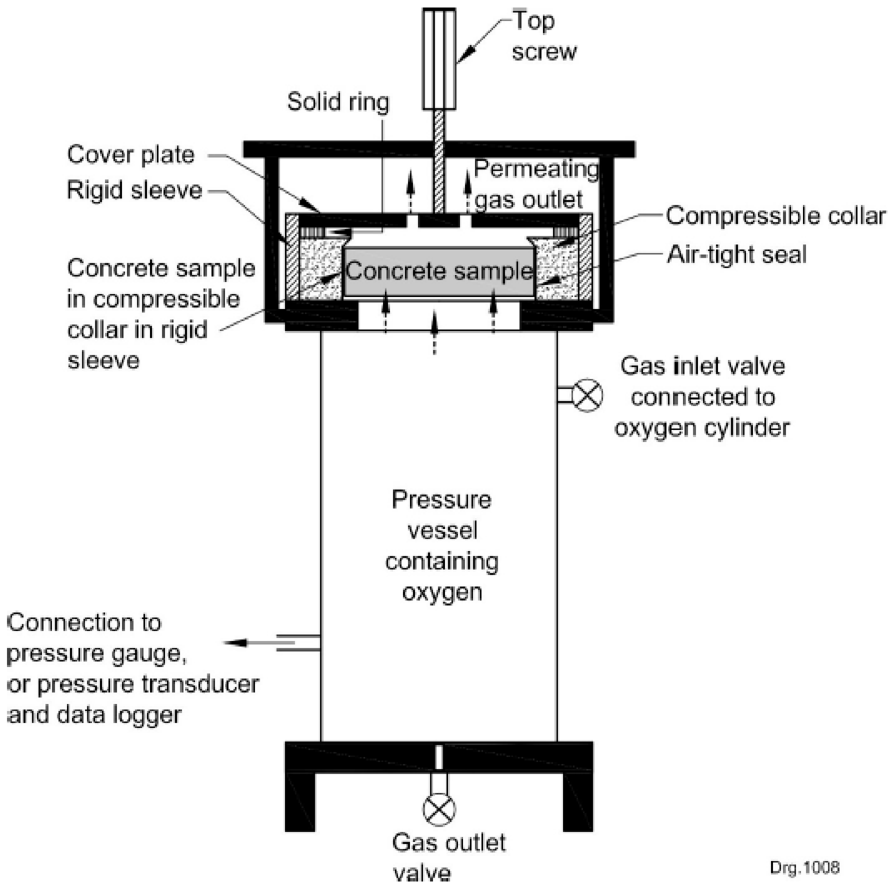

Figure 2.1: Permeability Cell Arrangement, (SANS3001-C03-2, 2015)

The rate of pressure decay is monitored and used to calculate a D'Arcy coefficient of permeability k (m/s), which is later transformed into an oxygen permeability index (Stanish, et al, 2006). The coefficient of permeability k is calculated for each specimen and an oxygen permeability index (OPI) given an average of the individual OPI values. Indexes are logarithmic values and typically range from 8 to 11, with the higher index indicating less permeable concrete (Alexander, et al, 2008).

D'Arcy coefficient of permeability k (m/s), is calculated as per equation below (SANS3001-C03-2, 2015):

$$k = \frac{\omega \times \mathrm{V} \times \mathrm{g} \times \mathrm{d} \times \mathrm{z}}{\mathrm{R} \times \mathrm{A} \times \mathrm{T}}$$

Equation 2.1

Where:

- k – is the coefficient of permeability of the test specimen in metres per second (m/s);
- ω - is the molecular mass of oxygen (i.e., 0.032 kg/mol), in kilograms per mole (kg/mol);
- V – is the volume of the permeability cell, recorded to the nearest 0.01 litre or 0.00001 m^3. The volume of the permeability cell includes the volume of the cell up to the lower face of the specimen. The volume shall be determined by dimensional measurement, accurate to the nearest mm, or by the volume of water contained at 23 ± 2 ºC.
- g – is the gravitational acceleration (i.e., 9.81 m/s^2), in metres per second squared (m/s^2);
- d – is the average specimen thickness, to the nearest 0.02 mm, in metres (m);
- z – is the slope of the linear regression line forced through the (0,0) point, in reciprocal seconds (s^{-1});
- R – is the universal gas constant (8.313 Nm/Kmol), in newton metres per Kelvin mole (Nm/Kmol);
- A – is the cross-sectional area of the specimen, in square meters (m^2);
- T – is the absolute temperature in Kelvin (K).

2.4.1.2 Water sorptivity index test (WSI)

WSI test provides a useful measure of water penetrable porosity of the concrete specimen (Alexander, 2017b). The actual sorptivity value achieved is strongly dependent on construction factors, primarily curing, and less dependent on concrete material compositions; therefore it can serve as a check on construction quality (Alexander, et al, 2008). The test set-up is shown in Figure 2.2 – 2.4.

Additional components of the test equipment are described in the test method by Alexander (2017b). Concrete samples as per specimens described in Section 2.4 above are exposed to a free water surface only on one side (testing side) by sealing the sides, and the weight gain is monitored with time and normalised by the water-accessible porosity as determined by vacuum saturation (Stanish, et al, 2006). The testing liquid is a solution of tap water saturated with calcium hydroxide.

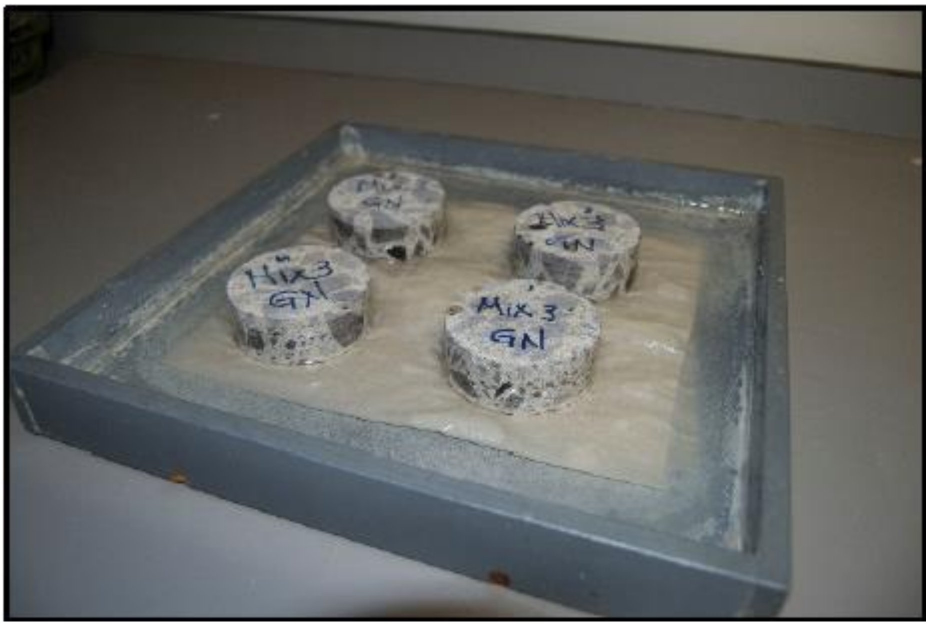

Figure 2.2: Test setup using paper towels, (DI Manual, Alexander, 2017b)

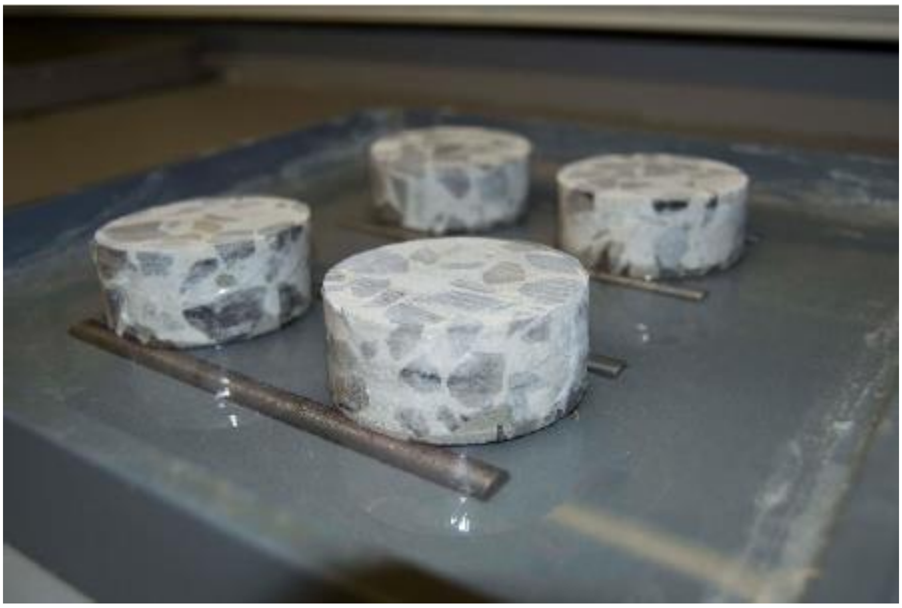

Figure 2.3: Test setup using supports, (DI Manual, Alexander, 2017b)

Figure 2.4: Proper solution depth, (DI Manual, Alexander, 2017b)

From the test results, the water sorptivity of the specimen (S) in mm/hr$^{0.5}$ is calculated for each specimen and the overall sorptivity of concrete tested is an average of the individual (S) values. Water sorptivity values vary from approximately 5 mm/hr$^{0.5}$ for well cured grade 30-50 concretes to 15-20 mm/hr$^{0.5}$ for poorly cured grade 20 concretes (Alexander, et al, 2008).

Water sorptivity (S) in mm/hr$^{0.5}$, is calculated as per equation below (Alexander, 2017b):

$$S = \frac{Fd}{M_{sv} - M_{s0}}$$

Equation 2.2

Where:

S – water sorptivity of the specimen in mm/√h,

F – is the slope of the best fit line, in grams per square root of hour ;

d – is the average specimen thickness to the nearest 0,02 mm, in mm;

M_{sv} – is the vacuum saturated mass to the nearest 0,01 g of the specimen, in grams;

M_{s0} – is the mass to the nearest 0,01 g of the specimen at the initial time (t0), in grams.

2.4.1.3 Chloride conductivity index test (CCI)

CCI test is used to measure the electrical resistance of concrete when saturated with a standard, highly ionic chloride solution (Alexander, et al, 2008); and to calculate concrete's conductivity which can be related to the concrete's resistance to chloride ingress (Beushausen and Alexander, 2008). The test set-up is shown in Figure 2.5. The test set-up is summarised here, an elaborative test set-up is presented in SANS3001-C03-3:2015.

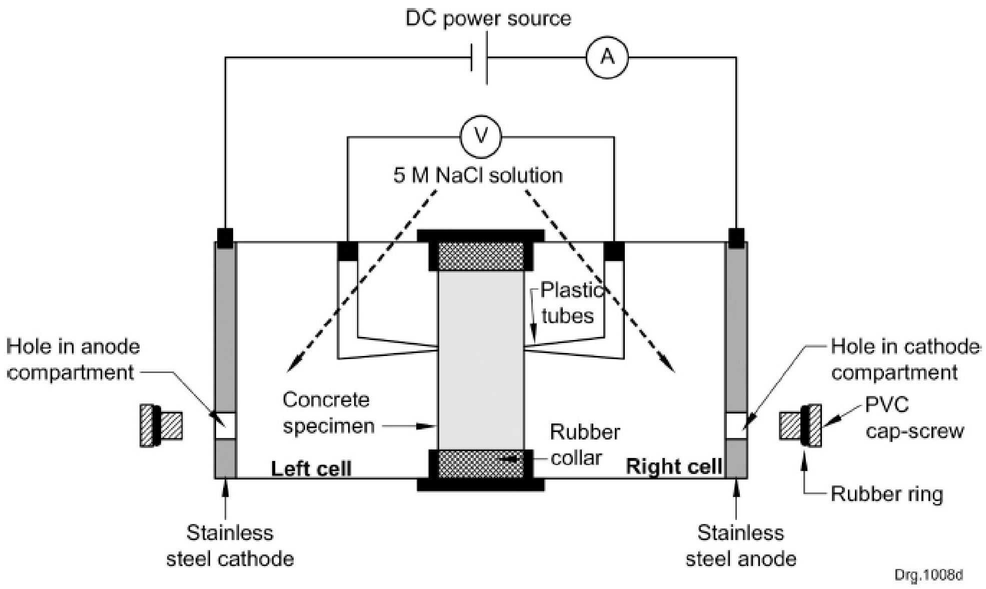

Figure 2.5: Simple Cell Arrangement, (SANS3001-C03-3, 2015)

The conduction cell with anode and cathode parts permanently marked on the outside of the cell, and with flexible rubber collars free of cracks or tears is required. Additional components of the test equipment are described in the test method in SANS3001-C03-3:2015. Concrete samples as per specimens described in Section 2.4 above are vacuum saturated in a 5M NaCl solution and then placed in a test rig with a cell filled with the same solution on either side (Stanish, et al, 2006).

Conductivity is calculated by measuring the current that results when voltage of approximately 10V is applied across the sample, and note that this is actual voltage measured by probes in the test chambers rather than the voltage applied by the power supply (Stanish, et al, 2006). Chloride conductivity values range from 2,5mS/cm or greater for plain cement concretes which have low resistance to chloride ingress to 0,5mS/cm or less for highly chloride-resistant blended cement concretes (Alexander, et al, 2008).

Chloride conductivity is calculated as per equation below (SANS3001-C03-3, 2015):

$$\sigma = \frac{\mathrm{id}}{\mathrm{VA}}$$

Equation 2.3

Where:

σ – is the chloride conductivity of the specimen (mS/cm)

i – is the electric current (mA)

d – is the average thickness of specimen (cm)

V – is the voltage difference (V)

A – is the cross-sectional area of the specimen (cm^2)

2.4.2 Current status of the developments of durability index tests

For more than a decade, the Durability Index tests have been through a rigorous process of undergoing laboratory refinement and practical implementation of the tests on construction sites, prior to the tests being put forward as SANS Standard Test Methods (Alexander, 2017a). The durability index test values have been assessed in a study involving numerous laboratories for repeatability and reproducibility by Stanish, et al, (2006). The repeatability is the coefficient of variation for a single operator and reproducibility is the coefficient of variation between laboratories (Stanish, et al, 2006).

The results of the study by Stanish, et al, (2006), were used to determine adequacy of test procedures and test apparatus, and further recommended remedial work for improvement thereof. The repeatability and reproducibility values for this study fit within the range of values presented in the Durability Index Testing Procedure Manual (2017). This is noteworthy as the tests described above and presented in the Durability Index Testing Procedure Manual (2017) have been incorporated into SANS test methods; except for the water sorptivity (Alexander, 2017a; Alexander, 2017b). These tests have been issued as SANS Test Methods as listed below:

1. SANS3001-C03-1:2015 – for preparation of test specimens.
2. SANS3001-C03-2:2015 – for oxygen permeability test.
3. SANS3001-C03-3:2015 – for chloride conductivity test.

Based on the above information, South Africa is advancing towards full performance-based specifications. Henceforth, the application of these test methods on actual projects should be done. In line with this, Nganga, et al, (2013) carried out a study on practical implementation of the durability index performance-based design approach. These durability index (DI) tests can be used as a practical approach to control the quality of structures for durability, as durability of reinforced concrete structures can be guaranteed when as-built quality of the cover layer is verified (Nganga, et al, 2013).

From the study by Nganga, et al, (2013), it was found that it is possible to implement these tests with stricter controls in place, as the magnitude of variability depends on this; as seen on a comparison with precast concrete structures (Nganga, et al, 2013). The production of precast concrete is done in a factory and stricter quality controls are put in place as it is feasible to do so in a factory environment. A replica of these controls in a construction site will then be beneficial to produce better results.

2.4.3 South African standards on design and specification of concrete

Kessy, et al, (2015) proposed that South African standards SANS 10100-1, SANS 10100-2 and SANS 2001, be redrafted adopting EN 206-1 and EN 13670; and be accompanied by 'guidance documents' for required contextual information and reference. This is due to the South African standards lacking elaborative descriptions of environmental exposure classes, guidance on concrete cover contradicting durability requirements, limits on water/cement ratio for some exposure conditions not provided, etc. To this end, it was decided in principle by the standards committee to implement the approach applied in the Eurocode (Kessy, et al, 2015), this is presented in Table 2.6. The 'guidance documents' will present both prescriptive and performance-based alternatives as performance-based only may not be necessarily suitable for every project at every location.

The proposed methodology for durability specification includes (i) stage 1: specifications by client or designer, (ii) Stage 2: construction and testing by supplier and contractor, (iii) Stage 3: verification by the client (Kessy, et al, 2015). This methodology will ensure compliance with specifications as the as-built structure will require verification and acceptance by the client, with a possibility of stipulated corrective measures for non-compliance as can be seen from the practical examples below (Nganga, et al, 2013). Selection and proportioning of materials for durability have been covered in the SANS 10100-2:2014, clause 6.2; however, testing for durability is not covered specifically in this standard. To this end, the durability standards have been issued as covered in Section 2.4.2 above.

2.4.4 Practical implementation projects

The projects mentioned below are proof of the industry's awareness regarding durability design and specification of concrete structures. It is further encouraging knowing that durability index tests were implemented in actual projects noting that the durability index tests were not yet incorporated into SANS standards when some of these projects were executed. It is important to note that follow-up enquiries to the project participants were made by the researcher to obtain more information where possible.

2.4.4.1 The Gauteng Freeway Improvement Project (GFIP)

The Gauteng Freeway Improvement Project (GFIP) was initiated by the South African National Roads Agency SOC Limited (SANRAL). This was with an aim to alleviate traffic congestion on Gauteng freeways by increasing the number of traffic lanes in existing freeways, and construction of interchanges (Nganga, et al, 2013). The project was reported to have adhered to very tight control on the quality of concrete for the several bridge and ramp structures, and the testing regime included durability tests such as oxygen permeability and water sorptivity (Sustainable Concrete, *IMIESA*, 2013).

SANRAL, the client on the project, have adopted the performance-based approach by enforcing the Durability Index test approach in all their new construction, which included this project (Alexander, 2017a). The limiting values obtained from the durability index prediction model that considers the exposure conditions and binder type used were specified for this project; and for control, these specified limiting values and reduced payment criteria were applied (Nganga, et al, 2013).

Nganga, et al, (2013), elaborated on the results achieved and reported that for the OPI, results were in the range of 9.75 to 11.10; the minimum value being more than the specified minimum value (9.70) which means that permeability was within the expected values. The specified maximum value for WSI was 10 $mm/hr^{0.5}$. The achieved values were under this value with a few exceptions of some being very close to the maximum and one exceeding the maximum value to 14.4 $mm/hr^{0.5}$.

2.4.4.2 N4 upgrade project

The N4 upgrade project consisted of the construction of a new bridge, the extension of an existing bridge, and the construction of six in-situ concrete culverts and associated drainage works (Roads, *IMIESA*, 2015). Readymix concrete with a high cementitious content was used to ensure optimum durability, with the mix designs being tested for durability through durability index tests which included water sorptivity, chloride conductivity and oxygen permeability (Roads, *IMIESA*, 2015); no tests were reported on as-built structures however.

For the full performance-based approach, in-situ tests are required to ensure that structural performance is as envisaged. Performance of the as-built structure was not reported, therefore, it is assumed that a ‘hybrid’ approach was applicable in this project. The concrete was reported to have met all the durability specifications. Due to insufficient information on the published article (Roads, *IMIESA*, 2015), follow-up enquiries with the author were not possible. Further, the initiative to follow-up with the contractor on the project proved to be difficult due to the fact that the company had been acquired by another company.

2.4.4.3 Maputo Bridge

Although slightly outside the borders of South Africa, Maputo is located in the Southern African region. The concrete for construction of the Maputo Bridge which was reported to be underway at the time of writing of this report, involved testing for durability requirements. The mix design involved the use of Portland cement blended with 40% Fly Ash (FA) or 40% Pulverised Fuel Ash (PFA), it is important to note that this is more than the usually recommended 30% (Ballim, et al, 2009a), but was reported to have produced impressive results (Greene, 2017).

A follow-up enquiry with Greene, who was the project leader, revealed that the durability index tests performed were oxygen permeability index (OPI), water sorptivity index (WSI), and chloride conductivity index (CCI). The results achieved were reported to be in the range of 11.06 to 11.61 for OPI, 3 to 5 mm/hr$^{0.5}$ for WSI, and 0.14 to 0.22 mS/cm for CCI. A review of these results in line with the allowable results stipulated in Sections 2.4.1.1, 2.4.1.2 and 2.4.1.3 above indicates that the performance of this concrete exceeded the normalised values. Further, the use of cement extenders produced cost savings to the project and further drastically reduced the cementitious CO_2 emissions of the concrete making a contribution to sustainability (Greene, 2017).

2.5 Durability Design and Specification - A Review of International Standards

At a global level, various approaches to performance-based specifications have been proposed and some are being implemented. Approaches from a selection of countries are discussed below with some critique of their current provisions.

2.5.1 United States of America (ACI 318:2011)

This code provides minimum requirements or minimum acceptable standards for materials, design and construction practices of structural concrete members. The code is mostly prescriptive on the durability requirements with the stipulation of exposure classes, limits to maximum water-cement ratio and minimum compressive strength. Testing is done by compressive strength test except for low permeability concrete whose properties should be evaluated using ASTM C1202 Rapid Chloride Permeability Test. The concrete cover is specified in line with the intended use rather than exposure conditions. The durability requirements for this standard are presented in Table 2.1.

Table 2.1: ACI 318 (2011) Durability Requirements, Refer to the standard for additional requirements

Category	Class	Severity	Condition	Max w/c	Min 28 day f_c, MPa
F Freezing and thawing	F0	Not applicable	Concrete not exposed to freezing and thawing cycles.	N/A	≤ 20
	F1	Moderate	Concrete exposed to freezing and thawing cycles and occasional exposure to moisture.	0.45	31
	F2	Severe	Concrete exposed to freezing and thawing cycles and in continuous contact with moisture.	0.45	31
	F3	Very severe	Concrete exposed to freezing and thawing and in continuous contact with moisture and exposed to de-icing chemicals.	0.45	31
S Sulphate	S0	Not applicable	Water-soluble sulphate in soil, % by mass, $SO_4 < 0.10$ Dissolved sulphate in water, ppm, $SO_4 < 150$	N/A	≤ 20
	S1	Moderate	Water-soluble sulphate in soil, % by mass, $0.10 \leq SO_4 < 0.20$ Dissolved sulphate in water, ppm, $150 \leq SO_4 < 1500$ Seawater	0.5	28
	S2	Severe	Water-soluble sulphate in soil, % by mass, $0.20 \leq SO_4 \leq 2.00$ Dissolved sulphate in water, ppm, $1500 \leq SO_4 \leq 10{,}000$	0.45	31
	S3	Very severe	Water-soluble sulphate in soil, % by mass, $SO_4 > 2.0$ Dissolved sulphate in water, ppm, $SO_4 > 10{,}000$	0.45	31
P Requiring low permeability	P0	Not applicable	In contact with water where low permeability is not required.	N/A	≤ 20
	P1	Required	In contact with water where low permeability is required.	0.5	28
C Corrosion protection of reinforcement	C0	Not applicable	Concrete dry or protected from moisture.	N/A	≤ 20
	C1	Moderate	Concrete exposed to moisture but not to external sources of chlorides.	N/A	≤ 20
	C2	Severe	Concrete exposed to moisture and an external source of chlorides from de-icing chemicals, salt, brackish water, seawater, or spray from these sources.	0.4	35

2.5.2 Canada (CSA A23.1/23.2)

Through the standard CSA A23.1/23.2, requirements for materials and methods of construction are provided; presenting both prescriptive and performance for durability specification, and thus a ‘hybrid’ specification (Kessy, et al, 2015). The processes, materials, or activities used by the contractors, manufacturers, and materials suppliers are left to their discretion; whilst the performance concrete specification is defined as a method of specifying a construction product in which a final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods (Hooton and Bickley, 2014). The durability requirements for this standard are presented in Table 2.2.

Table 2.2: CSA A23.1/23.2 (2009) Durability Requirements, (Kessy, et al, 2015)

Exposure Category	Class of Exposure	Prescriptive Requirements				Performance requirements
		Maximum w/b*	Minimum compressive strength, MPa and age (d) at test*	Air content for 14-20 mm nominal aggregate size	Curing type for normal concrete***	
Extreme chloride	C-XL	0.37	50 within 56 d	4-7% or 5-8% if exposed to freezing	Extended	ASTM C1202** < 1000 Coulombs at 56 d, with no single value > 1250 Coulombs
Chloride and/or chemical	C-1 or A-1	0.40	35 at 28 d	4-7% or 5-8% if exposed to freezing	Additional	ASTM C1202** < 1500 Coulombs at 56 d, with no single value > 1750 Coulombs
	C-2 or A-2	0.45	32 at 28 d	5-8%	Additional	-
	C-3 or A-3	0.50	30 at 28 d	4-7%	Basic	-
	C-4 or A-4	0.55	25 at 28 d	4-7%	Basic	-
Freezing and thawing	F-1	0.50	30 at 28 d	5-8%	Additional	ASTM C457 Average spacing factor < 0.23mm, with no single test > 0.26mm
	F-2	0.55	25 at 28 d	4-7%	Basic	-
Negligible	N#	As per mix design	For structural design	None	Basic	-
Sulfate	S-1	0.40	35 at 56 d	4-5%	Additional	CSA A3004-C8 Maximum expansion < 0.05% at 6 months, or 0.10% at 12 months
	S-2	0.45	32 at 56 d	4-7%	Basic	
	S-3	0.50	30 at 56 d	4-7%	Basic	CSA A3004-C8 Maximum expansion < 0.10% at 6 months

Notes:

1. * The w/b shall not be exceeded for a given class of exposure, regardless of exceeding the strength requirement.
2. ** Where calcium nitrite corrosion inhibitor is to be used, the same concrete mixture, but without calcium nitrite, shall be pre-qualified to meet the requirements for the permeability index in this table.
3. *** *Basic curing* - 3 days at ≥ 10˚C or the time necessary to attain 40% of the specified strength; *Additional curing* - 7 days at ≥ 10˚C and the time necessary to attain 70% of the specified strength; *Extended wet curing* - A wet-curing period of 7 days at ≥ 10˚C. The curing types allowed are ponding, continuous sprinkling, absorptive mat, or fabric kept continuously wet.
4. # To allow proper finishing and wear resistance, Type N concrete intended for use in an industrial concrete floor with a trowelled surface exposed to wear shall have a minimum cementing materials content of 265kg/m^3.

2.5.3 India (IS 456 (2000))

The Indian standard lists the factors influencing durability which include permeability to the ingress of water, oxygen, carbon dioxide, chloride, sulphate, etc. The exposure conditions are presented as qualitative, e.g. mild, moderate, severe, etc. It is important to further elaborate on these or to include forms of attack the concrete is to be protected against, in order to afford the designer a chance to make an appropriate selection for adequate protection. This standard is accompanied by a guidance document in this regard presenting the promotion of the use of cement extenders as advantageous for concrete exposed to sulphates, but no prohibition is stated for use of Portland cement only.

The standard is largely prescriptive as material constituents are given such as minimum cement content and maximum water-cement ratio, and further stipulates the concrete cover. The recommended cover is within the agreeable range (20 mm for moderate to 75 mm for extreme exposure conditions). Note that the concrete cover can be reduced for some exposure conditions provided that the concrete grade is M35 and higher, this is against durability design as it assumes that higher grade concrete is of better quality. The testing procedures are only for concrete strength, no testing procedures are outlined for assessing permeability of concrete as would be required for durability design. The durability requirements for this standard are presented in Table 2.3.

2.5.4 Europe (EN 206-1 (2013))

EN 206-1 has adopted a ‘hybrid’ specification approach as the performance-based test methods for inclusion in the standard (Kessy, et al, 2015). However, the exposure classes (Table 2.4) are well defined to the effect that they were adopted in South Africa and the UK, and possibly more countries. A requirement for durability is that concrete be tested and proven that it has an equivalent performance with respect to environmental actions, in comparison to reference concrete conforming to deemed-to-satisfy requirements for relevant exposure classes (Kessy, et al, 2015).

Table 2.3: IS 456 (2000) Durability Requirements

Exposure Environment	Exposure Conditions	Min Cement Content (kg/m^3)	Max Free Water-Cement ratio	Min Grade of Concrete	Min Concrete Cover (mm)
Mild	Concrete surface protected against weather or aggressive conditions, except those situated in coastal areas.	300	0.55	M20	20
Moderate	Concrete surfaces sheltered from severe rain or freezing whilst wet. Concrete exposed to condensation and rain. Concrete continually under water. Concrete in contact or buried under non-aggressive soil/ground water. Concrete surfaces sheltered from sulphated salt air in coastal areas.	300	0.5	M25	30
Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation. Concrete completely immerged in sea water. Concrete exposed to coastal environment.	320	0.45	M30	45
Very severe	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet. Concrete in contact with or buried under aggressive sub-soil/ground water.	340	0.45	M35	50
Extreme	Surface of members in tidal zone. Members in direct contact with liquid/solid aggressive chemicals.	360	0.4	M40	75

Notes:

1. Minimum cement content includes SCMs.
2. For exposure condition 'severe' and 'very severe', reduction of 5mm may be made, where concrete grade is M35 and above.
3. Workmanship to obtain full compaction and efficient curing.
4. Acceptance criteria and testing prioritises compressive strength testing.
5. Applicable to normal weight aggregate of 20mm nominal maximum size.

Table 2.4: Exposure Classes in EN206-1

Class Designation	**Description of the environment**	**Informative examples where exposure classes may occur**
XO	No risk of attack	Applies to all exposure categories where there is no risk of attack, e.g. reinforced concrete in a very dry condition
Corrosion induced by carbonation (reinforced concrete exposed to air and moisture)		
XC1	Permanently dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact, e.g. many foundations
XC3	Moderate humidity (60% - 80%)	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure Class XC2
Corrosion induced by chlorides from sea water (reinforced concrete in contact with chlorides from sea water or air carrying salt originating from sea water)		
XS1	Exposed to airborne salt but not in direct contact with sea water	Reinforced concrete surfaces near to or on the coast
XS2a	Permanently submerged	Reinforced concrete surfaces completely submerged and remaining saturated, e.g. concrete below mid-tide level [A)]
XS2b*	XS2a + exposed to abrasion	As above, but with heavy wave action with abrasion
XS3a	Tidal, splash and spray zones	Reinforced concrete surfaces in inetrtidal, splash, or spray zones [B)]
XS3b*	XS3a + exposed to abrasion	As above, but with heavy wave action with abrasion
Corrosion induced by chlorides other than from sea water (reinforced concrete in contact with water containing chlorides, including de-icing salts from other sources)		
XD1	Moderate humidity	Concrete structures exposed to airborne chlorides Parts of structures exposed to slightly chloride conditions
XD2	Wet, rarely dry	Reinforced concrete surfaces totally immersed in water containing chlorides A)
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides, e.g. pavements and car park slabs
Freeze/thaw attack with or without de-icing agents (for concrete exposed to significant attack by freeze/thaw cycles whilst wet)		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures expsoed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing splash zones for marine structures exposed to freezing

Chemical attack (for concrete exposed to sulphate attack from natural soils and ground water)		
XA1*	Slightly aggressive chemical environment acc to Table 2#	Natural soils and ground water
XA2*	Moderately aggressive chemical environment acc to Table 2#	
XA3*	Highly aggressive chemical environment acc to Table 2#	

Notes:

1. * Additional sub-clauses for South African coastal conditions.
2. A) Concrete members where one surface is immersed in water containing chlorides and another is exposed to air are potentially more vulnerable, especially where the dry side is at a high tempreature. Specialist advice should be sought where appropriate, to develop a specification that is appropriate to the actual conditions likely to be encountered.
3. B) Exposure XS3a covers a range of conditions. The most extreme conditions are in the splash and spray zone. It is recommended to take into account the most extreme conditions within this class.
4. + Sulphate attack from natural soil and ground water.
5. # Table 2 refers to the relevant table in EN 206-1 (2013).

2.5.5 United Kingdom (BS 8500-1:2006)

The standard is titled, "Method of Specifying and Guidance for the Specifier" and provides guidance for specifying concrete, and further, it is a complementary British standard to EN 206-1. The specifications are mostly prescriptive with the stipulation of minimum cement content, maximum water-cement ratio, etc. The exposure conditions are as described in the EN 206-1, with an extended scope to cover local conditions. The testing methods outlined do not cover assessing permeability of concrete, only compressive strength testing and the recommendations for concrete cover are decreasing with an increasing strength of concrete. This is contrary to durability design as it assumes that higher strength concrete is of better quality.

The BS EN 206:2013 standard outlines requirements for concrete specification, performance, production and conformity. It is an adoption of the European standard EN 206. The durability requirements for this standard are presented in Table 2.5.

The factor Δ_c that appears in Table 2.5 is defined as allowance in design for deviation of the cover to reinforcement; a fixing precision that allows for inaccuracies in the dimensions of the formwork and in bending and fixing of reinforcement (McDonald, 2015). Recommended values of Δ_c as below:

In-situ concrete generally	Δ_c= 15mm
Precast concrete generally (factory controlled)	Δ_c= 5mm
In-situ concrete slabs 150mm or less thick	Δ_c= 5mm
In-situ concrete slabs between 150 and 250mm thick	Δ_c= 10mm
In-situ concrete slabs over 250mm thick	Δ_c= 15mm

2.5.6 Australia (AS 3600 (2001) and AS 1379 (2007))

As elaborated by Kessy, et al, (2015), Standard AS 3600(2001) stipulates prescriptive requirements for durability, exposure classes are defined and durability requirements are given in terms of minimum compressive strength and types of curing for different exposure classes. Standard AS 1379(2007) covers requirements to comply with specified properties of fresh concrete (materials, production, testing for slump and maximum aggregate size) and hardened concrete (strength grade and exposure classes). Performance-based requirements are to be further developed due to lack of testing of as-built structures.

Table 2.5: BS 8500-1 (2006) Durability Requirements

Use	Exposure class	Nominal cover[A)] mm	Minimum designated concrete [B)]
Reinforced and pre-stressed concrete inside enclosed buildings except poorly ventilated rooms with high humidity	XC1	$(15 + \Delta c)$	RC20/25
External reinforced and pre-stressed vertical elements of buildings sheltered from, or exposed to, rain[C)]	XC3/XC4 + XF1	$(20 + \Delta c)$	RC40/50
		$(25 + \Delta c)$	RC32/40
		$(30 + \Delta c)$	RC28/35
Horizontal elements with high saturation without de-icing agent and subject to freezing while wet[C)]	XC4 + XF3	$(20 + \Delta c)$	RC40/50XF
		$(30 + \Delta c)$	PAV2
		$(35 + \Delta c)$	PAV1
Reinforced or pre-stressed buried foundation in AC-1 where the hydraulic gradient is not greater than 5	XC2/AC-1	50[D)]	RC25/30
		75[E)]	
C25/30 reinforced or pre-stressed buried foundation in AC-2 or more aggressive ground conditions	AC-2 to AC-5m	50[D)]	See[F)]
		75[E)]	

A) Check the appropriate design code to see of it is recommended that the minimum cover to pre-stressing steel is adjusted by a factor $\Delta c_{dur,\gamma}$.

B) See A.4.5 (Table A.14) for details of the specification associated with the designation.

C) If IVB-V cements and combinations are to be specifically permitted under 4.2.3a), increase the minimum cover by 5mm.

D) For casting against blinding.

E) For casting directly against soil.

F) Provided that a minimum compressive strength class of C25/30 is adequate, use A.4.4 (Table A.9) to determine the DC-class and replace the "DC-" with "FND" to obtain the designation of the appropriate designated concrete, e.g. "DC-3s" becomes "FND3s". If a higher compressive strength class is required, specify a designed concrete using the required compressive strength class and the DC-class.

Limiting values given for 20 mm maximum aggregate size

Maximum w/c ratio	Minimum cement or combination content kg/m^3
0.70	240
0.65	260
0.60	280
0.55	300
	320
0.50	320
	340
0.45	340
	360
0.40	380
0.35	380

2.5.7 Switzerland (SIA 261/1 (2003))

The Swiss standard SIA 261/1:2003 advocates for designing and testing as-built concrete structures for durability characteristics (Beushausen, et al, 2008). The approach generally appears to be similar to the South African approach; the durability tests are air permeability tests, chloride migration tests and sorptivity tests (Beushausen, et al, 2008). It is foreseen that an update to this standard would be an improvement to the current ‘hybrid’ approach, with reports on practical implementation.

2.5.8 South Africa (SANS 10100-2:2014 and SANS 2001-CC1:2012)

These standards cover concrete materials and execution of concrete work. The exposure conditions are qualitative with more elaborated descriptions to assist the designer to the right selection. Concrete cover is stipulated in line with exposure conditions and concrete strength. Concrete cover reduces with an increasing concrete strength, this is not in line with durability requirements as it assumes that higher concrete strength is of better quality and meets durability requirements. The standards include limits on overall maximum cement content (550 kg/m^3) due to workability and cracking for all types of concrete, and maximum water-cement ratio only for concrete exposed to freezing and thawing (0.53) and concrete for water-retaining structures (0.50), and chloride and sulphate contents.

It is a positive that the standards give the designer an opportunity to request and review the concrete mix design as this provides a chance to design a mix that will meet durability requirements, assuming that the designer is aware of these, which is part of this research through survey questionnaires. SANS 10100-2 specifies tests for compressive strength and does not cover tests for permeability of concrete. SANS 2001-CC1 specifies compressive strength tests, tests for water-tightness (penetrability) and tests for sulphate content. This testing methodology is suitable to some extent for performance-based approach; therefore, the standard is a ‘hybrid’ approach. The durability requirements for this standard are presented in Table 2.6. Ballim, et al, (2009a) proposed the specifications shown in Table 2.7 for concretes exposed to the atmosphere as guidance to designers/specifiers. It is important to note that no correlation is made between concrete cover and concrete strength, which is in line with the durability design requirements.

Table 2.6: SANS 10100-2:2014 / SANS 2001-CC1:2012 Durability Requirements

1	2		3	4	5	6	7
Conditions of exposure	Description of member/surface to which the cover applies		Class of concrete				
			20	25	30	40	50
			Characteristic minimum cover mm				
Moderate	1.1	Surfaces protected by the superstructure, such as the sides of beams and the undersides of slabs and other surfaces not likely to be moistened by condensation	50	45	40	30	25
	1.2	Surfaces protected by a waterproof cover or permanent formwork not likely to be subjected to weathering or corrosion					
	1.3	Enclosed surfaces					
	1.4	Structures or members that are permanently submerged in water					
Severe	2.1	All exposed surfaces	NA	50	45	40	35
	2.2	Surfaces on which condensation takes place					
	2.3	Surfaces in contact with soil					
	2.4	Surfaces permanently under running water					
	2.5	Cast in-situ piles:					
		i) Wet cast against casing	50	50	50	50	50
		ii) Wet cast against soil	75	75	75	75	75
		iii) Dry cast against soil	75	75	75	75	75
Very severe	3.1	All exposed surfaces of structures within 30 km from the sea	NA	NA	NA	60	50
	3.2	Surfaces in rivers polluted by industries	NA	NA	NA	60	50
	3.3	Cast in-situ piles, wet cast against casings	NA	NA	NA	80	80
Extreme	4.1	Surfaces in contact with sea water or industrially polluted water	NA	NA	NA	65	65
	4.2	Surfaces in contact with marshy conditions					

NOTE 1 The cover values are characteristic minimum cover values and not more than 5 % of cover measurements should fall below these values, in addition, no single cover measurement should fall below 5 mm less than the relevant cover value indicated above.

NOTE 2 In uncracked concrete the degree of protection that the concrete affords the reinforcing steel depends on the quality and thickness of the cover. Apart from the class of the concrete, the quality of the cover will among other things be affected by the method and duration of curing and the type of binder used, for example well-cured fly ash concrete without extenders. If the quality of the cover can be proven to be satisfactory to the requirements of the engineer, by for example using improved curing techniques or extended cement, the requirements in table 3 can be relaxed at the discretion of the engineer. For additional information see 2.2 and the bibliography.

NOTE 3 NA = Not applicable.

Table 2.7: Recommendations for concrete exposed to the atmosphere, (Ballim, et al, 2009a)

Specification for concrete to be used	Type of environment			
	Non-polluted	Polluted	Corrosive	Highly corrosive
Minimum cement content, kg/m^3	As dictated by strength requirements	340	380	420
Cement type	Any cement complying with SANS 50197-1 70% CEM I + 30% FA 50% CEM I + 50% GGBS			
Maximum w:c	As dictated by strength requirements	0,55	0,50	0,45
Minimum cover to steel, mm	25	30	40	50
Minimum strength	As per structural requirements			

Definitions of type of environment (Ballim, et al, 2009a):

Non-polluted – Mostly non-industrialised rural and sparsely populated urban areas situated more than 20 kilometres from the coast.

Polluted – Mostly urban areas where there is heavy vehicular traffic conditions and moderate industrial activity; and rural areas within 20 kilometres of the coastline.

Corrosive – Areas in the immediate proximity of heavily air-polluting activities.

Highly Corrosive – Areas where acid rain occurs as a result of the corrosive gases, condensing onto structures or being washed onto them by the scrubbing action of naturally occurring rain.

2.6 South African Durability Indexes in Comparison to International Tests

Beushausen and Alexander, (2008) carried out a comparative study between South African durability index tests and international durability index test methods. It was found that the South African chloride conductivity and oxygen permeability test methods produced comparable results in evaluating concrete durability characteristics, and have similar merit in establishing material properties as internationally accepted durability test methods; viz. Cembureau permeability test, Torrent permeability test, Rapid chloride permeability test (ASTM C 1202), and Bulk diffusion test (NTBuild 492 1999). The water sorptivity index test presented some difficulties in results as it was reported to have failed to reliably differentiate between certain concrete mixes compared to Absorption rate test method by RILEM (RILEM TC116-PCD 1999). Further work for clarification was recommended for the water sorptivity index test.

2.7 Durability Design and Specification - Material Selection and Quality

Durability design can be optimised by the selection and use of alternative concrete materials e.g. supplementary cementitious materials (SCMs) (Tang, et al, 2015), and recycled aggregates (Manzi, et al, 2013). Designing, specifying and constructing durable concrete will contribute to sustainability as natural resources will be preserved. This means that structures will remain in service for longer periods or meet their design service life with minimal to no repair work required. This will result in drastically reduced requirement for extraction of natural resources for the production of new construction materials, for the purposes of repair work or premature re-construction.

The quality of concrete is one of the parameters that the designer can specify to achieve the desired service life under the exposure conditions; increasing material quality means a denser, less penetrable concrete which slows the rate of ingress of aggressive agents (Alexander, et al, 2008).Various interventions on the selection of materials are currently in use in the design and specification of concrete structures with some still under research and development phases as discussed below. Also, the quality and thickness of the concrete cover is very important in ensuring that aggressive agents are deterred from entering concrete.

2.7.1 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a byproduct of the blastfurnace process which is used to produce iron. It consists mainly of silica and alumina, derived from the iron ore, and lime or dolomitic lime added as a flexuring agent. It is manufactured by quenching the hot slag with water ensuring rapid cooling and then milled to a fine powder (Grieve, 2009). This is a powder with specific surface of about 400 to 600 m^2/kg and average particle size of 0.45 micron and can be used to replace a certain cement content in the concrete mix (Grieve, 2009).

GGBS reacts with and in water to form cementing compounds when it is alkali activated. The hydration products are the same as for Portland cement except that no calcium hydrate (CH) is liberated (Grieve, 2009). Thejaskumar and Ramesh, (2015) found in their study that replacing cement with up to 55% of GGBS did not affect the strength and durability of concrete, it is important to note that chloride binding capacity still needs to be established for this replacement content.

The chloride binding effect of this extender was also established by Potgieter et al, (2011). What can be deduced from their work is that there is a possibility that a higher composition of the extender will have more chloride binding effect. Plain cement mixes outperformed maximum 30% blended cements with regard to chloride binding, but reported that previous work by Hirao and Yokohama found that blended Ordinary Porland Cement (OPC) and Ground Granulated Blast Furnace Slag (GGBS) cement had increased chloride binding compared to OPC alone, with a 60 % GGBS addition to OPC.

2.7.2 Fly Ash (FA)

FA is extracted by electrostatic precipitators or bag filters from the flue gases of furnaces fired with pulverised coal. After extraction, fly ash is classified into fine and coarse fractions. The fine fraction is used as an extender and the coarse fraction is used in other applications; with specific surface of about 300 to 500

m^2/kg and an average particle size of 0.20 micron, although some fly ashes can have surface areas as low as 200 m^2/kg and as high as 700 m^2/kg (Grieve, 2009).

FA reacts with calcium hydroxide ($Ca(OH)_2$) in water to form cementing compounds and does not react with water; the cementing compounds formed are the same as those formed by the hydration of Portland cement (Grieve, 2009). Careful selection of FA containing high proportions of sulfate ions (SO_4^{2-}) and free lime (CaO_f), and fineness of around 560 m^2/kg was found to not have a negative effect to the chloride resistance, durability of concrete and compressive strength (Chousidis, 2016). Also, the chloride binding capacity of FA is higher than that of plain cement due to a high aluminate content and it offers a limited peak in temperatures of mass concrete pours, controlling thermal diffusion (Sheath, 2010).

2.7.3 Silica Fume (SF)

SF is a byproduct of the ferrosilicon smelting process and is the condensed vapour from the process. SF is extremely fine with the reported specific surface of about 20 000 m^2/kg and an average particle size of 0.15 micron (Grieve, 2009). Due to this fineness, it is not possible to achieve dense packing with the resulting bulk density of about 200 kg/m^3 and consequent difficulty in handling and transportation; therefore, in order to make the material more manageable, it is densified by means of electrostatic forces that cause particles to agglomerate into small pellets about 0,5 mm in diameter improving the bulk density to about 600 kg/m^3 (Grieve, 2009).

SF reacts in the same way as FA above. As a result of its reaction with calcium hydroxide ($Ca(OH)_2$), it slightly reduces the pH value of pore water. It further necessitates the use of superplasticisers due to the effect it has on workability, these have no effect on pore structure and the process of corrosion (Neville, 1995).

2.7.4 Durability of sustainably sourced/recycled aggregates

Selection of non-reactive aggregates is vital as it contributes to the durability of concrete structures (Hooton, 2015). Natural resources such as gravel and sand pits and rock quarries provide the main sources for aggregates and raw materials for concrete production in South Africa, with course aggregates being totally sourced from crushed rock (Muigai, et al, 2013). Aggregates, both fine (<4.75mm) and coarse (>4.75mm – 40mm) account for 65% to 80% of the volume of concrete (Muigai, et al, 2013). With the aforementioned volume content, it is foreseen that there is likely to be a depletion of the natural resources in the near future due to extraction thereof; this is coupled with the associated carbon dioxide (CO_2) emissions which are deleterious to the environment.

Interventions to prevent depletion of natural resources include utilisation of recycled aggregates, (e.g. demolished concrete as aggregates, crumb rubber from tyres, etc.). However, these interventions are still under development with numerous researchers investigating the structural impacts and effects on the durability of concrete due to the use of these alternatives (Muigai, et al, 2013). In line with this, recycled concrete aggregates (RCA) have become increasingly popular for mostly sub-base material and low grade concretes (Dodds, et al, 2017).

Though, there seems to be a general consensus in the literature on that there is a loss in the physical and mechanical properties of concrete. The use of supplementary cementitious materials (SCMs) has been proven beneficial for use in the recycled aggregates concrete (Dodds, et al, 2017). Dodds et al, (2017) recommended that the replacement of cement (CEM1) and natural aggregates (NA) be limited to 50% and 30% respectively where the 28day characteristic strength is required.

On durability performance tests, blended cement concrete samples with recycled aggregates appeared to perform better than unblended CEM1 concrete samples with natural aggregates (Dodds, et al, 2017). This is further confirmed by Manzi, et al, (2013), in that the use of RCA can lead to very dense microstructures, resulting in reduced permeability. Thomas, et al, (2013) however, linked better durability performance of RCA to the low water/cement ratio.

2.7.5 Quality of the concrete cover

Through the careful selection and proportioning of concrete mix ingredients, good quality concrete should be arrived at in relation to the environment the concrete structure will be exposed to. The construction processes of adequate compaction and prolonged curing will ensure that required performance is achieved (Neville, 1995). Good quality concrete cover means a denser, less penetrable concrete which slows down the rate of ingress of aggressive agents (e.g. chloride ions or CO_2), resulting in improved durability (Alexander, et al, 2008). The durability of reinforced concrete is greatly enhanced if adequate cover is provided to the reinforcement (Alexander and Mackechnie, 2003). Adequate concrete cover is one of the key factors to make concrete more durable (Perrie, 2017).

The concrete cover should not be too thick as to ensure the composite action of concrete and reinforcement, or too thin as this may result in aggressive agents being transported rapidly to the surface of the steel (Neville, 1995). For practical purposes, concrete cover depth is usually restricted to between 25 mm and 80 mm depending on the exposure conditions; and the actual value is specified by the designer, noting that typical minimum cover depths are 30 mm for a carbonating environment and 50 mm for a seawater environment (Alexander, et al, 2008). Concrete durability also depends on proper curing as improper or inadequate curing will lead to a more penetrable surface or surface defects such as cracks due to shrinkage, etc. (Łaskawiec, et al, 2015), allowing rapid ingress by aggressive agents.

From the review of literature, contributions by stakeholders to the production/construction of a new concrete structure through the different stages of the project should closely be as presented in Figure 2.6.

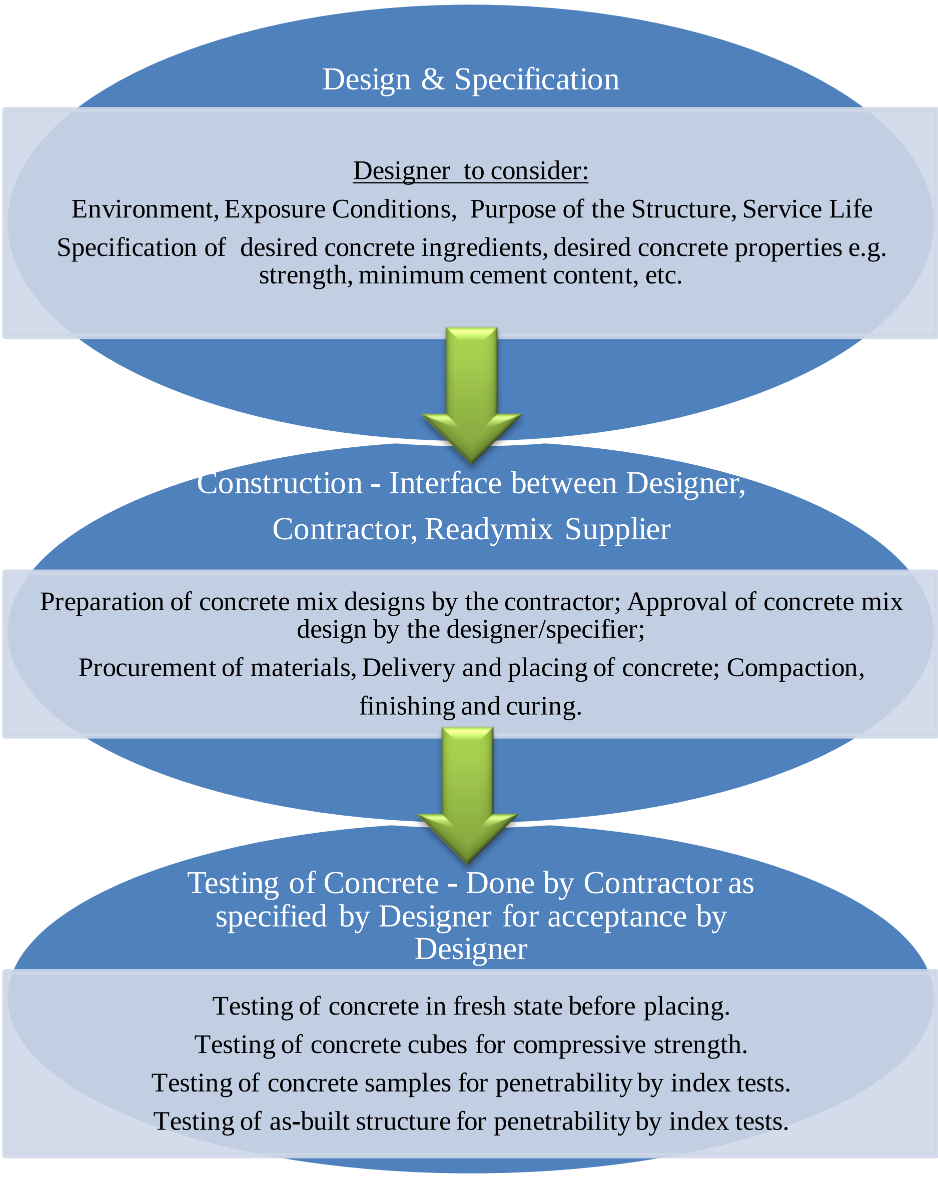

Figure 2.6: Sequence of activities for durability design and construction of new concrete structures

2.8 Conclusions on the Literature Review

As can be seen from the literature review, most specifications are largely prescriptive and testing methods do not cover for assessment of the penetrability of as-built concrete. In South Africa, the specifications are ‘hybrid’ and the testing methods to assess the penetrability of concrete have been developed and formalised as national standards. The ‘hybrid’ approach is a step towards implementing full performance-based design and construction as it is prescriptive specifications with emphasis on performance-based specifications. Through this research, the awareness of stakeholders in the industry will be established through industry surveys, and further to what extent is durability design considered in practice. The testing methods applied in the industry will also be evaluated with an objective to establish how the penetrability of concrete is assessed in practice.

A few points are drawn below based on the literature review:

a) The selection of binder composition and content is important in improving the pore structure of concrete resulting in less penetrable concrete that can withstand ingress by aggressive agents.
b) The use of SCMs is important in keeping with environmental preservation and reducing cement production thereby reducing CO_2 emissions.
c) The selection of aggregates is also vital in producing durable concrete structures. However, in keeping with the preservation of natural resources, alternative aggregates need to be sourced which possibly leads to future research needs in South Africa.
d) In comparison to international standards, South Africa has made substantial progress in durability design and specification noting that the durability index tests have been formalised into SANS standards. This should form the basis of moving to full performance-based approach.
e) Mostly, in a global level, standards are more leaning towards prescriptive specifications even though research work is underway in some countries to transform to performance-based specifications.

Chapter 3

3 RESEARCH DESIGN & METHODOLOGY

3.1 Research Design

With the nature of this research, the method adopted to obtain required information was a survey through the use of structured questionnaires. The survey questionnaires were designed to obtain qualitative and quantitative information to address the study objectives as follows:

a) to establish the awareness of practicing engineers on the subject of durability design, specification, construction and testing of concrete structures; and how they apply the durability approach.
b) to review the curricula of South African institutions of higher learning in civil engineering to establish how concrete durability has been incorporated therein.
c) to establish the awareness of other stakeholders in the construction industry on the subject of concrete durability approaches.

3.1.1 Questionnaire design and rating scale

For this research, a survey was done in form of questionnaires designed to source information required from respondents. These were electronic mail questionnaires addressed to the selected respondents or administered in person by the researcher. Due to the study limitations, the survey through electronic mail was more economical than individual interviews; however, individual interviews were carried out depending on the need during the research period. The questionnaires were designed to cover the focal points of the study; namely, design, specification, construction and testing of concrete.

The survey was designed with close-ended questions and some open-ended questions as follow-up to close-ended questions. The close-ended questions were assigned a 1 to 5 Likert scale rating, for the purposes of standardisation and comparison of responses. The Likert scale is one of the simplest and most widely used scales for research purposes (Othman, et al, 2005). The respondents were able to rate the statements in the questionnaire using a five-point scale: (1) Strongly agree, (2) Disagree, (3) Neutral, (4) Agree, (5) Strongly Agree.

3.1.2 Identification of target population

A stratified random sampling was used in this research to identify the target population and select a representative sample. A stratified sampling is a selection of a subset or group of individuals with similar interests from the target population; whereby, a random sampling is where each individual within the target population is chosen by chance thereby reducing the likelihood of bias (Wright, 2009). The concrete industry is broad with numerous stakeholders, a selection of relevant stakeholders was carefully considered in line with the research objectives. These were individuals involved in designing, specifying, constructing and testing of concrete.

The response rate has to be taken into consideration when determining a sample size, particularly in a randomly selected sample; the response rate being a number of returned questionnaires with complete responses. In general terms, the design and structure of a survey questionnaire and duration thereof will have an impact on the response rate (Fincham, 2008); and this has to be borne in mind when designing a questionnaire. A sample is selected from the relevant population as access to the entire population at a given time may not be feasible (Field, 2013). Therefore, a small group representative of the population was selected for this reason.

The identification of the sample population and selection of the sample size are as equally important as a small sample will not result in reliable results (i.e. large sample error which will affect reliability of the survey) or adequate sample representativeness (i.e. sample representative of the relevant population) (Ramsey and Hewitt, 2005). Other factors that influence the sample size are confidence level and confidence interval; these are used as input in determining the sample size (Wright, 2009). A confidence level being a percentage certainty with which one can state the characteristic measured by a question, whereas a confidence interval is a population range within which the characteristic can be said to be applicable (Check.Market.com).

As evident from the literature review, practical applications of durability design and construction (performance-based approach) have not been implemented completely, and currently a 'hybrid' approach is in place. On this basis, it is deemed suitable to establish the larger effects for this survey as it will be determined on a wide scale how durability design and construction are applied on actual projects and to what extent. With this in mind, a confidence level of 95% and a confidence interval of 20% were selected, resulting in sample sizes for relative subgroups. A confidence interval of 20% is in this case feasible to determine the larger effects across the actual populations (Field, 2013), this is the range within which the results can be said to be reliably applicable (-20%; +20%).

The selection took into consideration previous similar studies in terms of relative sample sizes (Oosthuizen and Nienaber, 2010). There is a general notion that participation in a survey by the industry practitioners is low. Ugwu and Haupt (2007), also reported on this, in that industry participants have a history of non-responsiveness when it comes to electronically distributed survey questionnaires. This then had an impact on the expected response rate for this study. The sample selection and sample size for each group is shown in Table 3.1.

Table 3.1: Sample selection and sample size calculation

Sample Size Calculation			
Population Group	Source of Population Identified	Population Size	Sample Size (Confidence Level / Confidence Interval - 95%/20%)
Tertiary Institutions	Tertiary Institutions	12	8
Engineers	CESA Database	144	21
Contractors	CIDB Database	87	19
Readymix	SARMA Database	15	9
Cement	CEMNET Database	4	4
Admixtures	Internet search	5	4

As can be seen in Table 3.1, a database of companies for stakeholders relevant to this survey was accessed through industry bodies that were accessible on the internet. It is envisaged that a company should represent a unit of analysis and the individual represent the unit of relative practice. This, on the basis that companies have standardised issuance of information or practices; and individuals usually follow these closely with some variations as and when required. It is important to acknowledge innovation and a better way of doing things over the years; hence, surveying one person per company would not be sufficient. For this survey, different views within the same organisation were sourced to realise a difference of opinions from individuals, regardless of the company they represent.

Tertiary Institutions – the sample was selected from institutions of higher learning and entailed 3rd year students in the BSc and National Diploma and 4th year students at the BTech level in civil engineering (2 to 3 students per institution); for the purpose that graduates of these courses are mostly positioned as consulting engineers or engineers for construction companies in practice.

CESA – Consulting Engineers Southern Africa, a database of consulting engineers is provided by this organisation and it warrants access to a large number of practicing engineers. A discipline involved (civil and structural) was used as a selection tool for this survey. Also, the geographical location was taken into consideration, bearing in mind that survey respondents may have been involved in projects outside of this location, thereby providing information based on experience and project involvement rather than the current location.

CIDB – Construction Industry Development Board, a database of construction entities is provided by this organisation and it warrants access to a large number of construction entities. These entities are registered in different disciplines and grades (1 to 9 depending on the value and scale of projects). The highest grade means that an entity is involved with construction of large scale projects with values in excess of R130 million. For this survey, the entities with the highest grade were selected as it is envisaged that they get involved in prominent structures, structures that would be expected to be of much priority to employ the approach of performance-based design and construction. Also, the geographical location was taken into consideration, bearing in mind that survey respondents may have been involved in project outside of this location, thereby providing information based on experience and project involvement rather than the current location.

SARMA – South African Readymix Association, a database of readymix concrete entities is provided by this organisation and it warrants access to a large number of readymix concrete entities. These were selected in line with the geographical location for this study. This database was supplemented by search engines on the internet.

CEMNET – Cement Productors, a database of cement production entities is provided by this organisation and it warrants access to a large number of cement production entities. These were selected in line with the geographical location for this study.

Concrete admixture production entities were obtained by means of internet search and selected in line with the geographical location for this study.

The ratio of stakeholders accessed for this survey is presented in Figure 3.1 and the ratio of the sample sizes from each subgroup is presented in Figure 3.2.

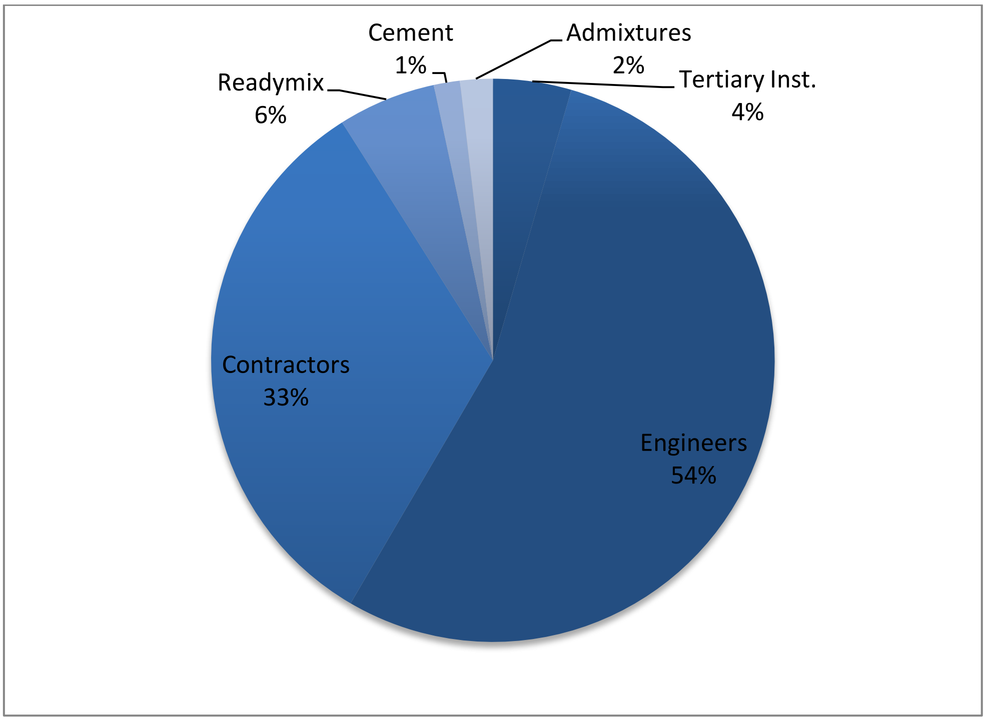

Figure 3.1: Population statistics for this research

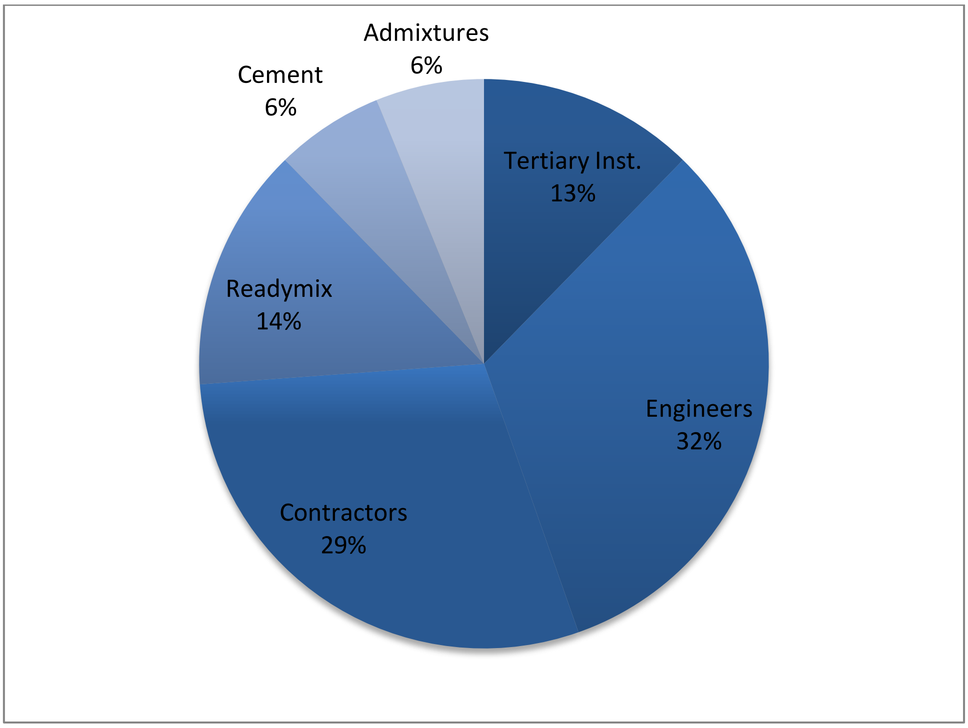

Figure 3.2: Sample size for confidence level 95% and confidence interval 20%

3.2 Methodology

The production of concrete requires a number of stakeholders who contribute by supplying designs, specifications, construction materials and the construction of elements. It is important to understand the contribution of each of the stakeholders to the production of durable concrete. In this study, information from stakeholders as described below was obtained in a form of industry surveys; these would be supported by oral interviews where necessary and possible.

The survey sought to establish current processes followed by designers to design and specify concrete, leading to construction and testing practices which were also reviewed. From this information, it would then be surmised as to whether durability design is catered for in the way concrete is designed, specified, constructed and tested. Recommendations on the way forward or improvements in the current practises will be arrived at. The questionnaires used are included in Appendix A.

3.3 Stakeholders Involved in the Production of Concrete

3.3.1 Tertiary Institutions

The contribution made by tertiary institutions is through education on concrete materials, design, specification, construction methods and testing of concrete. The civil engineering curriculum from a selection of tertiary institutions was perused through surveys to establish how concrete durability design is covered therein. It is important that durability design be included at this level of education as it is conceivable that understanding the subject makes it more approachable to implement in practice. For the survey, information below was required from these respondents in order to assess their understanding of durability design, specification, construction and testing:

- Whether or not the importance of exposure conditions being taken into consideration when designing concrete structures was covered in the curricula.
- Whether or not the selection of concrete mix ingredients and proportioning thereof was covered in the curricula.
- Whether or not the testing of concrete in the fresh and hardened states was covered and testing methods therefor.

3.3.2 Consulting Engineers

Consulting engineers are in a position to specify, review and approve concrete mix designs from concrete producers. Their understanding of the subject of durability is expected to come from tertiary education and industry awareness. As per our current standards, SANS 10100-2 and SANS 2001-CC1, the responsibility to design, specify concrete properties required, and review and accept test results for concrete structures lies with the consulting engineer.

Mandated tests are compressive strength test of concrete; durability testing in terms of DI tests is additional (not mandated) and therefore, the consulting engineers should include these in project specifications in order for contractors to allow in the cost and project schedule and further execute accordingly. It is with this in mind that survey responses from the stakeholders in following sections are viewed as confirmatory information to the responses from the consulting engineers for the purposes of this study.

If additional tests are not specified in project specifications during the tender stage, they will not be undertaken in a project as these will present a cost and time implication, unless necessary approvals of these factors are given. This study sought to review the concrete specifications issued by consulting engineers to establish how durability is taken into consideration. For the survey, information below was required from these respondents in order to assess their understanding of durability design, specification, construction and testing:

- How exposure conditions are taken into consideration when designing concrete structures.
- How the selection of concrete mix ingredients and proportioning is done; further, what procedures are used to review and approve these before construction.
- The awareness about the use of cement extenders and concrete admixtures.
- The tests done for testing of concrete in the fresh and hardened states.

3.3.3 Contractors

Contractors ensure implementation of the engineer’s specifications, but this has to be done with a certain level of understanding. Further, they provide advice in cases where alternative construction methods are necessitated by a design. However, for the purposes of this study, the information they provided was to confirm whether or not, specifications as issued by consulting engineers includes performance-based design. For the survey, information below was required from these respondents in order to assess their understanding of concrete durability:

- How the selection of concrete mix ingredients and proportioning is done; further, what procedures are used to review and approve these before construction.
- The awareness about the use of cement extenders and concrete admixtures.
- The tests done for testing of concrete in the fresh and hardened states.
- The overall awareness with regard to concrete durability.

3.3.4 Readymix Concrete Producers

Readymix concrete producers gather concrete mix ingredients (coarse aggregate, fine aggregate, water, cement and cement extenders, and admixtures where required). These are mixed in certain proportions following relevant standards and specifications to produce concrete. A concrete mix design should be produced and tested in the laboratory prior to batching of bulk concrete. Aggregates should be carefully selected for the production of concrete in the sense that reactive aggregates should be avoided; this is to prevent undesired reactions from taking place resulting in damaged/defective concrete. This study sought to evaluate how concrete mix designs take into consideration the durability of concrete. For the survey, information below was required from these respondents in order to assess their understanding of concrete durability:

- How the selection of concrete mix ingredients and proportioning is done; further, what procedures are used to review and approve these before construction.
- How the concrete mix ingredients for use in a project are sourced.
- The awareness about the use of cement extenders and concrete admixtures.
- The tests done for testing of concrete in the fresh and hardened states.
- The overall awareness with regard to concrete durability.

3.3.5 Cement Producers

Cement producers are important stakeholders in the design and specification of durable concrete. Amongst the factors that affect penetrability of concrete, the cement type and content has an impact on the penetrability of concrete which in turn affects durability. To this end, it will be established how cement producers have embraced the concept of durability design, and their input therein. Further to this, literature on the types of cements in current production as provided by cement producers was perused. For the survey, information below was required from these respondents in order to assess their understanding of concrete durability:

- The type of cement mostly in use or in high demand.
- The evaluation of the developments in the cement production industry.
- The overall awareness with regard to concrete durability.

3.3.6 Concrete Admixture Producers

Concrete admixtures are used for different requirements in the production of concrete; not limited to improved workability with low water usage in fresh concrete and water resisting (waterproofing) to discourage ingress of water in hardened concrete, etc. Their use has primary effects on concrete in the fresh state (such as better workability with the reduced water content, etc.), and may have secondary effects on concrete in the hardened state (such as impact on strength gain, etc.). For the survey, information below was required from these respondents in order to assess their understanding of concrete durability:

- The type of admixture mostly in use or in high demand.
- The evaluation of the developments in the concrete admixture production industry.
- The overall awareness with regard to concrete durability.

3.3.7 Employers/Clients

Employers are usually the project funders who have enlisted the services of the designer (consulting engineers) to design and oversee the construction of structures on their behalf. Some employers have capacity to design and oversee the construction of structures. Further, these employers sometimes stipulate the testing methods they require for their structures and the limits within which structures can be accepted.

3.3.8 South African National Standards – Concrete

This is a body of professionals who prepare and publish the recommendations for design and construction of concrete structures in a standardised manner. These standardised recommendations are to ensure that a structure designed and constructed on this basis would be fit for purpose. They provide an informed guidance in this regard for practicing professionals. Their inclusion in this study is to evaluate how durability is presented in the current standards.

3.4 Stakeholder Interaction

The interaction of stakeholders highlights a critical exchange of information in any given project. This is important as it ensures that the end product meets the requirements and objectives with which the project was initiated. By way of the employer communicating their needs to the engineer, the engineer should produce a design based on the employer's requirements and standards. The engineer further liaises with the appointed contractor during construction to enforce quality control procedures. The contractor, through liaisons with the readymix concrete producer interacts with other concrete material suppliers, i.e. cement suppliers and admixtures suppliers.

The engineer, in furtherance of quality control responsibilities receives, reviews and approves the concrete mix design by the readymix concrete supplier through the contractor; an indirect liaison with the material suppliers. It is important to note that there are circumstances where the engineer should have direct liaisons with the material suppliers. The engineer should carry out site inspections during concreting activities to ensure that this is done according to industry norms, and should further enforce that testing is done as specified. As depicted in Figure 3.3, there is an exchange of information between the stakeholders who are all guided by the standards, and the outcome of these liaisons contributes to the production of a durable concrete structure.

The involvement of stakeholders and their respective contribution in the production of concrete structures is graphically illustrated in Figure 3.3

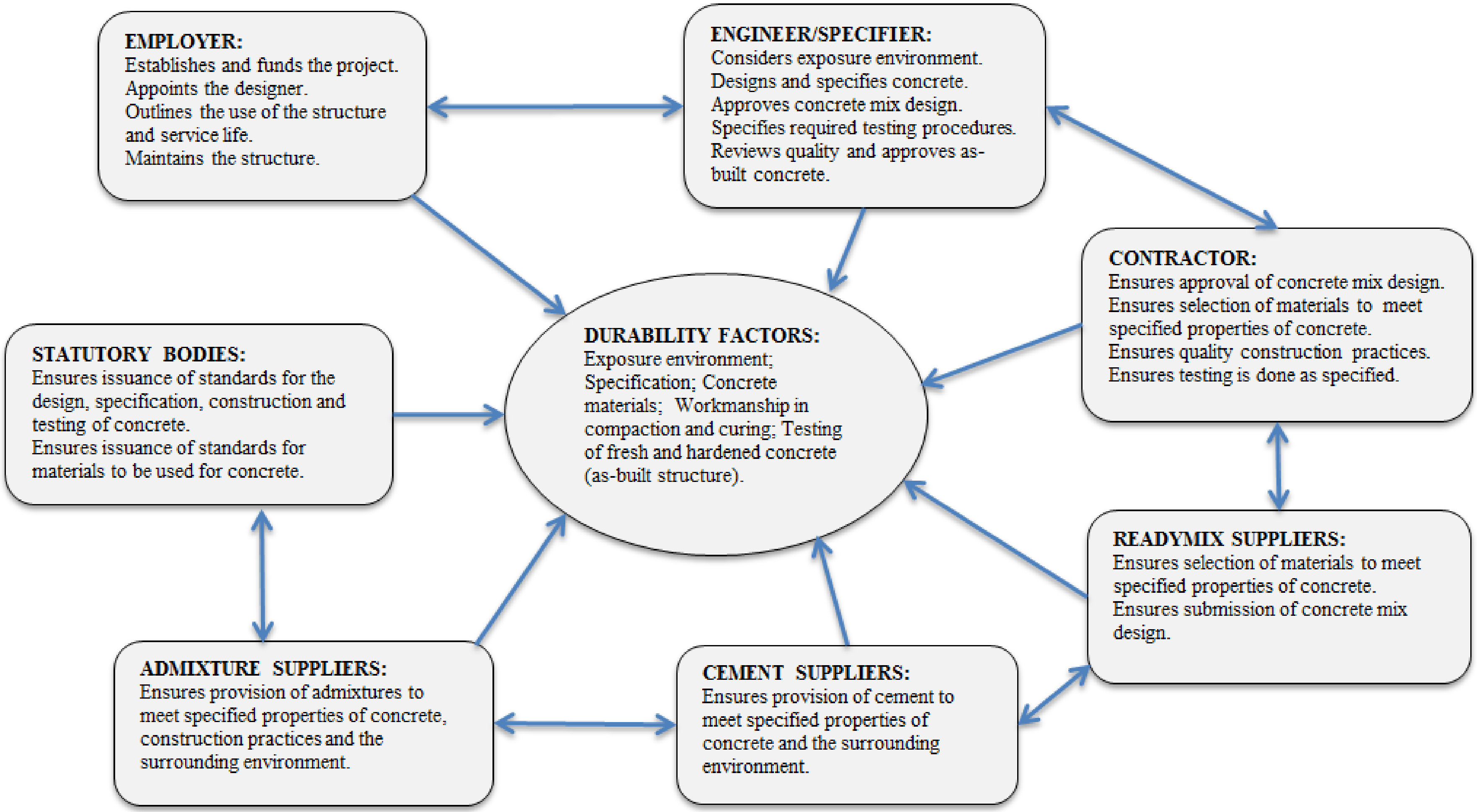

Figure 3.3: Stakeholder Interactions

Chapter 4

4 RESULTS AND DISCUSSION

4.1 Results

The survey questionnaires presented in Appendix A sought to find both qualitative and quantitative characteristics of concrete durability design, specification, construction and testing. This was done by the selection of an appropriate answer to the statements, in agreement or disagreement by survey respondents. The responses were then quantitatively evaluated by assigning scales from 1 to 5 on a Likert scale. The statistical methods used included evaluation of internal reliability test by means of computing Cronbach's Alpha, central tendency by median and variability by frequencies.

Internal reliability provides a meaningful estimation of the degree with which a set of questions in a survey measure a similar underlying characteristic, thereby determining the accuracy of measurement (Warmbrod, 2014); (Gliem and Gliem, 2003). Robinson, et al, (1991), provide the following ranges for Crobach's Alpha as a general criteria for reliability acceptance: > 0.80 is exemplary, > 0.70 is extensive, > 0.60 is moderate, and < 0.60 is minimal. With the data for this survey being ordinal, i.e. data in which an ordering ranking can be done but no measure of distance between the ratings can be done (Allen and Seaman, 2007); analysis by computation of median and frequencies was adopted as recommended by Boone and Boone, (2012).

The null hypothesis was tested and computed using a Chi-square test for independence; this test is used to determine whether the observed survey variables are related and further, the statistical significance of the relationship (Plackett, 1983). The strength of this association or relationship is determined by Cramér's V formula. All statistical computations mentioned above are briefly explained in Appendix B.

The surveys were run over a period of 14 weeks and the summary of responses received is presented in Table 4.1, extended to show the response rate.

Table 4.1: Survey response rate

Survey Response Rate			
Population Group	Sample Size (Confidence Level / Confidence Interval - 95%/20%)	Responses Received	Response Rate %
Tertiary Institutions	8	8	100%
Engineers	21	18	86%
Contractors	19	6	32%
Readymix	9	3	33%
Cement	4	3	75%
Admixtures	4	4	100%

The response rates shown are acceptable noting that the sample size selection was aimed at evaluating larger effects (Field, 2013). It is important to note that numerous follow-ups were made by the researcher in an effort to obtain more responses, even though some stakeholders show a low response rate.

It is important to note that Employers and the South African National Standards were not included as part of the survey in the current study. On the basis that in most cases, Employers are guided by practitioners in the design and construction of concrete structures; this excludes Employer bodies like SANRAL whose awareness of the developments in concrete durability have been covered in Chapter 2. The position of the South African National Standards can be established through the review of the current standards in comparison to the older standards in order to determine how concrete durability has evolved over the years. The review of the current standards has also been covered in Chapter 2 of this report. Therefore, the information already covered diminishes the need to survey these stakeholders as it is not foreseeable that information to the contrary would be obtained through the survey.

The Likert scale is shown in Table 4.2.

Table 4.2: Likert scale used

Likert Scale Used					
	1	2	3	4	5
Observed Characteristics	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Cronbach's Alpha coefficients for questionnaires were computed and resulted in a range of 0.62 to 0.90; moderate to exemplary (Robinson, et al, 1991), taking into consideration deletion of redundant questions (briefly explained in Appendix B) where applicable. Survey data was either analysed in a Likert scale whereby a series of questions is grouped or Likert type item whereby an individual question is analysed (Boone and Boone, 2012), as deemed appropriate as can be seen in the analysis below.

4.2 Analysis of Survey Data

The analysis of the survey data was carried out following two approaches namely:

a) analysis focusing on the responses of all stakeholders to similar survey questions. This was done to assess the views of the different stakeholders on similar durability-related aspects.
b) analysis focusing on each stakeholder's responses to specific survey questions. This was done to assess the views of individual stakeholders on durability-related aspects that are specific to that stakeholder.

4.2.1 Analysis focusing on specific durability-related aspects

This analysis was done by carefully selecting durability-related factors that have an influence in the durability of concrete. The factors selected were:

a) Exposure environment;
b) Selection of cement;

c) Selection of aggregates;
d) Compaction and curing of concrete; and
e) Testing of concrete penetrability, specifically the application of DI tests.

It is important to note that the survey questionnaires (Appendix A) were designed to cover the subject of concrete durability design, specification, construction and testing; with questions posed indirectly to the durability of concrete to avoid biased responses or leading the respondents' line of answering. All questionnaires were applicable to projects that were undertaken by stakeholders within the past five years. Table 4.3 below presents a summary of the survey questions used in the analysis of the various durability-related factors mentioned above.

Table 4.3: Summary of survey questions used for the analysis of durability-related factors

Stakeholder / Respondent	Survey questions used				
	Exposure environment	Selection of binder type	Selection of aggregates	Compaction and curing	Testing of concrete penetrability
Readymix concrete	Q3	Q5	Q11	-	Q29
Contractors	Q3	Q5	Q9	Q21,Q26,Q27, Q28,Q29	Q18
Tertiary institutions	Q1	-	-	-	Q24
Consulting engineers	Q4	Q6	Q9	Q24,Q25,Q26	Q22
Cement Producers	-	Q3	-	-	-

Note: See Appendix A for questionnaires for the respective respondents

4.2.1.1 Exposure environment

All stakeholders involved in the design, specification, construction and testing of concrete, i.e. Tertiary Institutions, Consulting Engineers, Contractors and

Readymix Concrete Suppliers showed a high level of agreement with the statements that the surrounding environment influences the selection of concrete mix ingredients. This is confirmation that concrete should be designed for a given environment and the specification must be site specific. In turn, this will ensure that concrete is durable within the given conditions over the design service life and can withstand those conditions without showing significant deterioration. Figure 4.1 shows a graphical presentation of response data received. This figure was plotted using averages of all the responses received from the respective stakeholders. The error bars were plotted in line with the confidence level selected as covered in Chapter 3.

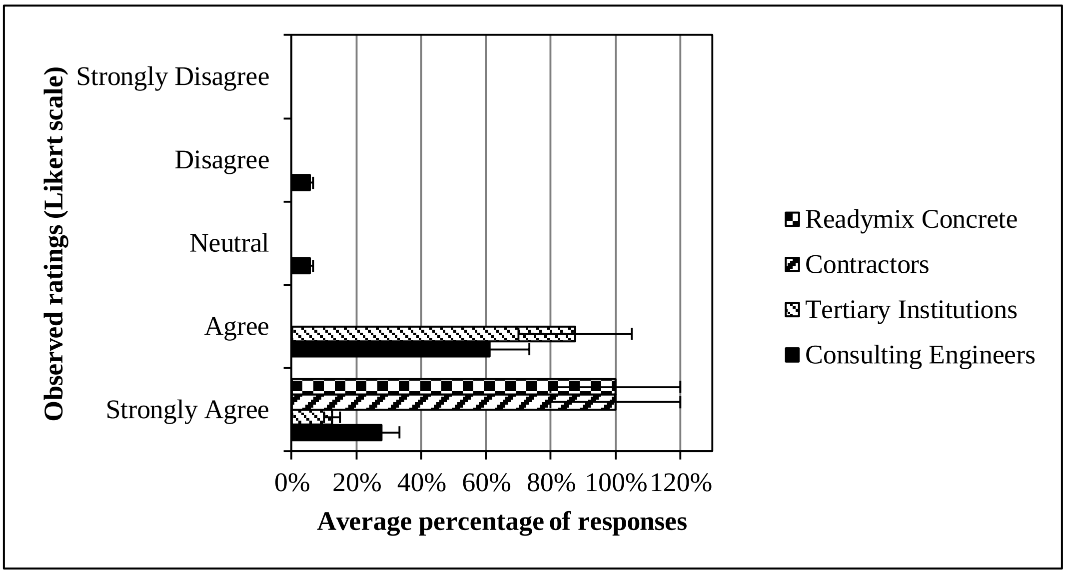

Figure 4.1: Responses of different stakeholders on the importance of considering the influence of exposure environment in durability design

4.2.1.2 Selection of binder type

From the survey data, the use of blended cement is more prevalent in the present times than the use of plain Portland cement. As covered in Chapter 2, the use of blended cements contributes greatly to the durability of concrete. Further, this is in line with the analysis of survey data received from cement producers as covered in Section 4.2.6. Figure 4.2 shows a graphical presentation of response data received. This figure was plotted using averages of all the responses received from the respective stakeholders. The error bars were plotted in line with the confidence level selected as covered in Chapter 3.

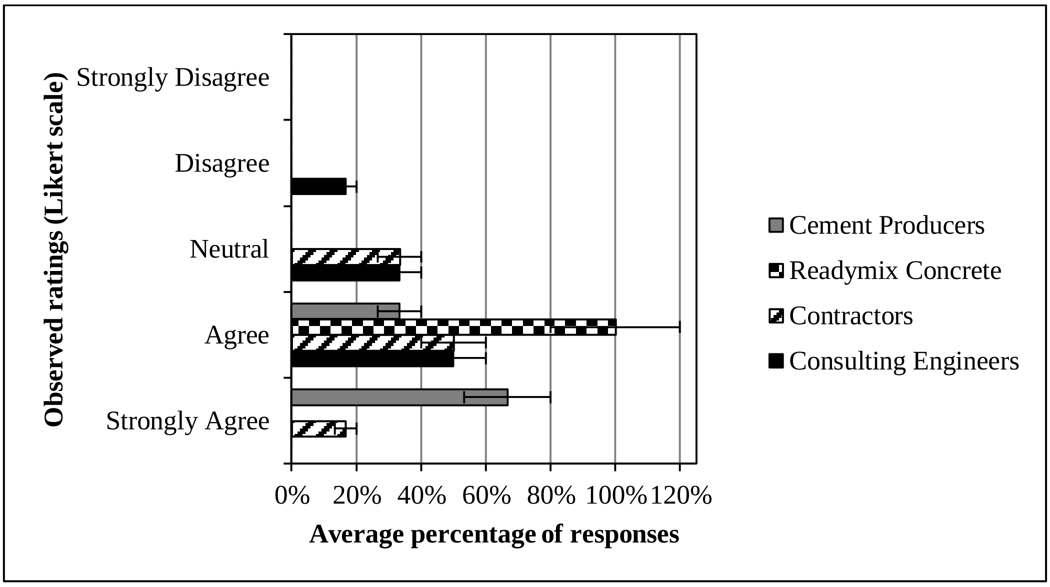

Figure 4.2: Responses of different stakeholders on the importance of selecting the binder type in durability design

4.2.1.3 Selection of aggregates

The selection of aggregates that pose no threat of reacting with other concrete ingredients ensures that the durability of concrete will not be negatively impacted. However, non-reactive aggregates are not always available at all different project locations. To assess the awareness of stakeholders in this regard, a question was formulated on how they deal with reactive aggregates if encountered. Figure 4.3 shows a graphical presentation of response data received. This figure was plotted using averages of all the responses received from the respective stakeholders. The error bars were plotted in line with the confidence level selected as covered in Chapter 3.

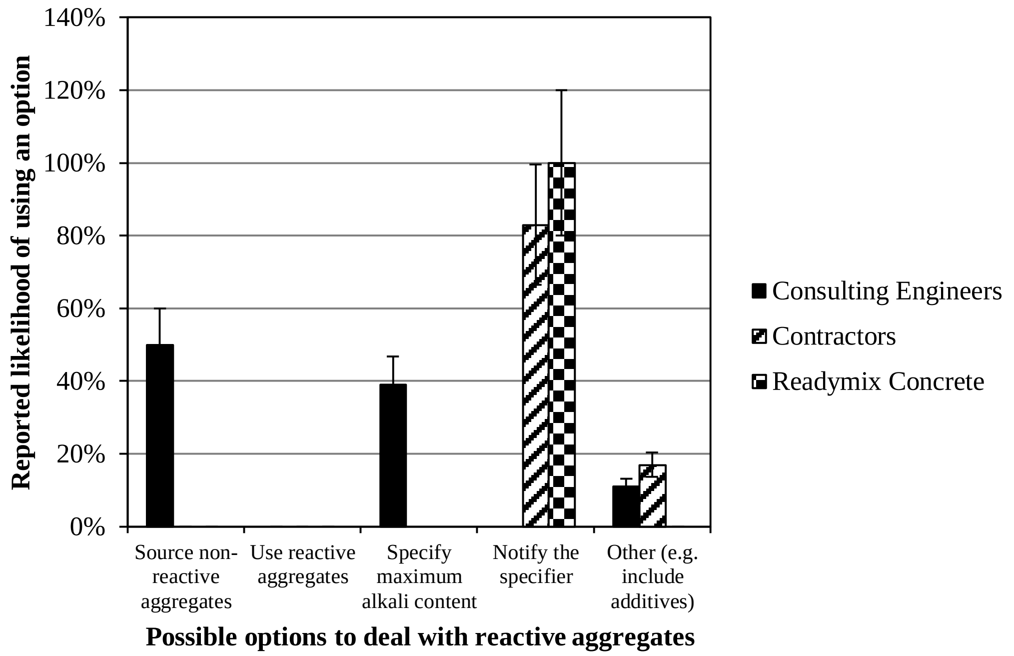

Figure 4.3: Responses of different stakeholders on the importance of selecting aggregates in durability design

As can be seen, while consulting engineers would either opt to source non-reactive aggregates at all cost or specify the maximum alkali content, contractors and readymix concrete producers would more than likely refer the matter back to consulting engineers. It is foreseen that liaisons between these stakeholders are likely to take place to arrive at a resolution that will benefit the project; such as in the case where reactive aggregates are encountered, discussions would take place in this regard to ensure that a best solution is decided upon.

4.2.1.4 Compaction and curing of concrete

Adequate compaction is required to ensure that concrete is cast correctly without any defects or cavities that would allow ingress of aggressive agents, thereby impacting durability of concrete negatively. Consulting engineers and contractors as the stakeholders involved in this process and ensuring correctness thereof were in agreement with the statements below (which were contained in the survey questionnaires – see Appendix A) to ensure adequate compaction of concrete.

In liaisons with one another, compaction should be:

a) Planned ahead and a suitable compaction method decided upon; this might be impacted by reinforcing steel, element type, method of casting, etc.
b) Recorded through inspections during concreting and photographic records, these are highly recommended as compaction should neither be under- or over- done. Overseeing this process by an experienced professional will ensure that compaction is done correctly.
c) Recorded through concreting checklists completed and signed by the responsible foreman (experienced professional), these are important for inclusion in the quality control documentation.

The data received in this regard is graphically presented in Figure 4.4.

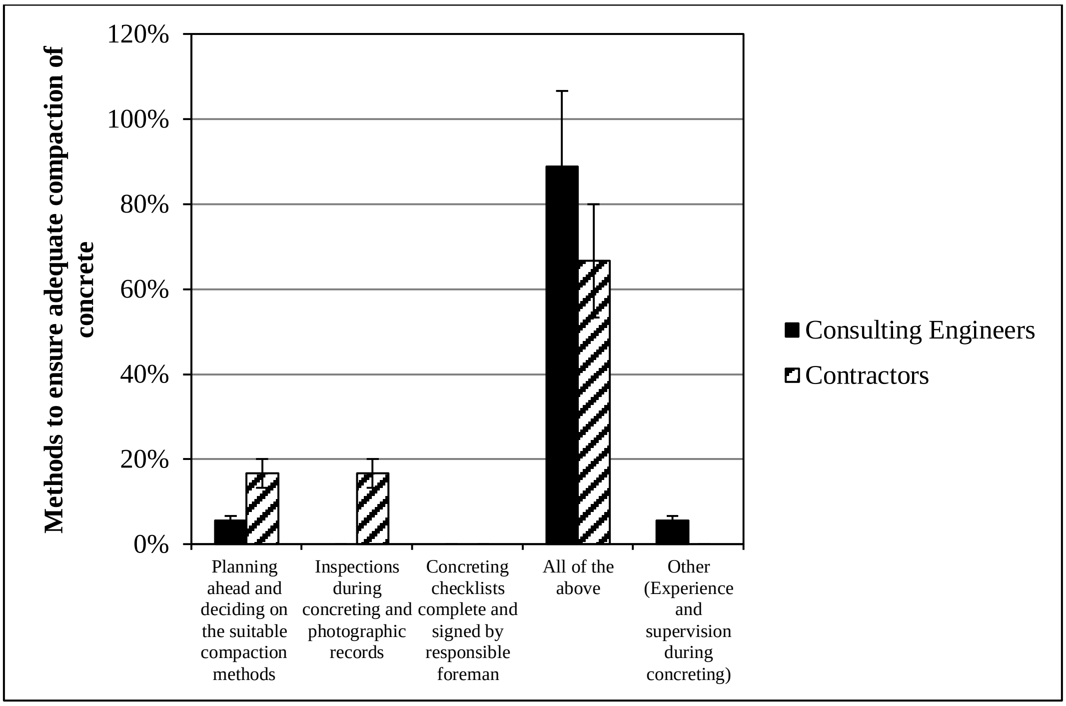

Figure 4.4: Responses of different stakeholders on the planning steps to ensure adequate compaction

Also, the method and duration of curing should be discussed and agreed upon by these stakeholders. The data received in this regard is graphically presented in Figures 4.5 and 4.6.

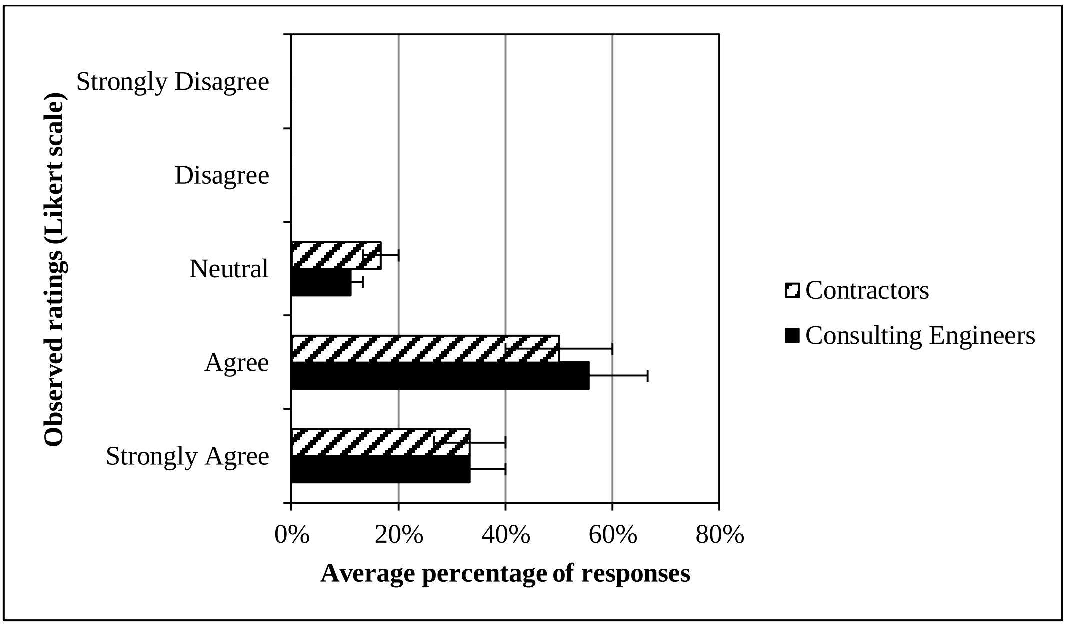

Figure 4.5: Responses of different stakeholders on the importance of selecting the method of curing in durability design

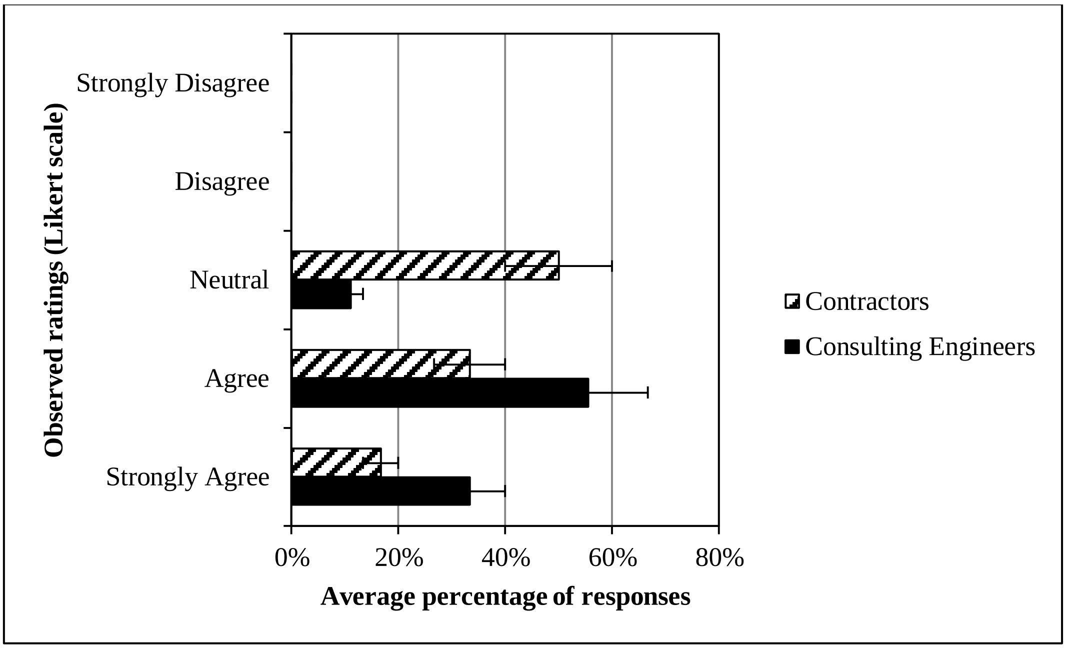

Figure 4.6: Responses of different stakeholders on the importance of selecting the duration of curing in durability design

4.2.1.5 Tests on hardened concrete

Based on the survey results, compressive strength testing is the most common test carried out on the hardened state. This means that test methods to assess the durability of concrete are mostly not specified and/or carried out in construction projects. In the following sections, this is further investigated across all stakeholders to whom this responsibility is applicable. The survey data received is graphically presented in Figure 4.7, note that only tests in the hardened state of concrete are considered. This figure was plotted using averages of all the responses received from the respective stakeholders. The error bars were plotted in line with the confidence level selected as covered in Chapter 3.

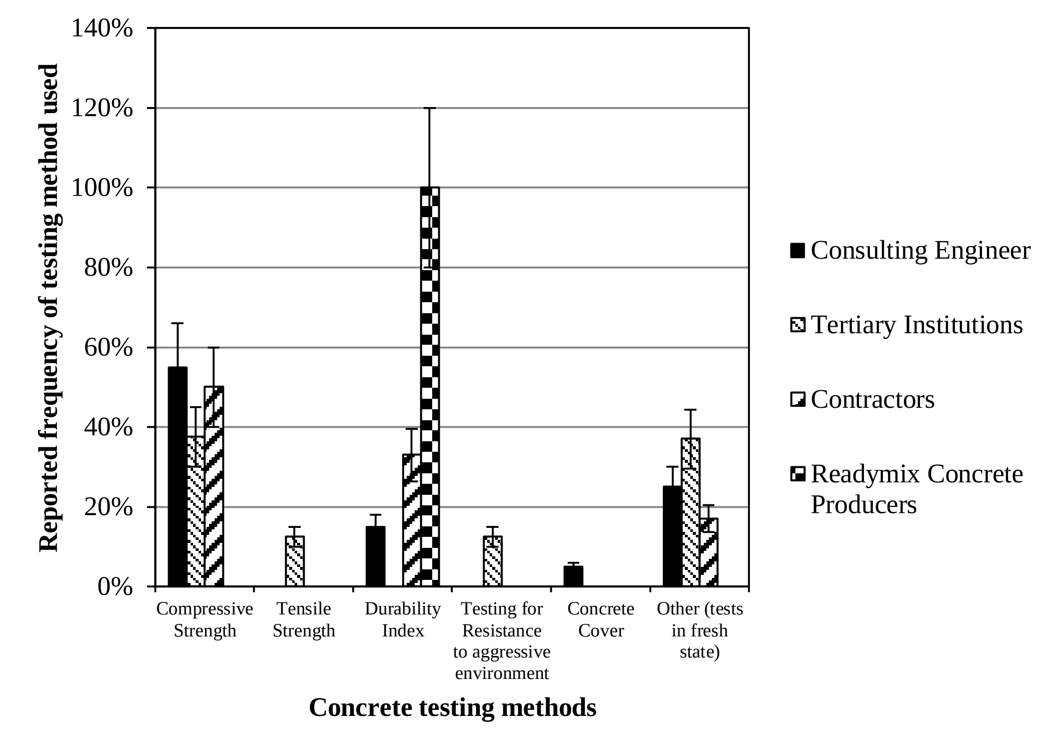

Figure 4.7: Responses of different stakeholders on testing of concrete in the hardened state

4.2.2 Analysis focusing on individual stakeholders

4.2.2.1 Consulting Engineers

Consulting engineers were the first of the main survey groups in the sense that the application of concrete durability in actual projects remains part of their responsibilities. The survey results indicate that in practice, engineers generally follow designs that contribute to enhancing durability, i.e. in the specification and material selection. However, these were mostly not complemented with durability testing which is an important aspect of performance-based approach.

Out of the 18 survey responses received, 70% reported that they have more than 10 years of experience in the industry, and the rest of the respondents, 30% have less than 10 years of experience. This is important as it gives an indication of whether highly experienced practitioners are more inclined to apply the performance-based approach in concrete durability design and specification. Further, 85% reported location of projects as being mostly inland, 10% of projects were equally balanced between inland and coastal locations, and 5% reported that most projects were located in coastal regions.

The computation for central tendency under design and specification questions was found to be 4. This means that there was a high level of agreement with the statements which sought to investigate the design and specification approaches, e.g. exposure environment influencing the durability design of a structure, blended cements being used more, etc. This data is presented graphically in Figure 4.8.

The computation for central tendency for construction and quality was computed to be 4.5. Similarly, there was a high level of agreement with the statements which sought to investigate the conduct of consulting engineers towards construction and quality monitoring. This data is presented graphically in Figure 4.9.

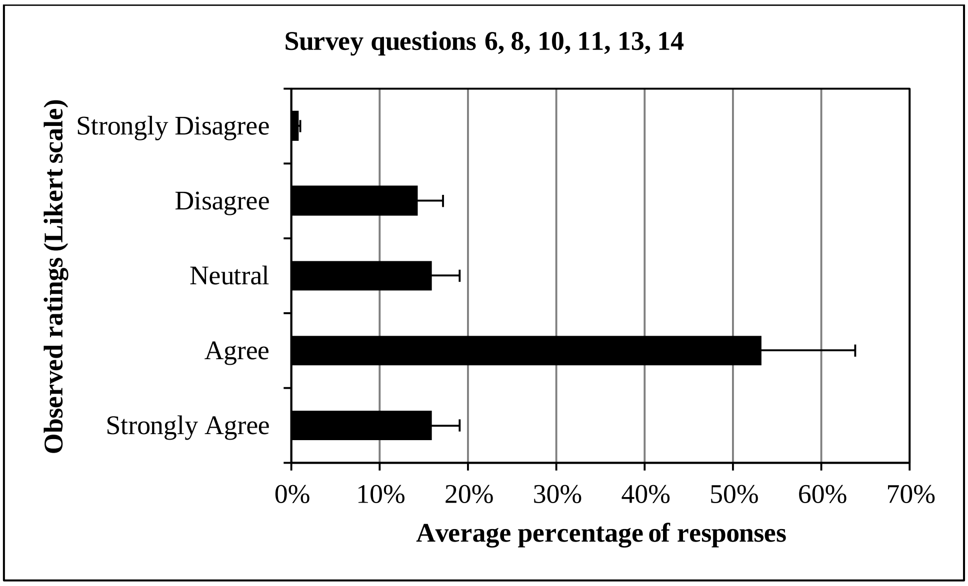

Figure 4.8: Responses of consulting engineers to Likert scale questions for design and specifications

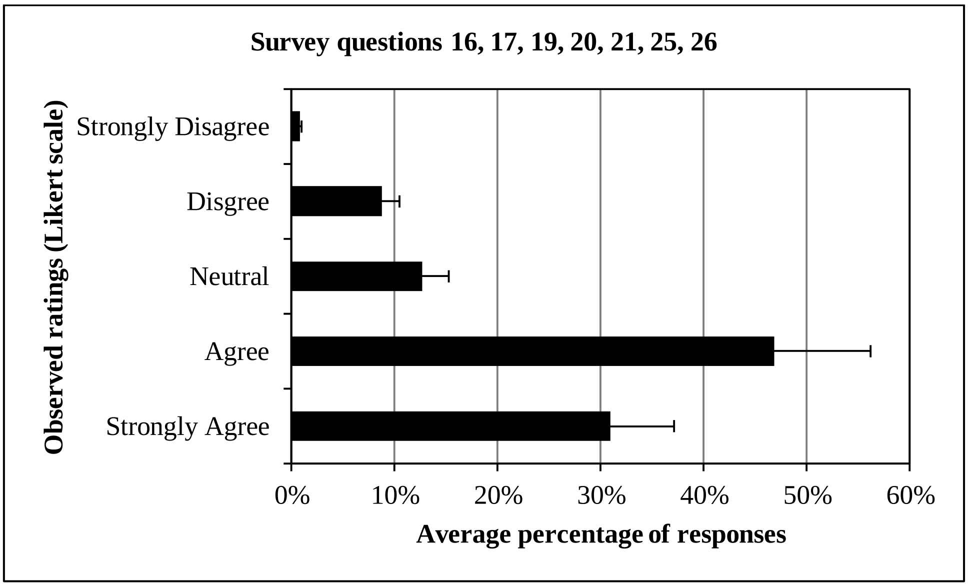

Figure 4.9: Responses of consulting engineers to Likert scale questions for construction and quality

Based on an average of the results above, it can be reported with the confidence level of 95% that about 50% to 90% engineers do follow concrete durability design concepts in practice; this is a measure of large effects as discussed in Chapter 3. Further, this is in line with the current specifications being 'hybrid', which means they represent both prescriptive and performance-based specifications.

The responses of consulting engineers to open-ended questions were also reviewed. The most important with regard to concrete durability design were the factors to be considered in the review of the concrete mix designs, and methods of testing as-built concrete in addition to the conventional compressive strength testing. Responses to the survey question 15 are presented in Table 4.4 in a descending order as ranked by the respondents from most important to least important factor. Responses to the survey question 24 are presented in Figure 4.9.

Table 4.4: Ranking of factors considered by consulting engineers in the review of concrete mix designs, Survey question 15

Factors considered in the review of Mix Design	Ranking
	High ranking
Materials	
Cement Content	
Slump	
w/c ratio	
Admixtures	
	Low ranking

These are the factors listed by consulting engineers for consideration in the review and approval of concrete mix designs, presented in the order of frequency of mentions. Scrutinising of materials included reviewing suitability of aggregate, cement and admixtures to be used in concrete. Considering responses to a follow-up question on how engineers deal with a possibility of using reactive aggregates in concrete, 50% of the respondents selected an option to source non-reactive aggregate at all costs. It is important to note that this may not be practical at all times, depending on the geographical location of the project, material availability and cost; therefore, more innovative ways should be considered on a case to case basis. Based on the survey responses, it can only be assumed that sourcing non-reactive aggregates is considered most often.

As can be seen in Figure 4.10, durability index tests were second lowest to be identified by engineers amongst other tests carried out in addition to compressive strength tests.

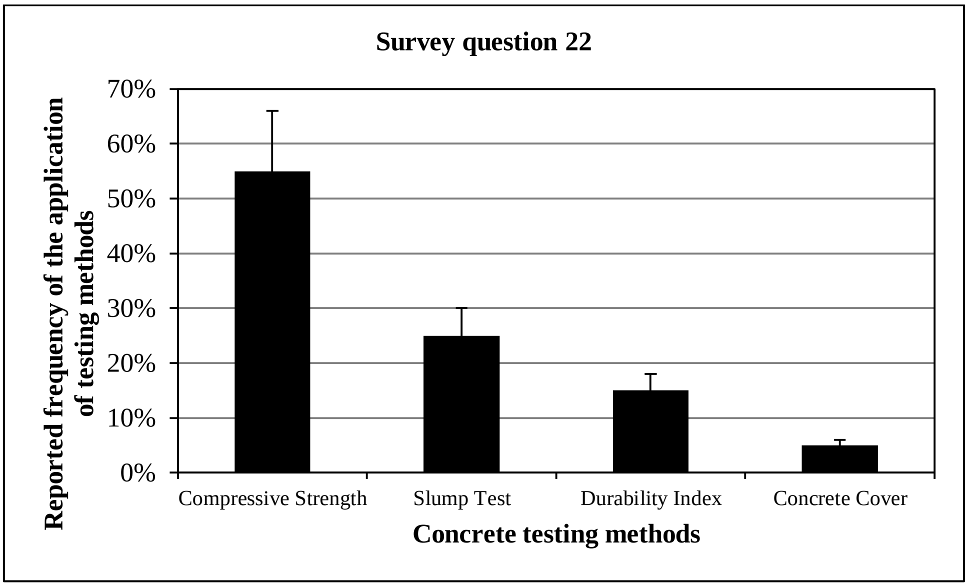

Figure 4.10: Responses of consulting engineers on testing of concrete in the fresh and hardened state

On the basis of the survey data received and analysed above, it can be concluded that design and specification in practice are still mostly based on prescriptive approaches, with an application of performance-based concrete durability design and specification approaches to a certain extent – performance-based in this sense being inferred from the specification of durability index tests. The characteristics of respondents mentioned earlier in this section, i.e. experience and project location, must be considered in conjunction with the survey results. This brings to question whether knowledge and application of durability index tests in projects is related to experience in the field and/or project location, or purely done when enforced by Employers/Clients.

These two hypotheses were tested and analysed statistically. A Chi-square test of independence was applied to evaluate whether a relationship exists between the responses and the characteristics of the respondents, also known as the null hypothesis. This test was carried out in an MS Excel spreadsheet following instructions for the test as presented on Statistical Package (SPSS) for the Social Science website. These computations are presented separately in contingency tables, Tables 4.5 and 4.6.

Table 4.5: Null Hypothesis 1 – Experience vs application of DI Tests (Consulting Engineers)

Chi-Square Test of Independence			
Observed Frequencies			
	DI Yes	DI No	Total
Experience <10	0	6	6
Experience >10	2	10	12
Total	2	16	18
Expected Frequencies (Variables Perfectly Independent)			
	DI Yes	DI No	Total
Experience <10	0.7	5.3	6
Experience >10	1.3	10.7	12
Total	2	16	18
Chi-Square Points = (Observed - Expected)^2/Expected			
	DI Yes	DI No	Total
Experience <10	0.67	0.08	0.75
Experience >10	0.33	0.04	0.375
Total	1	0.125	1.125
Chi-Square Statistic = Sum Chi-Square Points			
	χ^2	1.125	

Table 4.6: Null Hypothesis 2 – Project location vs application of DI Tests (Consulting Engineers)

Chi-Square Test of Independence			
Observed Frequencies			
	DI Yes	DI No	Total
Inland	1	14	15
Coastal	0	1	1
Inland/Coastal	1	1	2
Total	2	16	18
Expected Frequencies (Variables Perfectly Independent)			
	DI Yes	DI No	Total
Inland	1.7	13.3	15
Coastal	0.1	0.9	1
Inland/Coastal	0.2	1.8	2
Total	2	16	18
Chi-Square Points = (Observed - Expected)^2/Expected			
	DI Yes	DI No	Total
Inland	0.27	0.03	0.3
Coastal	0.11	0.01	0.125
Inland/Coastal	2.72	0.34	3.0625
Total	3.1	0.3875	3.4875
Chi-Square Statistic = Sum Chi-Square Points			
	χ^2	3.4875	

The Chi-square test is based on the following assumptions (SPSS):

a) Independent observations – this usually, not always, holds if each case holds a unique person or other statistical unit.
b) For a 2x2 table, all expected frequencies > 5. For a larger table, no more than 20% of all cells may have an expected frequency < 5 and all expected frequencies > 1.

As can be seen in the contingency tables, the second assumption of the Chi-square test has been violated and therefore, the test may be unreliable if continued to determine the relationship. Therefore, an alternative test to analyse the null hypothesis was used – the Fisher's exact test of independence. This test was found to be suitable as it is applicable to small sample sizes, and has been reported to be more accurate than the Chi-square test in small sample sizes (McDonald, 2014). The results of these tests are presented in Table 4.7.

Table 4.7: Results of analysis of survey data from consulting engineers by the Fisher's exact test of independence

Null Hypothesis	Table	p-value	Description of the results
There is no relationship between experience of the respondents and performance-based specification (DI Tests).	2x2	$0.43 > 0.05$	No relationship exists between the two variables.
There is no relationship between project location and performance-based specification (DI Tests).	2x3	$0.31 > 0.05$	No relationship exists between the two variables.

With the results of the independence tests, it can be intimated that the application of DI tests in projects is mostly implemented if enforced by the Employer/Client. This was reported by 50% of the respondents who specified DI tests; the comment was stated as 'SANRAL projects'. This was discussed in Section 2.4.4 of Chapter 2. There is seemingly no application of DI tests by the consulting engineers. There might be a variety of possible reasons for this:

a) Although the DI tests have been in existence for many decades in South Africa, they were only issued as SANS standards in 2015; it may have been difficult to get a buy-in from clients to have these specified in their projects in the past.
b) Cost implications related to durability testing in the laboratory and on-site in as-built structures.

It would be futile then to extend analysis of survey data from other industry stakeholders to determine whether DI tests are done in construction projects. Therefore, data was analysed to determine whether there is awareness regarding concrete durability.

4.2.3 Tertiary Institutions

Tertiary institutions were the second of the main survey groups in the sense that the application of concrete durability in actual projects remains part of their responsibilities through the knowledge covered in the curricula. Data from the survey showed a relatively pro-durability approach in the theory covered in the curricula. However, a similar trend to that for consulting engineers was noticed in that there was not adequate coverage of durability index tests in their curricula; these tests are important to the performance-based approach as they enable assessing the quality of the as-built concrete. The fundamentals of concrete durability were not complemented with elaborating on the performance-based approach.

The computation of the central tendency, the median, for the influence exposure environment has on the design and specification of concrete was found to be 4. This means that there is agreement that the importance of the exposure environment to which the concrete structure will be exposed, and taking it into consideration when designing and specifying concrete is covered adequately in the curricula of tertiary institutions. However, there is hindrance in applying this knowledge in practice due to standardised specifications applicable to individual companies; there usually is no room for changing this by graduates. This data was analysed and presented in Figure 4.11.

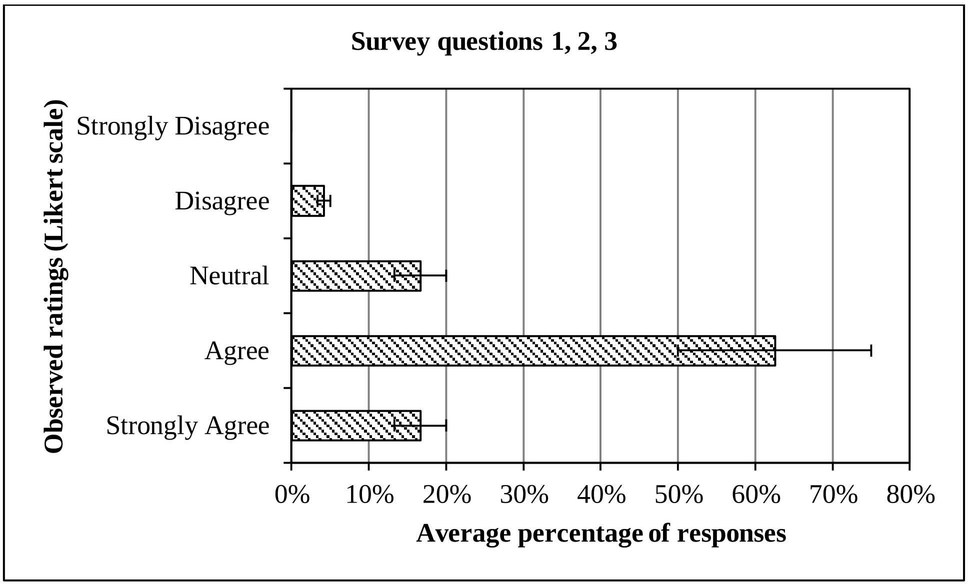

Figure 4.11: Responses of tertiary institutions on the influence of exposure environment in concrete durability

The computation of the central tendency, the median, for the selection and specification of materials was found to be 4. Similarly, the median for responses to the statements for construction and testing was found to be 4. This means that there is agreement that these design concepts were covered adequately in theory. This data was analysed and presented in Figures 4.12 and 4.13.

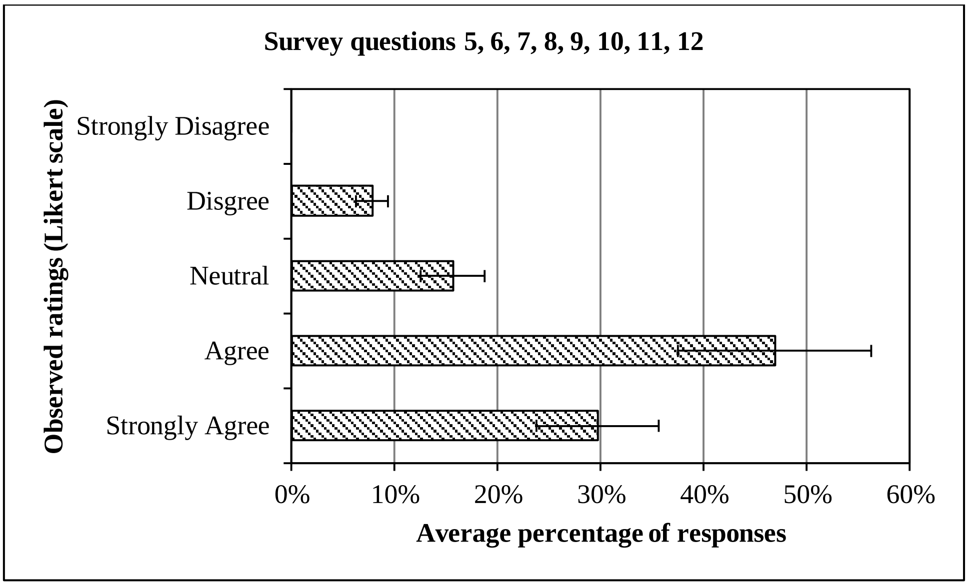

Figure 4.12: Responses of tertiary institutions on the selection of materials for concrete durability

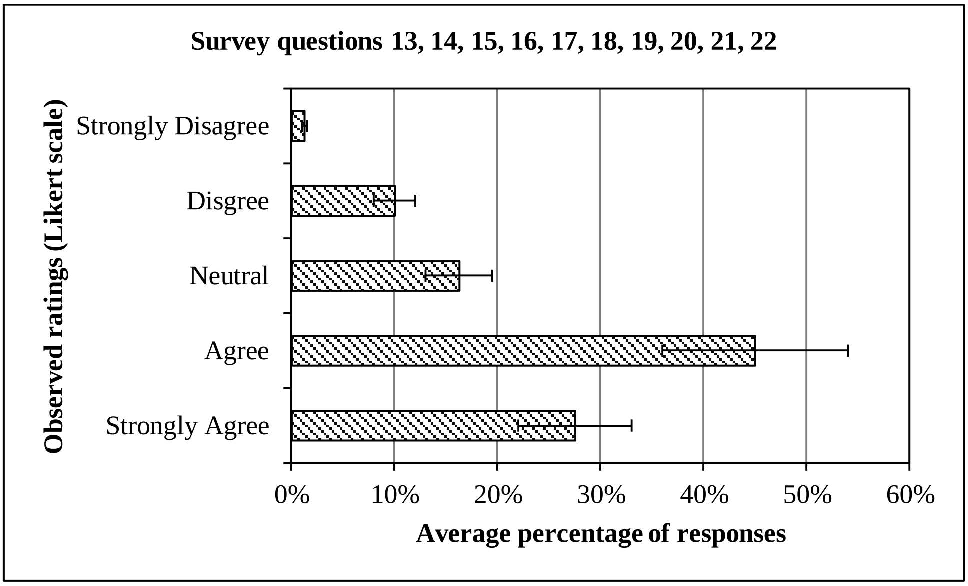

Figure 4.13: Responses of tertiary institutions on the concrete quality and testing

The responses from tertiary institutions to open-ended questions were also reviewed. These questions sought to establish the awareness of and the understanding of the purposes of using concrete admixtures, and methods of testing of as-built concrete in addition to the conventional compressive strength testing. 13% of the respondents reported "testing the ability to resist weathering attack and chemical attack", without specifically mentioning any tests. The responses are presented in Figures 4.14 and 4.15.

As can be seen, the testing methods covered for evaluating the quality of as-built concrete are mostly compressive strength. It is also clear that it is generally understood that the purpose of using admixtures in concrete is to modify concrete properties rather than compensating for bad materials, as these should be avoided completely. Whilst there is room for improvement in the testing methods implemented, it is good that there is awareness on the correct use of concrete admixtures.

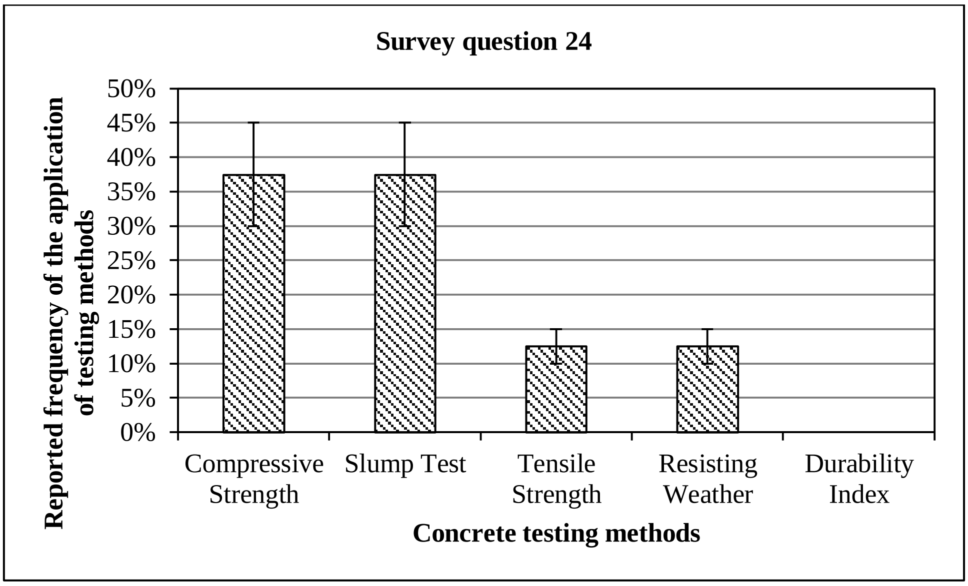

Figure 4.14: Responses of tertiary institutions on concrete testing methods covered in the curricula

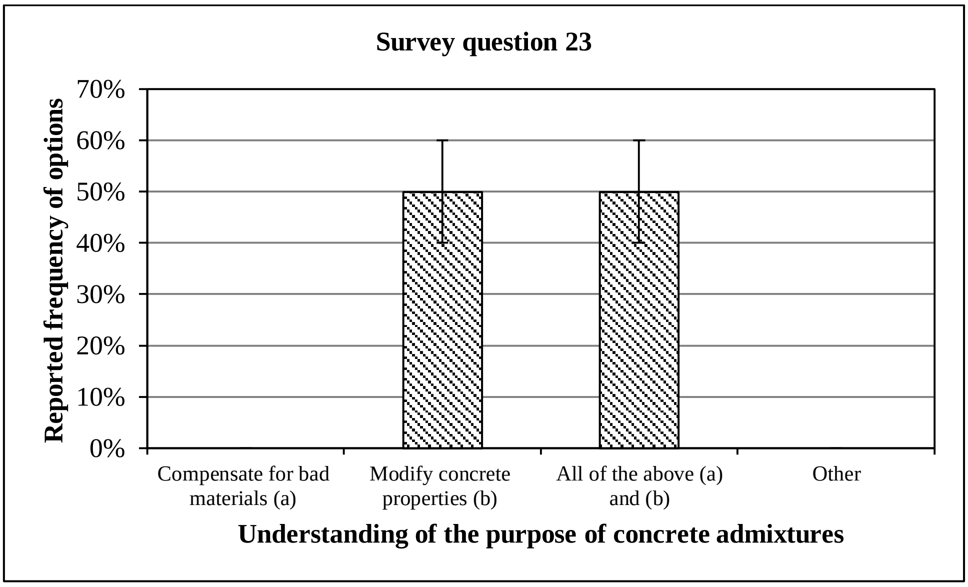

Figure 4.15: Responses of tertiary institutions on perceived purposes of the use of concrete admixtures

4.2.4 Contractors

Evaluation of survey data received from contractors shows that there is awareness and understanding of the relationship between concrete specifications and construction quality with respect to durability. There was a high level of agreement to statements that sought to establish the nature of current specifications with respect to durability as issued by the relevant stakeholders (consulting engineers or readymix concrete producers); these results are presented in Figure 4.16 and have a computed median of 4.3. On the open-ended questions regarding commonly specified testing methods, in addition to compressive strength testing, permeability tests (OPI) were mentioned by 33% of the respondents.

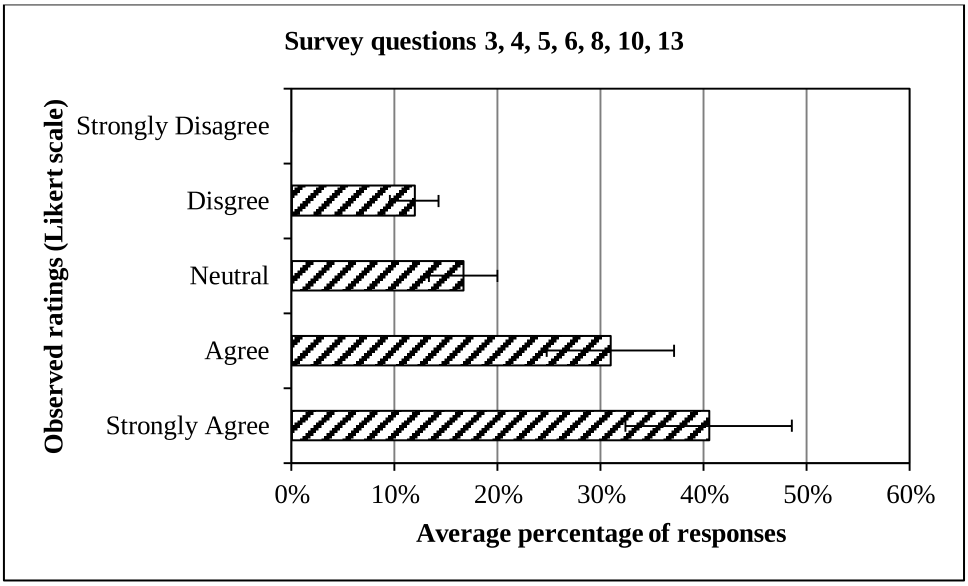

Figure 4.16: Responses of contractors on concrete specifications and construction quality

To establish why these tests were carried out, the survey question listed various options from which the respondents were to select a response. The reasoning selected for permeability tests was that "*these tests were enforced by the Employer/Client*". Responses are presented in Figures 4.17 and 4.18.

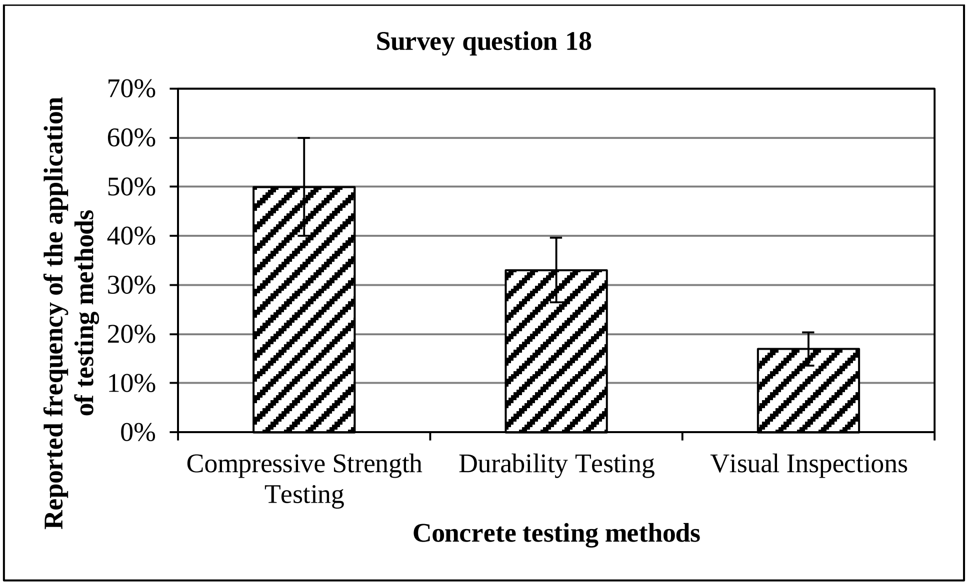

Figure 4.17: Responses of contractors on concrete testing methods carried out

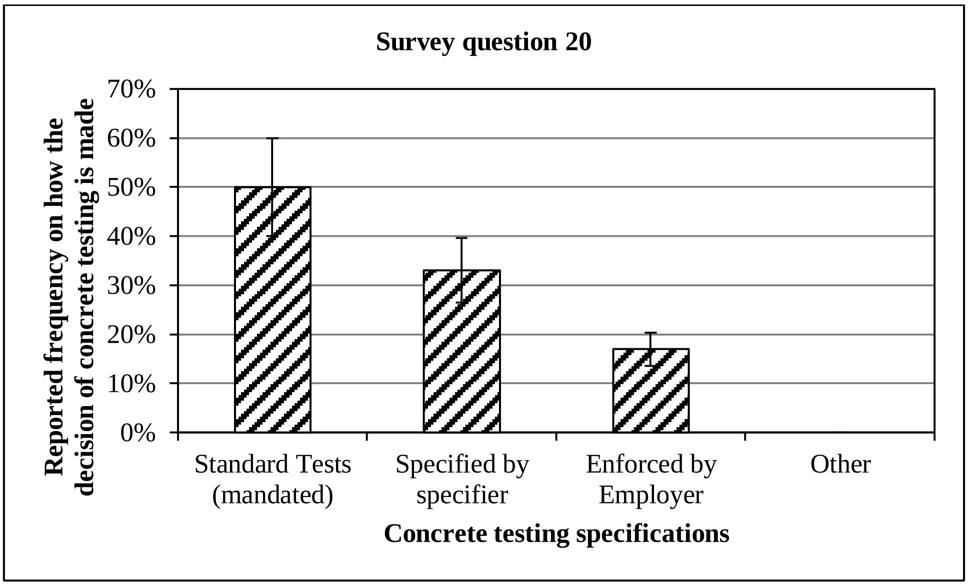

Figure 4.18: Responses of contractors on how concrete tests are specified

As mentioned above, the survey data was not evaluated for application of durability design and performance-based specification by way of DI tests, as these are not at the level where they are specified by consulting engineers currently, other than those enforced by Employers/Clients. However, contactors have shown awareness to a certain extent with regard to concrete durability.

4.2.5 Readymix Concrete Producers

Evaluation of survey data received from readymix concrete producers shows that there is awareness and understanding of the relationship between concrete design and specifications with respect to durability. The computation of the central tendency, the median, for the influence exposure environment has on the design and specification of concrete and the selection of binder type was found to be 4. This means that there is agreement that the exposure environment to which the concrete structure will be exposed and taking it into consideration when designing and specifying properties thereof is considered important by readymix concrete producers. Further, there is agreement that the selection of binder type takes into consideration the relevant factors, such as surrounding environment, concrete strength, etc. This data was analysed and presented in Figure 4.19.

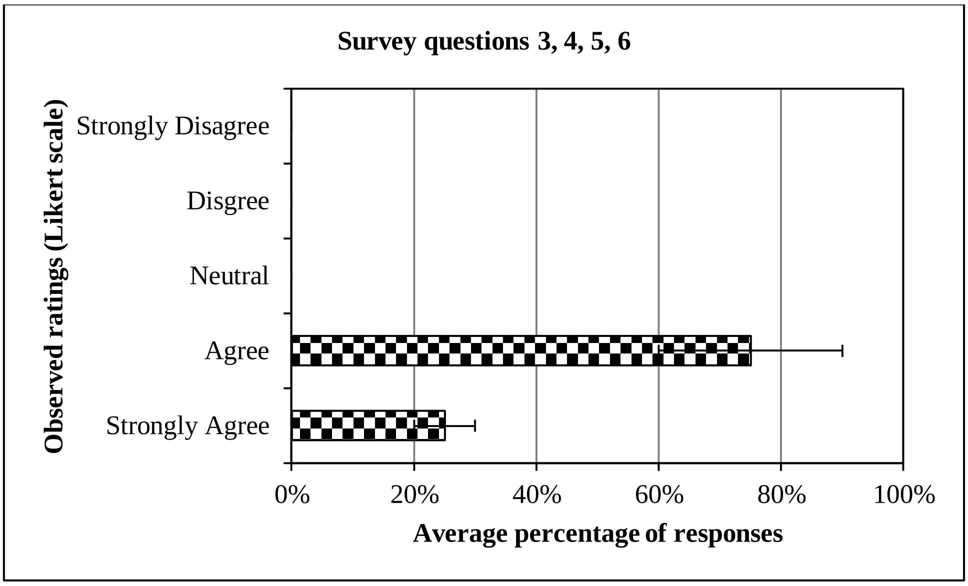

Figure 4.19: Responses of readymix concrete producers on concrete design and specifications

To evaluate awareness of concrete durability design concepts by readymix concrete producers, data received was analysed by frequency of mention of each factor and ranking of these factors by the respondents. These are shown in Tables 4.8 to 4.10.

Table 4.8: Factors considered in the selection of cement (Readymix Concrete Producers), Survey question 8

Factors as listed by respondents	Number of mentions by respondents	Ranking of factors by respondents (descending)
Strength	1	Strength, Cost, Performance
Cost	2	Durability, Availability, Consistency
Performance	2	Heat of Hydration, Influence on properties of fresh concrete
Durability	1	-
Availability	1	-
Consistency	1	-
Heat of Hydration	1	-
Influence on properties of fresh concrete	1	-

Table 4.9: Factors considered in the selection of aggregates (Readymix Concrete Producers), Survey question 10

Factors as listed by respondents	Number of mentions by respondents	Ranking of factors by respondents (descending)
Surrounding environment	1	Surrounding environment, Cost, Competency
Cost	2	Alkali Silica Reaction, Availability, Consistency
Competency	2	Surface abrasion, Characteristics, Compliance with SANS, Water demand
Alkali Silica Reaction	1	-
Availability	1	-
Surface abrasion	1	-
Characteristics	1	-
Consistency	1	-
Water demand	1	-
Compliance with SANS	1	-

Table 4.10: Factors considered in the selection of concrete admixtures (Readymix Concrete Producers), Survey question 14

Factors as listed by respondents	Number of mentions by respondents	Ranking of factors by respondents (descending)
Performance	2	Performance, Properties
Cost	3	Cost, Effect, Rheology
Rheology	1	-
Properties vs desired effect	1	-

For the purposes of the subject of this study, the ranking of factors could be better presented by respondents in that factors that influence concrete durability should be ranked higher than the other conventional factors. For example, the cost should be evaluated over the life cycle of a structure; thus, may not be the deciding factor during design and construction. As discussed in Chapter 2, saving cost during design and construction may lead to selection of less suitable materials for the project which might bring about premature deterioration. This situation would then lead to higher than expected maintenance, increasing the cost of the structure over its entire life span.

The frequency of the request for concrete mix designs by the consulting engineers for projects was evaluated as shown in Figure 4.20. This shows that the concrete mix design is requested, reviewed and approved for most projects but not all projects as presented in the survey questions 23, 24 and 25. These are responses that fall on the positive scale in Figure 4.20, and the negative scale presents responses to the negative effect as shown. This is important as the designer has to be involved in the selection of materials to be used in a project, to ensure suitability with respect to the desired concrete properties for a given project.

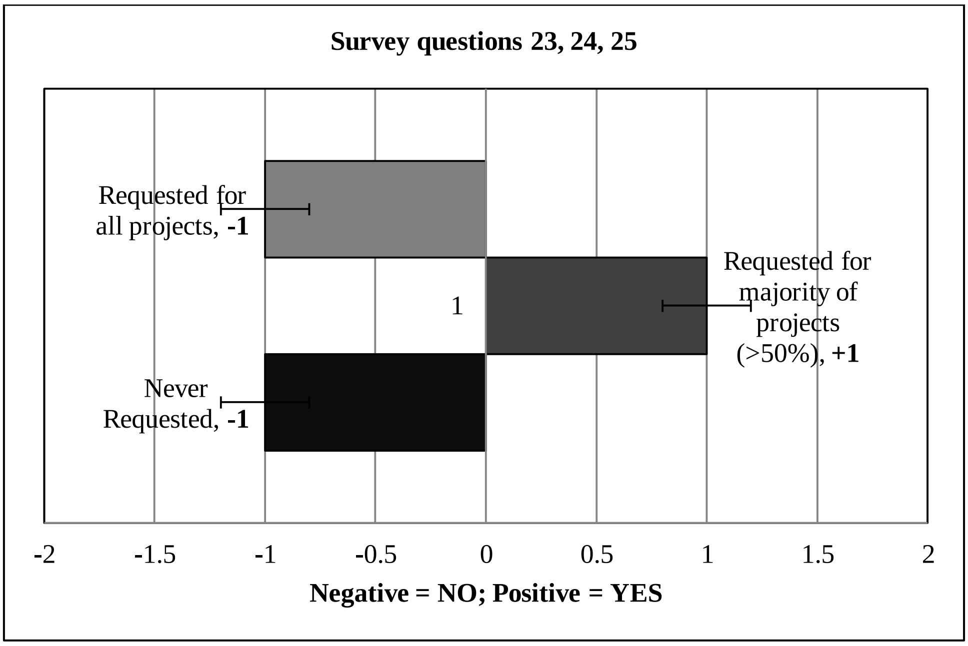

Figure 4.20: Responses of readymix concrete producers on the frequency of the requests for concrete mix designs

Additional testing (other than compressive strength) of concrete was reported to be durability tests (OPI, CCI, WSI) by all the readymix concrete producers. This confirms that there is awareness by these stakeholders, though it cannot be intimated as to the source of this awareness; whether it may be from the developments in the concrete industry, or their involvement in projects where DI tests are enforced by Employers/Clients.

4.2.6 Cement Producers

From the survey data, the use of plain cement is no longer common with a measured central tendency of 1.0 (strong disagreement), in comparison to the use of blended cement with a measured central tendency of 5.0 (strong agreement). This data is presented in Figures 4.21 and 4.22.

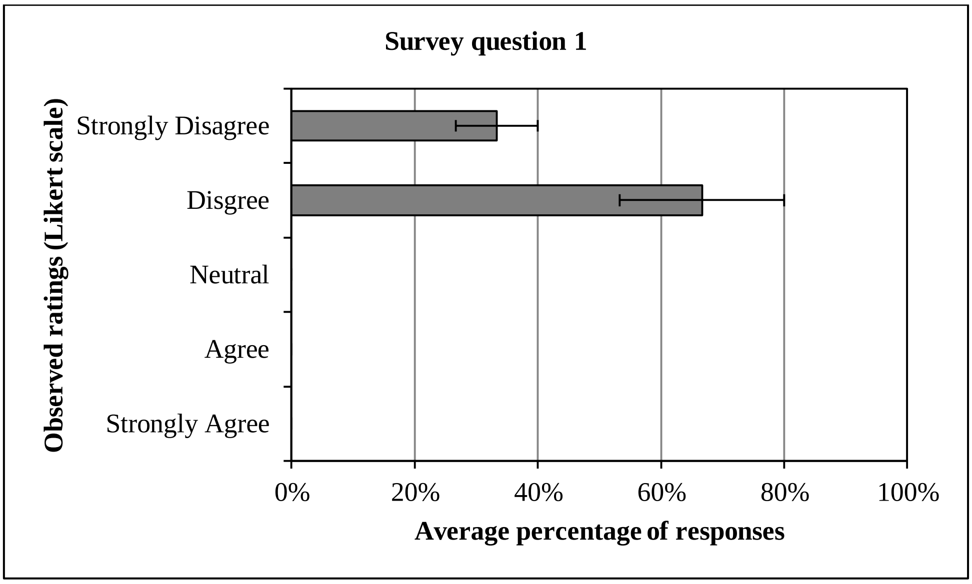

Figure 4.21: Responses of cement producers on the prevalence of use of Plain cement

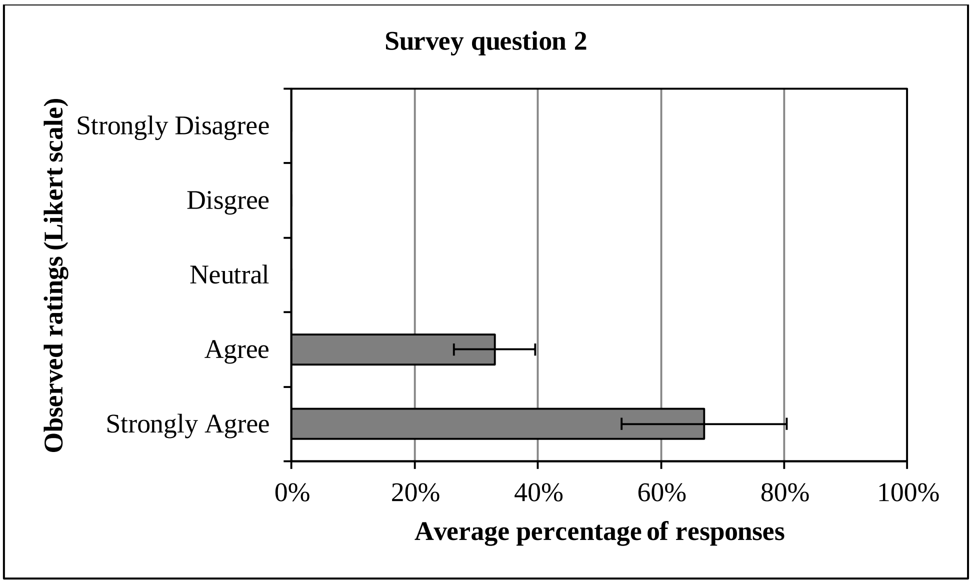

Figure 4.22: Responses of cement producers on the prevalence of use of blended cement

Further, there was a high level of agreement with the statements below as presented in Figure 4.23:

a) The use of blended cement results in longer services life of concrete structures.

b) The selection of cement takes into consideration relevant factors in liaisons with the contractor or readymix concrete producer.

c) The properties of concrete specified by the designer are taken into consideration when selecting cement.

A neutral central tendency was computed in the case of binder type varying with the project location.

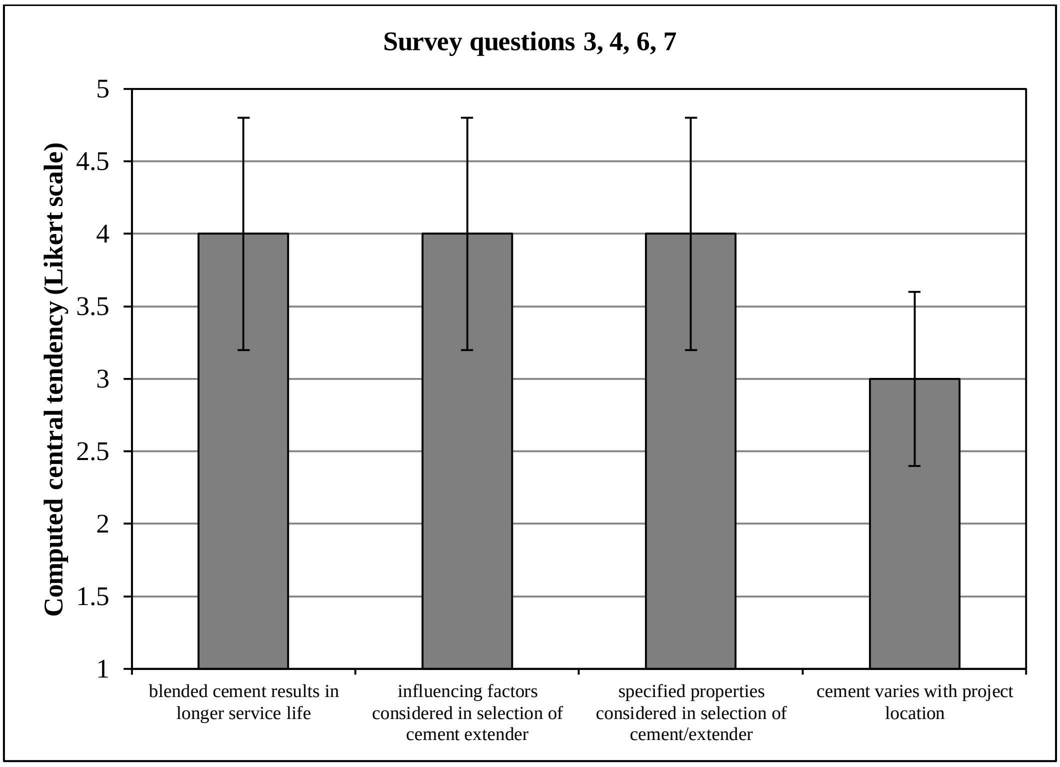

Figure 4.23: Responses of cement producers on the selection of cement for use in a given project

The factors taken into consideration when recommending binder type were reported by the respondents as follows:

a) Project application and location;

b) Influence of other materials (e.g. aggregates and admixtures);

c) Durability requirements;

d) Cost;

e) Reliability of supplier;

f) Greenstar requirements; and
g) Special requirements by the Engineer.

The developments in the cement production with regard to the production of less penetrable concrete were noted as listed below. These developments are driven by client specification (SANRAL) and clients wanting a Greenstar Rating (Green Building Council of South Africa).

a) Durability tests
b) Green building (lower carbon footprint)
c) Highly extended cements (Fly Ash)
d) Crystalline waterproofing additives.

As can be seen, there was a high level of awareness with regard to durability of concrete. Also, as reported by other stakeholders, durability testing is mostly enforced by the Employer/Client.

Further, from the review of product datasheets provided by the various cement producers who participated in the survey, the information presented in Table 4.11 was found, without naming the companies involved as no consent was received in this regard. The cements listed are as a result of developments in the cement manufacturing industry that take durability of concrete into consideration, i.e. cements that are readily made with the inclusion of cement extenders (such as Fly Ash, etc.) and applicable to structural concrete applications, with other added benefits (such as lower heat of hydration, better resistance to chemical attack, etc.). This information further supports the survey data in that blended cements are mostly produced and used at present.

One of the companies offers the services of a quality department that evaluates, amongst other things, aggregates prior to project commencement and recommendations on the subsequent concrete mix designs. This is useful in that all concrete ingredients available for a given project are evaluated and the concrete mix design formulated specifically to suite the project requirements and availability of materials. As can be seen from the product benefits put forward by cement producers, these cements provide benefits that promote durability of concrete.

Table 4.11: Current cement production as per Product Datasheets Reviewed

<table>
<tr><th colspan="6">Cement Producer</th></tr>
<tr><th>Company</th><th>Product Name</th><th>Cement Grade</th><th>Cement Composition</th><th>Supply (bagged/bulk)</th><th>Product Benefits based on Datasheets</th></tr>
<tr><td rowspan="4">Company A</td><td rowspan="4">Cement 1</td><td rowspan="4">42.5N</td><td rowspan="4">Portland cement and mineral components</td><td rowspan="4">Not stated</td><td>Reduces heat of hydration</td></tr>
<tr><td>Improves resistance to chemical attack</td></tr>
<tr><td>Improves resistance to ASR</td></tr>
<tr><td>Reduces permeability</td></tr>
<tr><td rowspan="17">Company B</td><td rowspan="2">Cement 2</td><td rowspan="2">52.5N</td><td rowspan="2">Portland cement and siliceous fly ash (CEM II/A-V 52,5N)</td><td rowspan="2">Bagged</td><td>High rate of early strength development</td></tr>
<tr><td>Better off-shutter finish</td></tr>
<tr><td rowspan="4">Cement 3</td><td rowspan="4">42.5N</td><td rowspan="4">Portland cement and siliceous fly ash (CEM IV/B-V 42,5N)</td><td rowspan="4">Bagged</td><td>Good early strength gain</td></tr>
<tr><td>Higher long-term strength and durability</td></tr>
<tr><td>Better resistance to chemical attack</td></tr>
<tr><td>Good impermeability</td></tr>
<tr><td rowspan="2">Cement 4</td><td rowspan="2">52.5N</td><td rowspan="2">Portland cement and siliceous fly ash (CEM II/A-V 52,5N)</td><td rowspan="2">Bulk</td><td>High early strength</td></tr>
<tr><td>Enhanced workability and flowability</td></tr>
<tr><td rowspan="4">Cement 5</td><td rowspan="4">42.5R</td><td rowspan="4">Portland cement and siliceous fly ash (CEM II/A-M (V-L) 42,5R)</td><td rowspan="4">Bulk & Bagged</td><td>Lower heat of hydration</td></tr>
<tr><td>Enhanced durability</td></tr>
<tr><td>Better workability and strength at all ages</td></tr>
<tr><td>Can be further extended with Durapozz or GGBS</td></tr>
<tr><td rowspan="5">Cement 6</td><td rowspan="5">32.5R</td><td rowspan="5">Portland cement and siliceous fly ash (40%) (CEM IV/B-V 32,5R)</td><td rowspan="5">Bulk</td><td>Good early strength gain</td></tr>
<tr><td>Lower heat of hydration</td></tr>
<tr><td>Higher long-term strength and durability</td></tr>
<tr><td>Better resistance to chemical attack</td></tr>
<tr><td>Good impermeability</td></tr>
</table>

Company C	Cement 7	42.5N	Portland cement and extender at varying % limestone, fly ash or GGBS (CEM II/A-L 42.5N)	Bagged	Early strength gain
	Cement 8	52.5N	Portland cement and limestone (CEM II/A-L 52.5N)	Bulk & Bagged	Early strength gain
	Cement 9	32.5N	May vary with factory of origin	Bagged	Improved workability and water retention
					Lower heat of hydration
					Lower permeability
					Improved resistance to aggressive agents
Company D	Cement 10	32.5N	Portland cement and fly ash (CEM II/B - L or CEM IV/B (V))	Bulk & Bagged	Long term durability
	Cement 11	42.5N	Portland cement and cement extenders (CEM II/A - L or CEM IV/A (V))	Bulk & Bagged	Long term durability
					Good early and late strength
	Cement 12	42.5R	Portland cement and fly ash (CEM II/A (V) 42,5R)	Bulk & Bagged	Offers a degree of sulphate resistance
					Low heat of hydration
					Enhanced durability

4.2.7 Concrete Admixture Producers

To evaluate awareness of concrete admixture producers to concrete durability design concepts, factors considered in recommending concrete admixtures were provided by respondents in the survey, and are listed below in no particular order:

- Waterproofing
- Durability
- Strength
- Ensure there is no calcium chloride
- Reinforcing steel
- Aggregate size
- Method of concrete placement

- Fit for purpose specifications (which include strength, reinforcing steel, etc.)

As can be seen, the factors listed are suitable to ensure construction of a structure with an acceptable level of durability that can be in service without premature deterioration. Whilst concrete strength is a structural requirement, reinforcing steel and aggregate size are to ensure that admixtures that do not contribute to corrosion of steel are used, and further, properly graded aggregates are required for bonding of concrete mix ingredients; concrete admixtures that aid this requirement are then recommended when required.

Developments in the production of admixtures with regard to the production of less penetrable concrete were listed by the respondents as below:

a) More use of high water reduction admixtures.
b) Use of self-healing admixtures and pore blocking admixtures for water retaining structures.
c) Use of crystalline admixtures - which make concrete waterproof and less permeable.

The above is further supported by the ranking of concrete admixtures that have high demand in the industry, as given in Table 4.12 based on the responses received.

Table 4.12: Ranking of concrete admixtures by industry demand (Concrete Admixture Producers), Survey questions 1 and 2

Demand for commonly used admixtures		**Demand for special admixtures**	
Type of admixture	**Ranking by demand**	**Type of admixture**	**Ranking by demand**
Plasticisers	1	Waterproofing admixtures	1
Super-plasticisers	2	Alkali-silica reactivity redu-ction admixtures	2
Accelerators	3		
Air-entrainers	4	Corrosion inhibitors	3
Retarders	5	Shrinkage reduction	4
		Colouring admixtures	5

1: Highest demand; 5: Lowest demand

As can be seen, admixtures that enhance workability with less water content (plasticizers and superplasticizers) are in high demand and so are waterproofing admixtures, both of which contribute towards durability by minimising the permeability of concrete and maximising the chemical resistance of concrete (Ballim, et al, 2009a).

4.3 Discussion of Results

As a point of departure, for concrete durability design and construction to adopt a performance-based approach, the quality of the as-built concrete should be tested using DI tests. From the survey results, it is clear that there is awareness on the subject of concrete durability, and this is considered in the design, specification, selection of materials and construction methods. The one aspect that is still lacking is the durability testing of as-built concrete. The survey results indicate that, compressive strength is still the most common test that is carried out on as-built concrete. This unfortunately comes across as if there is still a strong notion that the strength of concrete can be used as an indicator of its durability.

The test methods to evaluate penetrability of concrete (i.e. DI tests) are mostly not specified by consulting engineers except for projects where they are enforced by Clients/Employers – SANRAL projects were expressly mentioned in this regard by the respondents. Based on the statistical analyses carried out, it was noted that the trend of consulting engineers not specifying durability testing could be as a result of the durability index tests not being formalized by incorporation into the SANS documents. This was the case until 2015 when the DI tests were issued as SANS standards. Going forward, this move is expected to enhance the confidence of consulting engineers in specifying concrete durability which is complemented by testing.

The findings from the survey show that there is awareness regarding concrete durability amongst the stakeholders in design, specification and construction, with an exception of testing. Consulting engineers were mostly in agreement with the survey statements evaluating durability design, specification, construction and quality. This is further strengthened by a careful review of concrete mix designs prior to the construction of concrete. The selection of materials e.g. sourcing and using non-reactive aggregate is a matter of reviewing the impact of this on a given project individually as this may not be practical for all projects. The current durability-related practices by consulting engineers were found to be following a 'hybrid' approach, which reflects the current standards and also is a step closer to the implementation of the performance-based approach by the application of DI tests.

The survey results indicated that in tertiary institutions, learners are introduced to the concepts of the 'hybrid' approach of concrete durability design and specification. However, similar to consulting engineers, the learners seem to have a high regard for compressive strength testing as opposed to durability testing. With the recent issuing of DI tests as SANS standards, it is envisaged that these will be incorporated in the syllabi to prepare the learners with respect to a performance-based durability design, specification and testing of concrete.

The stakeholders involved in the supply of concrete-making materials and construction of concrete structures (i.e. contractors, readymix concrete suppliers, cement suppliers and concrete admixtures suppliers), showed a high level of awareness with regard to concrete durability. Contractors, readymix concrete suppliers and cement suppliers were in agreement that blended cements are preferred to plain Portland cement, with all mentioning that the former leads to longer service life. It was interesting to note that one of the reasons given for selecting blended cements was to lower a carbon footprint, and this is also enforced by clients in their pursuit to obtain a Green Building Star Rating (Green Building Council of South Africa). It is important to take note of this as concrete mix designs are carried out by the readymix concrete suppliers and not contractors, for approval by engineers.

The testing methods to evaluate the quality of concrete was reported by the contractors, readymix concrete suppliers, cement suppliers and concrete admixtures suppliers to be mostly compressive strength; except for projects where Clients/Employers enforced other testing methods, in this case, DI tests. Readymix concrete suppliers and cement suppliers reported a high level of knowledge of DI tests, but, this does not imply that these tests are being applied in practical projects as expected.

In the case of concrete admixture suppliers, it was noted that waterproofing admixtures are the most commonly used special concrete admixtures. This gives the notion of a belief that the inclusion of waterproofing admixtures results in adequately impermeable concrete thereby ensuring durability. While previous research has shown that this is plausible (Ballim, et al, 2009b), the costs associated with this approach are relatively high considering the frequency of maintenance required during the life of the structure. It is therefore important that more awareness is made on the advantages of ensuring inherent concrete durability by ensuring that suitable durability indices are specified.

In general, the responses from the different stakeholders show similarities in terms of awareness of the need to have durable concrete, but this awareness is not being implemented by applying measureable durability-related properties of concrete to evaluate its penetrability. With the DI testing methods being incorporated into SANS standards, it is expected that the industry implement these tests in construction projects with the aim of achieving durable concrete. Also, learners in tertiary institutions should be introduced to these test methods as a step towards creating awareness in the industry in which they eventually practice.

In order for the construction of concrete to realise the performance-based durability design, DI testing should not be viewed by the various stakeholders as an additional initial cost in projects; but rather, a necessary method to verify the quality of concrete in order to plan and develop appropriate maintenance strategies in the life of the structure. The need for maintenance of concrete structures during their service life was to some extent acknowledged in the survey by the various stakeholders (consulting engineers (38%), tertiary institutions (38%) and contractors (83%)).

Chapter 5

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, a critical appraisal of the developments in durability design, specification, construction and testing of concrete structures in South Africa was done. This was fulfilled by doing a critical literature review into the subject. The findings of the literature review were that the current South African standards present a ‘hybrid’ approach; whereby a mix of prescriptive and performance requirements are specified with emphasis on the performance criteria.

Further, developments in the durability design were brought about by means of establishing a framework for durability index tests. These were tested and further developed over the years. In the year 2015, the OPI and CCI were issued as SANS standards. The test method for WSI is available but this has not been incorporated into SANS standards yet.

These tests have been issued as SANS Test Methods as listed below:

1. SANS3001-C03-1:2015 – for preparation of test specimens.
2. SANS3001-C03-2:2015 – for oxygen permeability test.
3. SANS3001-C03-3:2015 – for chloride conductivity test.

To this end, the onus is on the industry participants (consulting engineers) to make use of these approaches and test methods in construction projects.

The aim of this research was to review work that has been done to develop and implement concepts for durability of concrete structures in South Africa. The objectives of this study and how this research addresses them are as listed below:

a) *to take stock of the work that has been done with regard to concrete durability design, specification, construction and testing of concrete structures in South Africa and around the world; and further provide a critique thereof.*

This objective was addressed by a critical review of literature. The developments in the durability design approaches were realised and further, it was found that the current South African standards present a 'hybrid' approach and the durability testing methods have been issued as SANS standards.

b) *to establish the awareness of practicing engineers on the subject of concrete durability design, specification, construction and testing of concrete structures; and how they apply the durability approach.*

This objective was addressed by an industry survey carried out in form of structured questionnaires. It was found that there is awareness with regard to durability design and specification; however, durability testing of as-built structures is mostly not undertaken. Further, it was determined by statistical data analysis that application of the DI tests does not depend on a practitioner's experience or geographical location of projects. It was intimated that implementation of the DI tests in construction projects is only done when enforced by Employers/Clients.

c) *to review the curricula of South African institutions of higher learning education in civil engineering to establish how concrete durability has been incorporated therein.*

This objective was addressed by a survey carried out in form of structured questionnaires. It was found that there is awareness with regard to durability design and specification and this is included in the curricula; however, durability testing and the importance of testing as-built concrete structures are not covered in the curricula.

d) *to establish the awareness of other stakeholders in the construction industry on the subject of concrete durability approaches.*

This objective was addressed by industry surveys carried out in form of structured questionnaires. It was found that there is awareness with regard to concrete durability when it comes to implementation, i.e. construction and quality; however, durability testing of the as-built structure is mostly not undertaken. This is due to the fact that the likelihood of these tests being carried out when not included in the project specifications by consulting engineers does not exist. These carry a cost and time implication which necessitates that they be included in the project documentation. Therefore, to enable improvement in this regard, the consulting engineers in agreement with Employers/Clients have to incorporate the specifications accordingly.

5.2 Recommendations

5.2.1 Recommendation from the current study

Below are recommendations based on the findings of this study:

a) Noting that the durability index tests have been issued as SANS standards, it is recommended that the practising engineers make use of these in driving the change in the design approach by specifying these test methods in projects. The ideal way forward is the performance-based design and construction of concrete structures.
b) The curricula in the tertiary institutions should incorporate the developments in durability design and further, the implementation of the performance-based design.
c) There has to be an awareness drive to make the client bodies aware of the developments in durability design and the importance of the implementation of performance-based design, more importantly now that the SANS DI testing methods are available. This will also help in implementing verification by the client bodies.

d) There is a need to possibly update the scope and guidance of the durability requirements in the current standards SANS 10100-2 and SANS 2001-CC1, to reflect the wealth of knowledge in the subject and further extend the durability requirements and testing methods beyond those provided for water-retaining structures.

5.2.2 Recommendation for future research

Below are recommendations for future research:

a) A study similar in nature to the current study, to evaluate the uptake of the durability tests in the construction industry, taking into consideration that these were formalised as SANS standards in the year 2015.
b) A cost comparison study based on current construction costs between performance-based design and the current hybrid approach. This may be extended to the overall life cycle cost analysis for these two options. It is believed that this will help in getting performance-based design implemented based on the results of the cost study.
c) An evaluation of the application of DI tests to concrete prepared with waterproofing concrete admixtures; to determine whether the inclusion of this type of admixture removes the need to test the penetrability concrete.

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APPENDIX A

SURVEY QUESTIONNAIRES

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Consulting Engineers

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 10 to 15 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

1	How long have you practiced in the field?					
	a) 1 to 3 years					
	b) 3 to 6 years					
	c) 6 to 10 years					
	d) More than 10 years					
2	As part of your practice, which one of the below closely describes your involvement in design and specification of concrete?					
	a) Design and specifying concrete mix and grade.					
	b) Design and testing concrete mix design to meet specified concrete grade.					
	c) Other (specify):					
3	Within the past five years, which of the following best describes the location of your projects involving construction of any concrete structures? Inland (e.g. Johannesburg); Coastal (e.g. Cape Town).					
	a) More projects located inland than in coastal areas.					
	b) More projects located in coastal areas than inland.					
	c) Projects equally balanced between inland and in coastal areas.					
	d) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
4	The project location or the surrounding environment to which concrete will be exposed influences the selection of concrete mix ingredients.					
5	The use of plain Portland cement remains highly common in our practice in the present day.					
6	The use of blended cements remains highly common in our practise in the present day.					

7	Whose duty is it to clearly specify the cement type in line with the factors that are to be considered in making selection?					
	a) Engineer/Designer.					
	b) Owner/Client.					
	c) Concrete supplier.					
	d) Contractor.					
	e) All of the above.					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
8	It is important for the designer or specifier to specify the cement content.					
9	It is desirable to use aggregates that do not react with other ingredients in concrete for various reasons; if the project location presents unavoidable use of reactive aggregates, what do you specify to take this into consideration?					
	a) Source non-reactive aggregates at all costs.					
	b) Use reactive aggregate regardless.					
	c) Specify maximum alkali content in the concrete.					
	d) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
10	The use of concrete admixtures remains highly common in our practise in the present day.					
11	It remains the duty of the designer or specifier to specify the type of concrete admixture to be used in line with the factors that are to be considered in making selection.					

12	What factors do you consider in the selection of the type of concrete admixture (if applicable to you)?					
	Answer:					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
13	There is awareness on the use of admixtures and their effects within your practice.					
14	It is imperative for the designer or specifier to review and approve the concrete mix design prior to site concrete works.					
15	What factors do you consider for approval of the concrete mix design?					
	Answer:					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
16	Amongst other factors, exposure conditions are important to consider when specifying the concrete cover.					
17	Amongst other factors, the concrete strength is important to consider when specifying the concrete cover.					
18	It is important for the designer or specifier to specify the exact concrete cover required for concrete elements rather than specifying minimum to maximum range.					
19	Higher strength concrete (40MPa, 50MPa, etc.) equate to better quality concrete (e.g. less penetrable by water).					
20	Specifying maximum water/cement ratio results in better quality concrete.					
21	Compressive strength (usually at 7 and 28 days) testing of concrete is an adequate quality check for concrete.					
22	In addition to the compressive strength testing of concrete, what other test methods do you specify (if any)?					
	Answer:					
23	What properties of concrete do the test methods in 22 above assess (if any)?					
	Answer:					

24	In your view, what informs adequate concrete compaction?					
	a) Planning ahead and deciding on the suitable compaction methods for a specific structure.					
	b) Inspections during concreting and photographic records.					
	c) Concreting checklists complete and signed by responsible foreman.					
	d) All of the above.					
	e) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
25	It is important for the designer or specifier to specify the curing method or review and approve the one proposed by the constructor for the construction of concrete structures.					
26	It is important for the designer or specifier to specify the curing duration or review and approve the one proposed by the constructor for the construction of concrete structures.					
27	What factors influence the selection of curing method and duration?					
	Answer:					
28	In your view, what would be the ideal curing period for reinforced concrete structures regardless of location or temperature?					
	a) Less than 3 days.					
	b) 3 to 7 days.					
	c) 7 to 10 days.					
	d) 10 to 20 days.					
	e) More than 20 days.					

29	It is unavoidable that there is a possibility of plastic shrinkage cracks developing in concrete structures. How do you deal with this possibility?	
	a) Specify the maximum crack width.	
	b) Make use of codified maximum crack widths.	
	c) Demolish structures that develop cracks larger than the specified crack width.	
	d) Develop a repair procedure for all unavoidable cracks.	
	e) All of the above.	
30	The maintenance phase for concrete structures should commence	
	a) Soon after construction.	
	b) 6 – 12 months after construction.	
	c) When the maintenance budget is made available.	
	d) When deterioration starts showing.	
	e) Not sure.	
31	Has your practice evolved over the years with regard to design, specification, construction and testing of concrete?	
	a) Yes. How?	
	b) No.	
	c) To some extent. How?	
32	In your view or knowledge, what informed these changes (if any)?	
	Answer:	

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Tertiary Institutions

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 10 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

The questions below aim to understand the current structure and content of the curriculum in tertiary institutions with respect to aspects relating to this study. Please read all questions or statements and kindly answer honestly to the best of your knowledge.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1	The design of concrete structures taking into consideration the environment they will be exposed to was covered adequately.					
2	The importance of the environment to which concrete structures will be exposed to when in service was sufficiently clarified.					
3	The manner in which concrete structures interact with their exposure environment including the transport mechanisms of various harmful substances (e.g. moisture, chlorides, carbon dioxide, etc.) in concrete was covered adequately.					
4	The physical and chemical deterioration mechanism in concrete (e.g. abrasion, erosion, carbonation, etc.) was covered adequately.					
5	The factors causing concrete attack (e.g. transport properties, physical properties, chemical properties, etc.) were covered adequately.					
6	The factors to consider when selecting the type of binder (e.g. Portland Cement, Fly Ash, Ground Granulated Slag, etc.) were covered adequately.					
7	The factors to consider when determining the binder content (e.g. 300kg/m^3, 400kg/m^3, etc.) were covered adequately.					
8	The factors to consider when selecting the type of concrete admixture to use in a project were covered adequately.					
9	The factors to consider when selecting the type of aggregates (fine and course) to use in concrete were covered adequately.					
10	The factors to consider when selecting the content of aggregates (fine and course) to use in concrete were covered adequately.					
11	The factors to consider when specifying the water-to-cement ratio (w/c) were covered adequately.					
12	The method/s to determine concrete mix ingredients (i.e. concrete mix design) were covered adequately.					
13	The factors to consider when specifying concrete cover to steel reinforcement were covered adequately.					

14	Amongst other factors, exposure conditions are important to consider when specifying the concrete cover.					
15	Amongst other factors, the concrete strength is important to consider when specifying the concrete cover.					
16	Transportation of concrete (e.g. from the point of delivery to the point of placing) on site during construction was covered adequately.					
17	Placing of concrete (at the point where concrete is to be cast) on site during construction was covered adequately.					
18	Compaction of concrete (e.g. by way of vibration, etc.) on site during construction was covered adequately.					
19	Curing of concrete (e.g. by covering with plastic sheeting after casting, applying a commercial curing compound after casting, etc.) on site during construction was covered adequately.					
20	Procedure for post concreting inspections to identify flaws (e.g. honeycombing, cracks, etc.) on site during construction was covered adequately.					
21	Testing of concrete in the fresh state was covered adequately.					
22	Testing of concrete in the hardened was covered adequately.					
23	What is the purpose of using admixtures in concrete?					
	a) To compensate for bad materials, good mix design and good workmanship.					
	b) To modify some of the properties of concrete as required in a project.					
	c) All of the above.					
	d) Other:					
24	In addition to the compressive strength (usually at 7 and 28 days) testing of concrete, what other test methods were covered (if any)?					
	Answer:					
25	What properties of concrete do the test methods in 24 above assess (if any)?					
	Answer:					

26	The maintenance phase for concrete structures should commence	
	a) Soon after construction.	
	b) 6 – 12 months after construction.	
	c) When the maintenance budget is made available.	
	d) When deterioration starts showing.	
	e) Not sure.	

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Contractors

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 10 to 15 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

1	How long have you practiced in the field?					
	a) 1 to 3 years					
	b) 3 to 6 years					
	c) 6 to 10 years					
	d) More than 10 years					
2	Within the past five years, which of the following best describes the location of your projects involving construction of any concrete structures? Inland (e.g. Johannesburg); Coastal (e.g. Cape Town).					
	a) More projects located inland than in coastal areas.					
	b) More projects located in coastal areas than inland.					
	c) Projects equally balanced between inland and in coastal areas.					
	d) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
3	The project location or the surrounding environment to which concrete will be exposed influences the selection of concrete mix ingredients.					
4	The use of plain Portland cement remains highly common in our present day-to-day construction practice.					
5	The use of blended cements remains highly common in our present day-to-day construction practise.					
6	The cement/binder type is always specified by the designer or specifier.					
7	The cement/binder type is always specified by the readymix concrete producer.					
8	The minimum cement content is always specified by the designer or specifier.					

9	It is desirable to use aggregates that do not react with other ingredients in concrete for various reasons; if the project location presents unavoidable use of reactive aggregates, what do you specify to take this into consideration?					
	a) Source non-reactive aggregates at all costs.					
	b) Use reactive aggregate regardless.					
	c) Notify the specifier and have liaisons to resolve.					
	d) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
10	The use of concrete admixtures remains highly common in our practise in the present day.					
11	The type of concrete admixture is always specified by the designer or specifier.					
12	The type of concrete admixture is always specified by the readymix concrete producer.					
13	The concrete mix design is always requested by the designer or specifier for review and approval prior to site concrete works.					
14	The exact concrete cover required for concrete elements is always specified by the designer or specifier.					
15	Higher strength concrete (40MPa, 50MPa, etc.) equate to better quality concrete (e.g. less permeable by water).					
16	A specified maximum water/cement ratio always results in better quality concrete.					
17	Compressive strength (usually at 7 and 28 days) testing of concrete is an adequate quality check for concrete.					
18	In addition to the compressive strength testing of concrete, what other test methods do you carry out (if any)?					
	Answer:					
19	What properties of concrete do the test methods in 18 above assess (if any)?					
	Answer:					

20	What informs your decision on which tests to carry out?					
	a) Specified by the specifier.					
	b) Enforced by the project funder/employer.					
	c) Standard tests. Which ones:					
	d) Other (specify):					
21	What measures do you put in place to ensure that concrete is compacted to meet the quality requirements during concrete operations on site?					
	a) Planning ahead and deciding on the suitable compaction methods for a specific structure.					
	b) Inspections during concreting and photographic records.					
	c) Concreting checklists complete and signed by responsible foreman.					
	d) All of the above.					
	e) Other:					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
22	It is the duty of the constructor to select the workability of concrete in line with the influencing factors.					
23	What factors do you consider to select the workability of concrete (if applicable to you)?					
	Answer:					
24	What test/s do you carry out to measure the workability of concrete?					
	Answer:					

25	How do you deal with concrete that does not meet the desired workability?					
	a) Use it for casting.					
	b) Pour more water if it is drier than required.					
	c) Mix in more dry ingredients (cement, aggregate) if wetter than required.					
	d) Reject concrete and order new.					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
26	The curing method is always specified by the designer or specifier.					
27	If the curing method is not specified by the designer or specifier, a curing method proposed by the constructor is submitted to the designer or specifier for approval.					
28	The curing duration is always specified by the designer or specifier.					
29	If the curing duration is not specified by the designer or specifier, a curing duration proposed by the constructor is submitted to the designer or specifier for approval.					
30	What factors influence the selection of curing method and duration if you were to propose the two?					
	Answer:					
31	In your view, what would be the ideal curing period for reinforced concrete structures regardless of location or temperature?					
	a) Less than 3 days.					
	b) 3 to 7 days.					
	c) 7 to 10 days.					
	d) 10 to 20 days.					
	e) More than 20 days.					

32	It is unavoidable that there is a possibility of plastic shrinkage cracks developing in concrete structures. How do you deal with this possibility?	
	a) Demolish and reconstruct.	
	b) Review against standard tolerances or tolerances by the specifier.	
	c) Source corrective measures for approval by the specifier.	
	d) Ignore them.	
	e) Other (specify):	
33	The maintenance phase for concrete structures should commence	
	a) Soon after construction.	
	b) 6 – 12 months after construction.	
	c) When the maintenance budget is made available.	
	d) When deterioration starts showing.	
	e) Not sure.	
34	Has your practice evolved over the years with regard to design, specification, construction and testing of concrete?	
	a) Yes. How?	
	b) No.	
	c) To some extent. How?	
35	In your view or knowledge, what informed these changes (if any)?	
	Answer:	

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Readymix Concrete Producers

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 10 to 15 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

1	How long have you practiced in the field?	
	a) 1 to 3 years	
	b) 3 to 6 years	
	c) 6 to 10 years	
	d) More than 10 years	
2	Within the past five years, which of the following best describes the location of your projects involving construction of any concrete structures? Inland (e.g. Johannesburg); Coastal (e.g. Cape Town).	
	a) More projects located inland than in coastal areas.	
	b) More projects located in coastal areas than inland.	
	c) Projects equally balanced between inland and in coastal areas.	
	d) Other (specify):	

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
3	The project location or the surrounding environment to which concrete will be exposed influences the selection of concrete mix ingredients.					
4	The cement selected for use in a project is selected in line with the influencing factors and liaisons with the cement producer.					
5	The cement extender selected for use in a project is selected in line with the influencing factors and liaisons with the cement producer.					
6	The specified properties of concrete by the designer or specifier (e.g. 30MPa, water retaining structures, etc.) are taken into consideration in selecting cements for use in concrete structures.					

7	What factors do you consider in selecting cements for use in reinforced concrete structures?					
	Answer:					
8	How would you rank the factors in order of importance; from most important to least important?					
	Answer:					
9	What factors do you consider in selecting the type of aggregates?					
	Answer:					
10	How would you rank the factors in order of importance; from most important to least important?					
	Answer:					
11	It is desirable to use aggregates that do not react with other ingredients in concrete for various reasons; if the project location presents unavoidable use of reactive aggregates, what do you specify to take this into consideration?					
	a) Source non-reactive aggregates at all costs.					
	b) Use reactive aggregate regardless.					
	c) Notify the specifier and have liaisons to resolve.					
	d) Other (specify):					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
12	The use of concrete admixtures remains highly common in our practise in the present day.					
13	What factors do you consider in selecting the type of concrete admixture?					
	Answer:					
14	How would you rank the factors in order of importance; from most important to least important?					
	Answer:					

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
15	There is awareness on the use of admixtures and their effects within your practice.					
16	A maximum water/cement ratio is always specified by the designer or specifier.					
17	A specified maximum water/cement ratio always results in better quality concrete.					
18	If you chose (d) or (e) in 16 above, on what basis do you formulate your determination?					
	Answer:					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
19	Usually, you are allowed to determine the water/cement ratio as part of your concrete mix design.					
20	The specified properties of concrete by the designer or specifier (e.g. 30MPa, water retaining structures, etc.) are taken into consideration in order to produce the concrete mix design.					
21	Amongst other factors, the specified concrete strength is the key factor to inform the selection of ingredients for the concrete mix design.					
22	What factors do you consider in selecting materials for the production of the concrete mix design?					
	Answer:					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
23	There is never a requirement for you to produce and submit the concrete mix design to the designer or specifier for review and approval prior to site concrete works.					
24	For the majority of projects (being more than 50%), the concrete mix design is always requested by the designer or specifier for review and approval prior to site concrete works.					
25	For all projects, the concrete mix design is always requested by the designer or specifier for review and approval prior to site concrete works.					

26	Concrete samples are always prepared and tested to evaluate properties of your proposed concrete mix design prior to the submission of the mix design to the designer or specifier.					
27	Concrete samples only for special mixes (e.g. water retaining structures, structures in tidal zones, etc.) are prepared and tested to evaluate properties of your proposed concrete mix design prior to the submission of the mix design.					
28	Compressive strength (usually at 7 and 28 days) testing of concrete is an adequate quality check for concrete.					
29	In addition to the compressive strength testing of concrete, what other test methods do you carry out (if any)?					
	Answer:					
30	What properties of concrete do the test methods in 29 above assess (if any)?					
	Answer:					
31	Has your practice evolved over the years with regard to design, specification, construction and testing of concrete?					
	a) Yes. How?					
	b) No.					
	c) To some extent. How?					
32	In your view or knowledge, what informed these changes (if any)?					
	Answer:					

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Producers of Cement

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 5 to 10 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1	The use of plain Portland cement remains highly common in the present day as requested by the constructor or readymix concrete producer.					
2	The use of blended cements remains highly common in the present day as requested by the constructor or readymix concrete producer.					
3	The selection of cement type varies with the project location; such that a certain type of cement is more demanded in a certain place than in other places.					
4	The use of blended cements in concrete result in longer service life of concrete structures.					
5	The cement selected for use in a project is selected in line with the influencing factors and liaisons with the constructor or readymix concrete producer.					
6	The cement extender selected for use in a project is selected in line with the influencing factors and liaisons with the constructor or readymix concrete producer.					
7	The specified properties of concrete by the designer or specifier (e.g. 30MPa, water retaining structures, etc.) are taken into consideration in selecting cements for use in concrete structures.					

8	What factors do you consider in recommending cements to the constructor or readymix concrete producer for use in reinforced concrete structures?
	Answer:
9	Do you take into consideration aggregates to be used in liaisons with the constructor or readymix concrete producer in recommending cements for concrete structures?
	Answer:
10	What have been the most noticeable developments in the cement production over the years with regard to the production of less penetrable concrete?
	Answer:
11	In your view, what would you say is the driver of these developments (if any)?

	Answer:	
12	In your view, have these developments produced outcomes that were envisaged?	
	a) Yes. How?	
	b) No.	
	c) To some extent. How?	
13	Within the foreseeable future, are there developments expected in line with current trends in the concrete industry?	
	a) Yes. How?	
	b) No.	

SURVEY QUESTIONNAIRE

Design, Specification, Construction and Testing of Concrete Structures in SA, University of the Witwatersrand, Johannesburg, March 2018

Producers of Admixtures

Dear Sir/Madam,

By answering this questionnaire you will provide valuable information on South Africa's current concrete construction practices and help in realising the objectives of this study. This survey aims at reviewing South Africa's current concrete construction practices with regard to the design, specification, construction and testing. Please read each question or statement carefully and kindly try to respond to all questions honestly and to the best of your knowledge. Completing the survey will take on average 5 to 10 minutes. Your responses will be treated with strict confidentiality and will only be used for the purposes of this research. Your participation in the survey is greatly appreciated.

By answering this questionnaire, I hereby give consent and understand

- That the information provided will be used for research purposes only;
- That I will give honest responses to the survey questions;
- That my identity will not be revealed;

Name: .... Signature: ....

Signed at: .... on this .... day of .... 2018.

		1 Most	2	3	4	5 Least
1	In a scale: 1 = most and 5 = least, please mark the type of admixture that is mostly demanded by readymix concrete producers.					
	a) Plasticisers.					
	b) Superplasticisers.					
	c) Air-entrainers.					
	d) Accelerators.					
	e) Retarders.					
2	In a scale: 1 = most and 5 = least, please mark the type of special admixture that is mostly demanded by readymix concrete producers.					
	a) Waterproofing admixtures.					
	b) Corrosion inhibitors.					
	c) Shrinkage reduction admixtures.					
	d) Alkali-silica reactivity reduction admixtures.					
	e) Colouring admixtures.					
		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
3	The product demand varies with the project location such that a certain type of admixture is more demanded in a certain place than in other places.					
4	The inclusion of admixtures in concrete results in longer service life of concrete structures.					
5	As part of normal procedure, testing the effects of the admixture on concrete (fresh and hardened) is be done by preliminary tests at all times.					
6	The primary effects of an admixture on fresh concrete are always disclosed to the user.					

7	The secondary effects of an admixture on hardened concrete are always disclosed to the user.					
8	There is awareness on the use of admixtures and their effects amongst all stakeholders involved in the production of concrete.					
9	How is this awareness driven (if applicable)?					
	Answer:					
10	What factors do you consider in recommending an admixture to the constructor or readymix concrete producer for use in reinforced concrete structures?					
	Answer:					
11	Do you take into consideration aggregates to be used in liaisons with the constructor or readymix concrete producer in recommending an admixture for concrete structures?					
	Answer:					
12	What have been the most noticeable developments in the production of admixtures over the years with regard to the production of less penetrable concrete?					
	Answer:					
13	In your view, what would you say is the driver of these developments (if any)?					
	Answer:					
14	In your view, have these developments produced outcomes that were envisaged?					
	a) Yes. How?					
	b) No.					
	c) To some extent. How?					
15	Within the foreseeable future, are there developments expected in line with current trends in the concrete industry?					
	a) Yes. How?					
	b) No.					

APPENDIX B

STATISTICAL COMPUTATIONS

Statistical Computations and Methods:

The statistical computations presented below can be found on SPSS website together with guidance tutorials.

Chi-Square Independence Test

The Chi-square independence test is a procedure fir testing if two categorical variables are related is some population, e.g. whether or not the engineer's years of experience in practice is related to the engineers specification of DI tests, as seen in this research. The Chi-square test statistic is calculated as

$$\chi^2 = \sum \frac{(oij - eij)^2}{eij}$$

where: χ^2 is a Chi-square test statistic

oij is the number for observed frequencies as obtained from survey data

eij is the number for expected frequencies determined on the basis that the two variables are completely independent

The Chi-square test is based on the following assumptions:

a) Independent observations – this usually, not always, holds if each case holds a unique person or other statistical unit.
b) For a 2x2 table, all expected frequencies > 5. For a larger table, no more than 20% of all cells may have an expected frequency < 5 and all expected frequencies > 1.

If these assumptions hold, the χ^2 test statistic follows a χ^2 distribution which indicates the probability of finding χ^2 = a certain numerical value. The significance level based on the degrees of freedom (df), is known as p-value, the number that determines the exact shape of the distribution.

If $p > 0.05$, it means there is no relationship between the two categorical variables.

If $p < 0.05$, it means a relationship exists between the two categorical variables.

If it is found that a relationship exists between two categorical variables, i.e. $p < 0.05$, the strength of this relationship is not known. This strength of relationship is known as the effect size, determined by Cramér's V, if at least one nominal variable is involved. Cramér's V is determined by equation

$$\phi_c = \sqrt{\frac{\chi^2}{N\,(k - 1)}}$$

where: ϕ_c denotes Cramér's V

χ^2 is a Chi-square test statistic

N is the sample size

k is the lesser number of categories of either variable

Values for Cramér's V range from 0 to 1, the closer 0 indicating a very weak association and the opposite is true for values approaching 1.

An alternative to the Chi-square independence test is the Fisher's Exact Test which is used when the Chi-square assumptions are violated or the data being analysed is from a small sample ($N \leq 300$). For this research, this computation was carried out in one of the available online statistical computations found on website www.vassarstats.net.

Internal reliability – Cronbach's Alpha

Internal reliability provides a meaningful estimation of the degree with which a set of questions in a survey measure a similar underlying characteristics, thereby determining the accuracy of measurement (Warmbrod, 2014), (Gliem and Gliem, 2003). Robinson, et al, (1991), provide the following ranges for Crobach's Alpha as a general criteria for reliability acceptance: > 0.80 is exemplary, > 0.70 is extensive, > 0.60 is moderate, and < 0.60 is minimal; calculated on computer scaling programmes. For this research, the ANOVA computation on excel was done.

The omission of some questions in a scale (deletion of redundant questions) means excluding questions that do not bear relevant in a characteristic being measured by a Likert scale (i.e. a group of Likert items).

The measure of the central tendency provides the means to evaluate whether the survey respondents are mostly in agreement or disagreement with a given statement or set of statements.

APPENDIX C

ETHICS CLEARANCE CERTIFICATE

Assessment of Ethics of Research Protocols in which humans are involved

Civil and Environmental Engineering Ethics Clearance Certificate No: CEECC-(1148077-2018)

Researcher: Nonhle Dlamini **Student No.** 1148077

All research in which humans are involved either as informants or subjects (carried out in the University by undergraduates, postgraduates, staff or affiliated staff in the name of the University) need to respect the rights of individuals by ensuring that:

- the informant or subject has consented to the research without coercion;
- the questions posed are not insulting or embarrassing;
- confidential matters that could place the informant in an embarrassing, false or compromising position vis-à-vis authorities, are handled circumspectly;
- the privacy and wishes of informants are respected, i.e. anonymity of the informant is maintained if required;
- the informant is informed as fully as possible as to the aims and possible implications of the research.

For MSc researchers on a half coursework half research (MSc 50/50) or the Master of Engineering (MEng) program, the assessment is carried out by the School Ethics Committee within the respective Schools.

The research proposal by Nonhle Dlamini includes the acquisition of information by the use of questionnaires and a School Committee composed of Dr T Ekneligoda, Prof J Ndiritu and Dr M Otieno assessed the proposed research protocols on 16th February 2018.

The committee found the research proposal to meet all the requirements set by the Human Research Ethics Committee (HREC Non-Medical) of the University of the Witwatersrand.

Prof John Ndiritu
Post Graduate Coordinator
School of Civil and Environmental Engineering