Investigation of a practical application of the Maturity Method to estimate the early-age strength of concrete

by

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Thesis presented in fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering in the Faculty of Engineering at Stellenbosch University

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December 2019

DECLARATION

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ABSTRACT

This study investigates the accuracy of the Maturity Method to estimate the early-age strength of concrete in a South African context towards the possible optimization of formwork removal of suspended slabs. The Maturity Method estimates the strength of concrete based on its temperature history. Temperature measurements of concrete cubes are taken, with the maturity calculated from the temperature history. The maturity is then correlated with compressive strengths through cube compression tests at various ages to develop a mix calibration.

The in-situ strength estimation is done by measuring the in-situ temperature history, and consequently maturity, and calculating the strength based on the maturity. The in-situ temperature measurement is done with newly developed wireless sensors called SmartRocks. SmartRocks are cast into concrete and measures the temperature history of concrete and transmits the data via Bluetooth to an application on a smartphone, with the maturity calculated and strength estimated by the application.

The maturity can be calculated with various maturity functions. Two maturity functions that were investigated in this study, are the Nurse-Saul and Arrhenius maturity functions. From the Laboratory Test Phase that was conducted in this study, it can be concluded that the Nurse-Saul maturity function is the easiest to apply, with sufficient accuracy. The Nurse-Saul maturity function requires a Datum Temperature as input. Values for the Datum Temperature can be obtained from literature, or it can be experimentally determined. Sets of cubes were cured at three temperatures with Strength-Maturity relationships developed for these temperatures. By comparing these relationships with each other, it can be concluded that the Maturity Method is sufficiently accurate to predict in-situ concrete strength. Different strength prediction models were also investigated in this study. These models were the logarithmic, hyperbolic and exponential models respectively. It is recommended that the exponential model be used to predict the Strength-Maturity relationship.

During the Site Test Phase, SmartRock sensors were cast into a slab on the construction site of an 11-storey residential development. A series of best practice guidelines for the use of SmartRocks on site is given. Two sensors were cast into the slab at the same position, in plan, at the top and bottom of slab to determine whether different maturities are developed. There was no significant difference between the maturities developed at the top and bottom of the slab.

Interviews were conducted with industry professionals to determine the applicability of SmartRocks in the South African construction industry. A few major conclusions can be made from the interviews with the industry professionals. Current techniques used for in-situ strength estimation are lacking. The majority of the industry professionals also feel that the concrete suppliers should be responsible for mix calibration and that the required skills to implement SmartRocks are available in the South African construction industry.

OPSOMMING

Hierdie studie ondersoek die akuuraatheid van die Rypheidsmetode om die vroeë-ouderdom sterkte van beton the voorspel in ‘n Suid Afrikaanse konteks, om moontlik optimisering van bekisting verwydering te bereik. Die Rypheidsmetode voorspel sterkte op grond van die beton se temperatuur geskiedenis. Die rypheid van beton word bereken van die beton se temperatuur lesings. Die rypheid word dan gekorrelleer met die druksterkte deur middel van kubus druktoetse by verskillende ouderdomme om ‘n meng kalibrasie te ontwikkel.

Die voorspelling van die in-situ beton sterkte word gedoen deur die in-situ temperatuur geskiedenis, en gevolglik, die rypheid, te meet. Die sterkte word voorspel gebasseer op die in-situ rypheid. Die in-situ temperatuur meting word gedoen met nuut ontwikkelde sensors, genaamd SmartRocks. Hierdie sensors word in beton gegiet, dit meet dan die in-situ temperatuur en dra die data oor met Bluetooth tegnologie na ‘n slimfoon. Die rypheid en sterkte word met ‘n toepassing op die slimfoon bereken.

Rypheid van beton kan met verskeie rypheidsfunksies bereken word. Twee rypheidsfunksies is ondersoek in hierdie studie, naamlik die Nurse-Saul – en Arrhenius rypheidsfunksies. Vanaf die laboratorium toetse wat gedoen is in hierdie studie, kan daar afgelei word dat die Nurse-Saul rypheidsfunksie die eenvoudigste is, met genoegsame akuuraatheid om toe te pas. Die Nurse-Saul rypheidsfunksie benodig ‘n Datum Temperatuur, as ‘n konstante. Waardes vir die Datum Temperatuur, kan van die literatuur verkry word, of dit kan eksperimenteel bepaal word. Kubus stelle is nabehandel by drie verkillende temperature en Sterkte-Rypheidsverhoudings is ontwikkel vir hierdie temperature. Deur hierdie verhoudinge met mekaar te vergelyk, kan daar afgelei word dat die Rypheidsmetode in-situ beton sterkte kan voorspel met genoegsame akuuraatheid. Verskillende modelle wat die Sterkte-Rypheidsverhouding voorspel, is ook ondersoek in hierdie studie. Hierdie modelle is logartimies, hiperbolies en exponensieël van aard. Dit word voorgestel om die eksponensiële model te gebruik.

Gedurende die tereintoetse, is SmartRock sensors ingegiet in ‘n blad op die konstruksie terein van ‘n 11-verdieping residensiële ontwikkeling. ‘n Reeks van beste praktyke vir die gebruik van SmartRocks word nou voorgestel. Twee sensors is op dieselfde posisie, in plan, aan die bo- en onderkant van die blad gegiet, om te bepaal of daar verskille is in die rypheid wat die beton aan die bo- en onderkante ontwikkel. Daar was geen noemenswaardige verskil in die twee ryphede nie.

Onderhoude is gevoer met professionele lui uit die siviel ingenieurswese industrie, om die toepaslikhied van SmartRocks in Suid Afrika te bepaal. ‘n Paar gevolgtrekkings kan gemaak word. Huidige tegnieke vir in-situ sterkte voorspelling skiet tekort en die meerderheid van die individue voel dat beton verskaffers verantwoordelik moet wees vir die meng kalibrasie. Verder, is die meerderheid van mening dat kontrakteurs oor die benodigde vaardighede beskik om die SmartRock effektiewelik toe te pas.

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my deepest appreciation toward my study leader, Professor Jan Wium for his constant support and guidance.

I would like to thank all the industry professionals who took the time to share their wisdom and experience towards the possible implementation of SmartRocks in South Africa. I would also want to extend gratitude towards the role players who supplied materials for my laboratory tests and assisted me on site.

A special thanks to the PERI who sponsored a significant number of sensors to be used throughout the course of the research.

In addition, I would like to thank my peers for the advice that you have given and the help which you provided in the laboratory.

Lastly, I would like to thank all my friends and family for their unwavering support and especially my fiancé, Alicia, for being with me, every step of the way.

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Introduction

1.1 Background

1.1.1 In-situ strength estimation of concrete

The strength development of concrete is a result of the hydration of cement when it comes into contact with water. The hydration of cement, and consequently the strength gain of the concrete, occurs rapidly after casting, but the hydration decreases steadily as time progresses. Many factors, such as available moisture and temperature, amongst others, influence the rate at which concrete will gain strength and the non-linear relationship thereof makes it difficult to obtain accurate in-situ strength estimations.

Many techniques and tests have been developed to estimate the in-situ strength of concrete. All of these techniques, however, have limitations and are either destructive, semi-destructive, requires specialized equipment or has questionable accuracy.

The crushing of concrete cubes (or cylinders) to obtain the compressive strength of concrete has been widely adopted as an in-situ strength estimation technique. The simplicity of the method is attractive to the construction industry and it has proven to yield sufficiently accurate results. However, similar to the other estimation techniques, the cube crushing method has limitations. The curing temperature experienced by the in-situ concrete is not taken into account, as the cubes used in the crushing test are often cured under controlled conditions. Therefore, even though the construction industry has accepted the accuracy of the cube crushing test, the level of accuracy of in-situ concrete strength estimations can be improved. The Maturity Method is an in-situ strength estimation technique that can improve on current techniques as this method takes the combined effect of temperature and time on the in-situ concrete strength development into account.

1.1.2 Maturity Method

The Maturity Method is a non-destructive in-situ concrete strength estimation technique. The hydration of cement is an exothermic reaction and the rate of cement hydration, and implicitly the strength gain of concrete, can be correlated to the internal temperature of concrete. Furthermore, the external curing temperature influences the rate of concrete strength gain.

The maturity of concrete at a specific time after casting can be calculated with various maturity functions using the measured temperature history of the concrete. This study investigates two maturity functions that has proven to give sufficiently accurate results and are also easy to apply. These functions are the Nurse-Saul and Arrhenius maturity functions. The Nurse-Saul maturity function uses a Datum Temperature constant, whilst the Arrhenius maturity function uses an Activation Energy constant. These constants are unique for different cementitious systems.

Each concrete mix, of which the strength is estimated, needs to be calibrated in order to use the Maturity Method. This is done with laboratory tests by correlating the compressive cube strength with maturity calculated with either the Nurse-Saul or Arrhenius maturity functions, using the measured temperature history of the concrete cubes. A Strength-Maturity relationship is then obtained. The in-situ strength estimation is made by calculating the in-situ maturity and obtaining the strength from the Strength-Maturity relationship.

1.1.3 SmartRock

Limited practical applications of the Maturity Method have been available until now. The systems available to the construction industry in South Africa for temperature measurement on site involves casting thermocouples into concrete elements. The wired thermocouples protrude from the elements with data loggers attached to the wires. This is inconvenient for contractors and the Maturity Method is hence, seldom seen as a viable method for in-situ concrete strength estimation.

Wireless concrete sensors, SmartRocks, have been developed that measure and record concrete temperatures. Using the temperature data, the sensors provide a real-time estimation of in-situ concrete strength by means of the Maturity Method. The SmartRocks are cast into concrete and the data is wirelessly transmitted via Bluetooth technology to a smartphone. These sensors are therefore a convenient way to apply the Maturity Method on site.

Real time estimations of in-situ concrete strength can have significant benefits for the contractor, provided that these estimations are accurate. Accurate estimations at very early ages can lead to contractors making the decision to strip formwork or tensioning tendons earlier with confidence and therefore relieving pressure on construction schedules. Accurate estimations beyond 7 days after casting have the potential to minimize the use of concrete cube crushing tests for quality control and assurance purposes.

1.2 Problem statement

The Maturity Method was first introduced in the 1950's by researchers in England (Saul, 1951). A significant amount of research has since been done on the concept of concrete maturity and this has developed the Maturity Method further. Various limitations of the Maturity Method have been identified in previous research and is summarized as follows:

- Different curing temperatures during mix calibration lead to different Strength-Maturity relationships (Carino, 1991).
- The Strength-Maturity relationship is mixture specific and every mixture must, hence, be calibrated to produce a unique Strength-Maturity relationship (ASTM C 1074, 2011).
- Variability in void content between the concrete used for mix calibration and the concrete used on site will lead to discrepancies between the strength predicted by the Maturity Method and the actual in-situ strength.
- Available moisture during curing will influence the strength development of the concrete. If insufficient moisture is available during curing, strength development will cease, but the maturity of the concrete will still increase. This is because after the initial hydration heat is dissipated, the concrete varies with ambient temperature and not with hydration temperature. It is unlikely though, that sufficient moisture will not be available at very early ages.

The use of SmartRocks, and the associated application of the Maturity Method on site has the potential to revolutionize concrete construction in South Africa through the optimization of formwork removal and improvement in current quality control and assurance techniques. The limitations of the Maturity Method will be investigated to ensure that accurate early age in-situ concrete strength estimations are obtained through the use of SmartRocks on site. Furthermore, the Maturity Method should be calibrated for use in South Africa by providing suitable Datum Temperatures and Activation Energy values.

Thorough guidelines need to be developed for the use of SmartRocks in South Africa. These guidelines must encompass everything from the procedure for mix calibration, maturity function to be used and practical instructions for the installation and procedure for using of the SmartRock on site.

1.3 Aims and objectives

The primary aim of this study is to investigate the accuracy of the Maturity Method as an estimation technique for the early-age strength of concrete. If this method proves to be sufficiently accurate for the South African construction industry, a further aim of the study will be to investigative the applicability of the use of SmartRocks in the South African civil engineering industry. To achieve this, the following objectives have been identified:

- Determine the effect of variable curing temperatures on the Strength-Maturity Relationship.
- Determine the relative accuracy of the Nurse-Saul and Arrhenius maturity functions.
- Determine the most applicable strength prediction model.
- Provide guidance on the implementation of SmartRocks on site.
- Verify the accuracy of the in-situ strength estimations provided by the Maturity Method.
- Determine the willingness of industry professionals to apply SmartRocks on a project, taking into account the conditions in the construction industry and the skills available to effectively apply SmartRocks.

1.4 Scope and limitations

This study investigated the accuracy of the Maturity Method to provide in-situ concrete strength estimations. Furthermore, the Maturity Method must be calibrated for use in South Africa and guidelines should be developed for proper use of SmartRocks on site. To achieve these objectives, laboratory tests as well as site tests were done.

The laboratory tests determined the effect of variable curing temperatures on the Strength-Maturity Relationship as well as the relative accuracy of the Nurse-Saul and Arrhenius maturity functions. Lastly, the laboratory tests calibrated the Maturity Method for use in South Africa. Different curing temperatures were investigated, but variable curing conditions such as curing in air relative to curing in water were not investigated.

It has been identified by the suppliers of the sensors that optimization of formwork removal for suspended slabs between 150 mm and 350 mm thick will hold the biggest advantage for contractors. Therefore, the concrete mixes that were tested were those that are most commonly used for suspended slabs. The strengths for these concrete mixes range between 25 MPa and 40 MPa. The concrete mixes were obtained from a concrete ready-mix plant.

Feedback was obtained from professionals in the civil engineering industry to determine the applicability of SmartRocks in South Africa.

1.5 Research approach

To achieve the objectives set out for this study, the following approach was followed:

1.5.1 Literature review

An extensive review of current and past literature was undertaken to understand the hydration of cement and the associated strength development of concrete. Current in-situ strength estimation techniques are discussed to illustrate the advantages of the Maturity Method. Furthermore, the detailed process to obtain in-situ strength estimations through the use of the Maturity Method is described. Lastly, the limitations of the Maturity Method identified by previous research were determined, so that these limitations can be addressed in the test phase of this study.

1.5.2 Laboratory test phase

Cube tests were performed in accordance with ASTM C 1074, 2011 (Standard Practice for Estimating Concrete Strength by the Maturity Method) and SANS 5863, on concrete cubes cured at three temperatures. This determined the effect of variable curing temperatures on the Strength-Maturity Relationship and also simulated different curing temperatures experienced on site. It was then investigated if the cubes cured at different temperatures, estimated each other's strength accurately. The relative accuracy of the Nurse-Saul and Arrhenius maturity functions was also determined at the three curing temperatures.

Besides curing at three different temperatures, sets of cubes were cast from three different concrete mixes commonly used for slabs. With the data obtained from the cubes cast from the three concrete mixes, Datum Temperatures and Activation Energies are proposed and the Maturity Method was calibrated for use in South Africa. The approach for this phase is shown schematically in Figure 1.1.

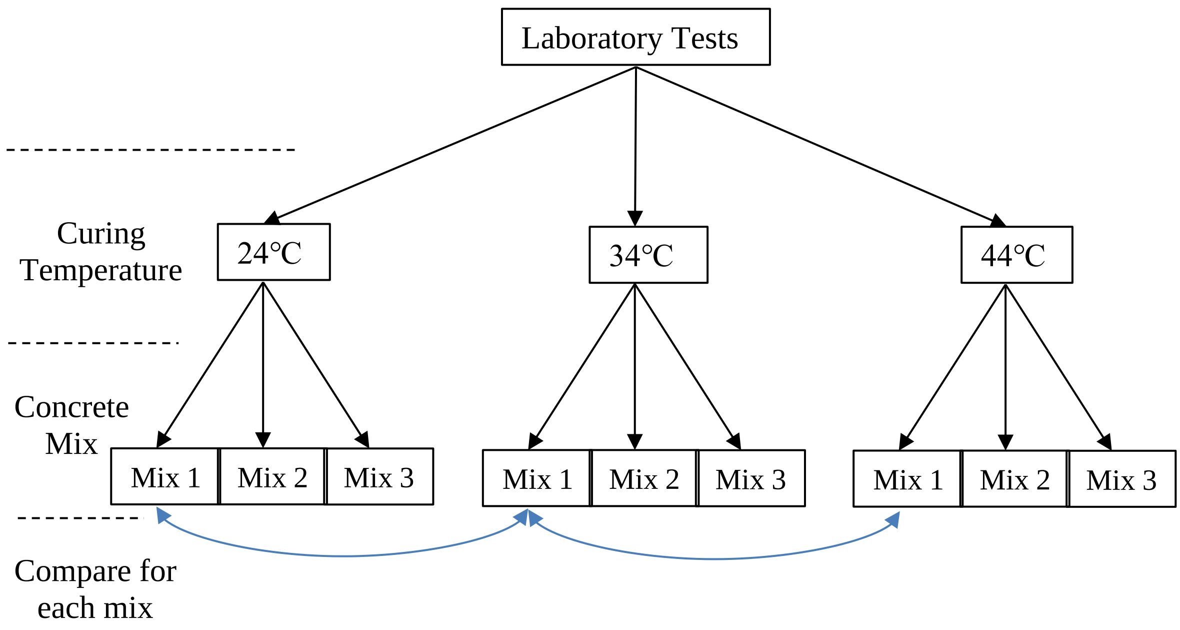

Figure 1.1: Laboratory test phase approach

1.5.3 Site test phase

The subsequent phase of testing involved casting the SmartRocks into slabs on a construction site. This was done to determine best practice for the use of SmartRocks in a South African context. The best practice included factors such as installation procedures and temperature measurement depths.

Interviews were conducted with professionals in the civil engineering industry to obtain feedback on the use of the SmartRocks on site. Even if the SmartRocks provide accurate in-situ strength estimations, it does not necessarily mean that it will be implemented on site. It is therefore important to obtain information on the willingness to apply SmartRocks in the industry.

1.6 Layout of this study

Chapter 2: A thorough review of literature is given regarding the use of the Maturity Method and the implementation thereof using SmartRocks.

Chapter 3: The methodology of the Laboratory Test Phase is given, along with the results that were obtained from these tests

Chapter 4: The methodology of the Site Test Phase is given, along with the results that were obtained. Summaries of interviews with professionals are also given.

Chapter 5: The conclusions that can be drawn from the Laboratory and Site Test Phases, as well as the interviews with the industry professionals are discussed. Recommendations for further studies are then given.

Chapter 2

Literature Review

2.1 Introduction

This chapter, firstly, explains the hydration of cement and the associated strength development of concrete and which factors influence this strength development. Current in-situ concrete strength estimation techniques are also briefly discussed. Another estimation technique- the Maturity Method- is explained in detail and the process is described that is followed to obtain in-situ strength estimations.

A practical application of the Maturity Method has been developed through wireless concrete temperature sensors. The operation of these sensors to ultimately obtain a real-time strength estimation is explained. Current practice of formwork removal is discussed with the effect of early formwork removal also explained. Lastly, the limitations of the Maturity Method are given.

2.2 Strength development of concrete

The compressive strength of hardened concrete is fundamentally important in the design of structures. It is also widely utilized to predict other concrete properties such as tensile strength and bond strength.

2.2.1 Hydration of Portland Cement

The compressive strength of concrete is gained over time by a combination of processes named setting and hardening. During setting, concrete develops stiffness. This happens rapidly after the concrete has been placed. The concrete is no longer a fluid but is still likely to be very weak. Hardening, on the other hand, can continue for years and it is in this phase that the concrete develops the desired compressive strength.

The process of setting and hardening is achieved with the hydration of cement particles to form Calcium Silicate Hydrates (CSH). The four main crystalline compounds of Portland Cement are referred to as C_3S, C_2S, C_3A and C_4AF. During hydration, each cement grain breaks up in several million particles, forming a poorly crystallized and porous solid called a CSH gel. Hydration is an exothermic reaction and the rate at which hydration occurs can be correlated to the amount of heat that is produced (Popovics, 1992).

The gel is formed when water comes into contact with a cement grain. The water dissolves the unhydrated part if the cement grain and the dissolved portion diffuses out of the grain, from its surface toward large spaces through the small pores of the previously created hydration products that formed around the cement grains. The newly formed hydration products then precipitate from the solution to form the CSH gel. The CSH gel's fine texture results in a high specific surface. This results in cement producing at least twice its own volume in hydration products. The volume of solids inside the boundaries of the gel therefore increases as a result of hydration, forms interlocking layers and reduces the overall porosity of the gel (Popovics, 1992).

Initial hydration occurs in the setting phase and this fixes the cement particles into weak structures to develop stiffness. Hydration is continued in the hardening phase and it will continue for several years provided that (Newman & Choo, 2003):

- **a)** there is cement available to react.
- **b)** there is enough water available for hydration.

Figure 2.1 illustrates the hydration of a single cement grain process over time.

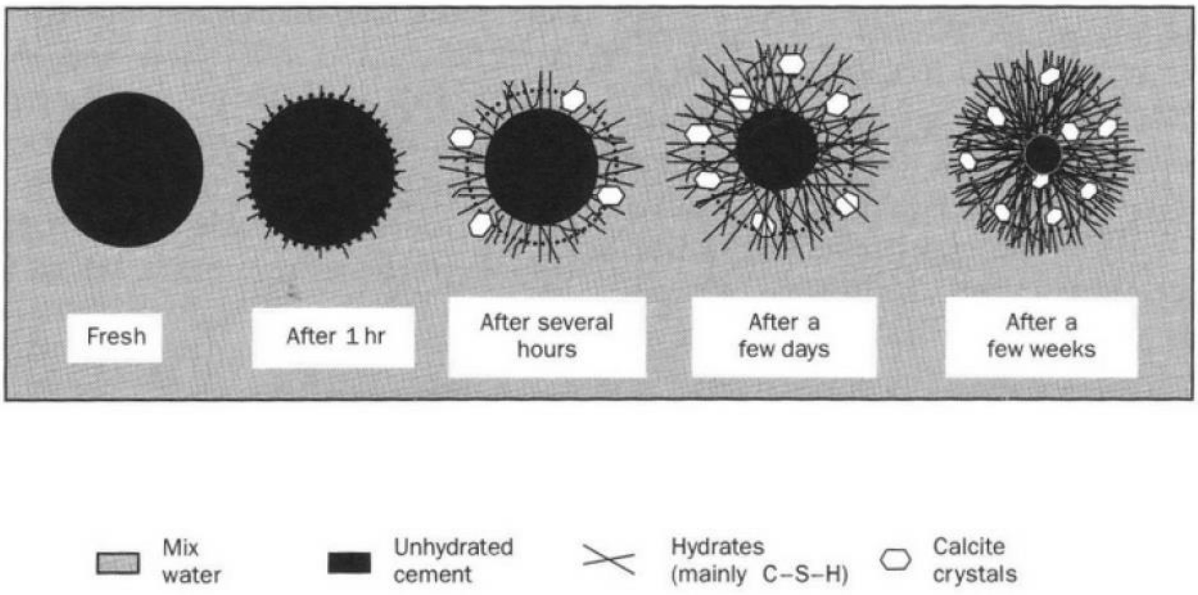

Figure 2.1: Hydration of a cement grain (Illston & Domone, 2001)

2.2.2 Heat of Hydration

Up to four stages of reaction rates have been observed during the hydration of cement. These four hydration stages are shown in Figure 2.2.

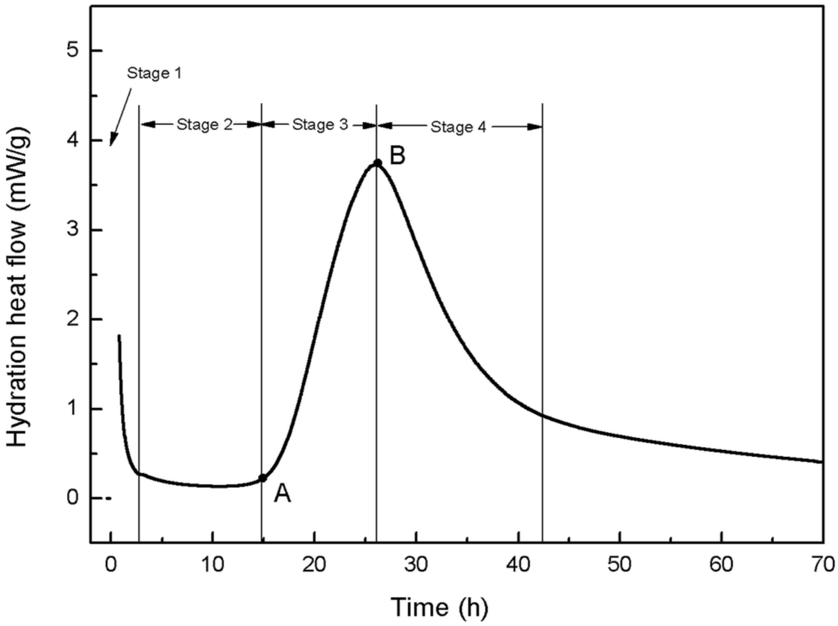

Figure 2.2: Heat rate versus time relationship for cement hydration (Zhao, et al., 2017)

a) Stage 1: Pre-induction

Almost instantly after the cement is mixed with water, an initial heat flow peak is reached. Along with this heat rate peak, a rapid dissolution of ions from a solid cement state to a liquid state occurs. This can be attributed to the rapid initial hydration of C_3S and C_3A. (Odler, 2003) .

b) Stage 2: Dormant

The initial hydration rate and subsequent heat evolution slows down quickly as the hydration products that forms around the cement particle creates a layer that acts as a barrier between the free water and the cement particle. The dormant stage lasts for a few hours after mixing (Odler, 2003).

c) Stage 3: Acceleration

At the end of the dormant stage, a rapid and sudden increase in the rate of hydration and subsequently, the heat flow rate can be observed. Initial setting occurs at point A with final setting occurring at point B (Copeland & Kanto, 1972).

d) Stage 4: Deceleration

The hydration rate gradually decreases as a result of the CSH gel that acts as a barrier between the cement particle and the remaining free water. Secondary to this, is that the cement particles' surface area has been reduced. The hydration rate is predominantly governed by the rate at which the free ions diffuse from the cement grain through the CSH gel (Odler, 2003).

During the initial stages, significant interactions occur between the main phases. This can be attributed to fineness of the cement grains. During the later phases of hydration, the phases can, however be considered to be occurring independently from each other due to the limited amount of free water present and also because of the barriers produced by the previously formed hydration products (Bye, 1999).

2.2.3 Time dependency of strength development

Figure 2.3 illustrates the typical strength development of fresh concrete over time. The relationship between compressive strength and time roughly follows a logarithmic trend (University of Memphis, 2017).

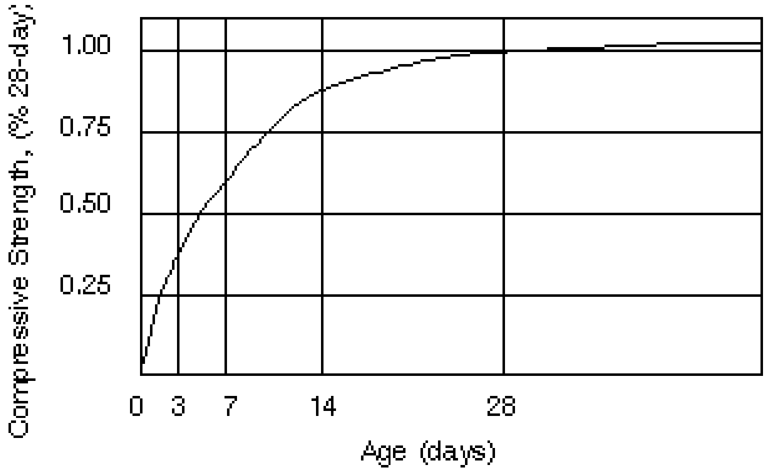

Figure 2.3: Concrete strength development over time (University of Memphis, 2017)

It can be seen that the initial strength gain of concrete occurs rapidly, and that after approximately 14 days, the strength development rate decreases significantly. The concrete strength at 28 days has widely been adopted as a reference point and specifications for recently cast concrete frequently refer to the 28-day strength. The ultimate strength can take up to 30 years to develop (University of Memphis, 2017). The strength development beyond the 28-day reference point is, however beyond the scope of this study, as only the early age strength of concrete is of interest.

2.2.4 Factors influencing concrete strength

Various factors influence the concrete strength development and therefore also the ultimate strength of the concrete. These factors result from changes in mix design, concrete placement and curing conditions

a) Water to Cement ratio

The water to cement ratio (w/c) is defined as the mass of the water in the cement paste divided by the mass of the cement. The w/c ratio generally ranges from 0.3 to 0.8. A w/c ratio in the range of 0.4 will result in a higher quality concrete as there is just enough water for all the cement to react. Larger w/c ratios will result in excess water that will remain in pores that will in turn, result in voids when the concrete dries out (Neuwald, 2010). Figure 2.4 shows the relationship between compressive strength and the w/c ratio

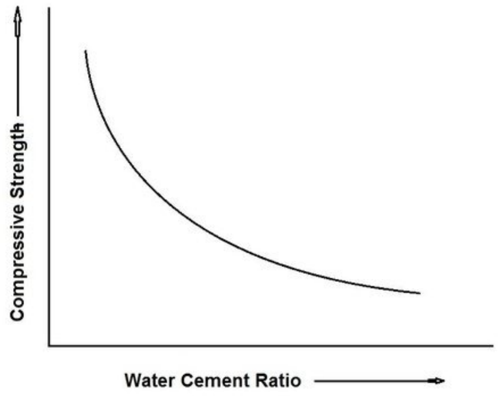

Figure 2.4: Compressive strength versus w/c ratio (Neuwald, 2010)

b) Extender content

It is common practice to substitute a portion of the cement content with other materials such as fly-ash or slag. These replacement materials are cheaper than cement and may yield desirable characteristics such as lower hydration heat, better workability and more environmentally friendly concrete, depending on the application thereof. These materials are referred to as cement extenders and are secondary products of other industries (Addis, 1986).

- **Fly-ash**

Fly-ash is a by-product of coal-burning in power stations. Advantages of fly-ash include the lowered cost of materials and a reduction in CO_2 emissions during the hydration, better workability and durability as well as reduced shrinkage and heat of hydration. A disadvantage of using fly-ash as a cement extender is slower strength development. (Addis, 1986)

The replacement of cement with fly-ash generally slows the early hydration but accelerates the hydration at later stages. However, the total heat generated in the concrete during the hardening process is lower when cement is substituted with fly-ash. The total heat generated is reduced (approximately) with the same portion with which the cement is replaced by fly-ash (Addis, 1986).

- **Slag**

Slag is a by-product of the iron and steel industry. Ground Granulated Blast Furnace Slag (GGBS) and Ground Granulated Corex Slag (GGCS) is commonly used in South Africa. Corex Slag is produced by the Corex process of the steel plant in Saldanha in the Western Cape (Alexander, et al., 2003).

The replacement of cement with GGBS offers the same advantages as fly-ash with regards to hydration heats at early ages. This reduces the probability of thermal cracking. Corex slag, however, has a much higher reactivity than GGBS and does not possess the same low hydration heat. It is good practice to assume a similar hydration heat for a concrete consisting only of cement and a concrete with Corex slag as an extender (Alexander, et al., 2003).

c) Concrete porosity

Concrete porosity refers to the presence of voids in the concrete. These voids can be filled with either water or air. As discussed earlier, a high w/c ratio can lead to voids, but insufficient compaction of the concrete can also result in voids. In general, the higher the void content in the concrete, the weaker it will be. An accepted rule is that the compressive strength decreases by approximately 5% with a 1% increase in air content. (Mindess, et al., 2003). High concrete porosity can also lead to durability issues later in the concrete's lifetime.

d) Cement paste- aggregate bond

A chemical bonding and physical bonding exist between the aggregates and cement paste. The chemical bonding is however assumed to be negligible. The physical bonding is as a result of micro- and macro texture of the aggregates, with micro texture being the critical factor (Alexander, 2014). Figure 2.5 shows the influence of cement paste-aggregate bond on compressive strength.

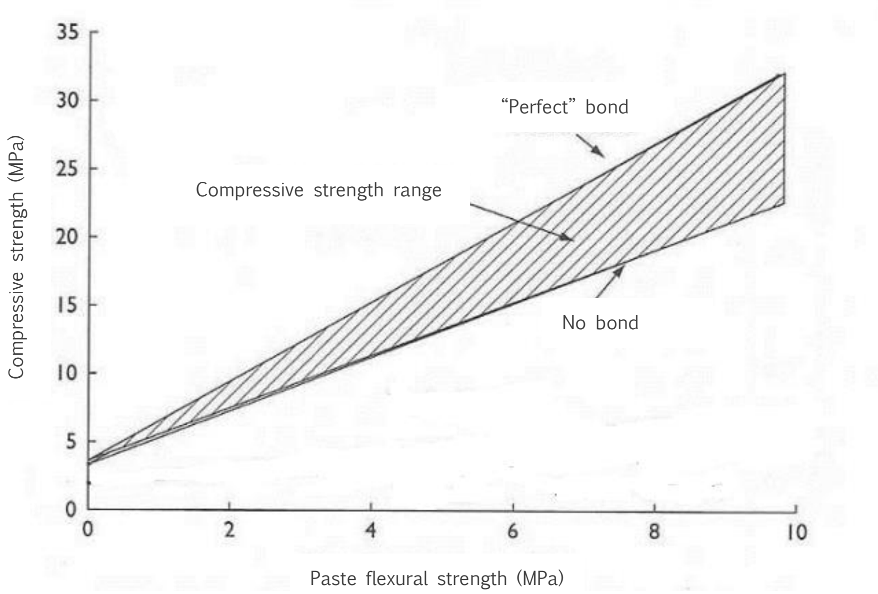

Figure 2.5:Influence of cement paste-aggregate bond on compressive strength (Alexander, 2014)

A w/c ratio gradient develops around aggregates in fresh concrete. This results in a difference in microstructure than that of the surrounding cement paste. This zone around the aggregate particles is known as the Interfacial Transition Zone (ITZ). The ITZ plays an important role in the cement paste- aggregate bond. ITZ's that are more porous, represent weaker surfaces with low bond strengths, whereas stiffer ITZ's allows for greater utilization of the aggregate's strength and stiffness (Ollivier, et al., 1995).

e) Coarse to fine aggregate ratio

Increasing the ratio of fines content to coarse aggregate content, will increase the total aggregate surface area. The increase in total surface area, will increase the water demand and this will subsequently increase the w/c ratio (Greensmith, 2005). As discussed earlier, a higher w/c ratio, will result in a lower compressive strength.

f) Curing of concrete

- **Humidity**

It is ideal to cure fresh concrete in moist environments. In the event that the fresh concrete is allowed to dry out prematurely, the hydration of cement will stop. It was discussed earlier, that enough water is needed for the hydration reaction to continue. If hydration ceases due to the concrete drying out, the ultimate strength of the concrete will be affected. Figure 2.6 illustrates the effect of different curing regimes with regards to moisture on the ultimate strength of concrete (Zemajtis, 2013).

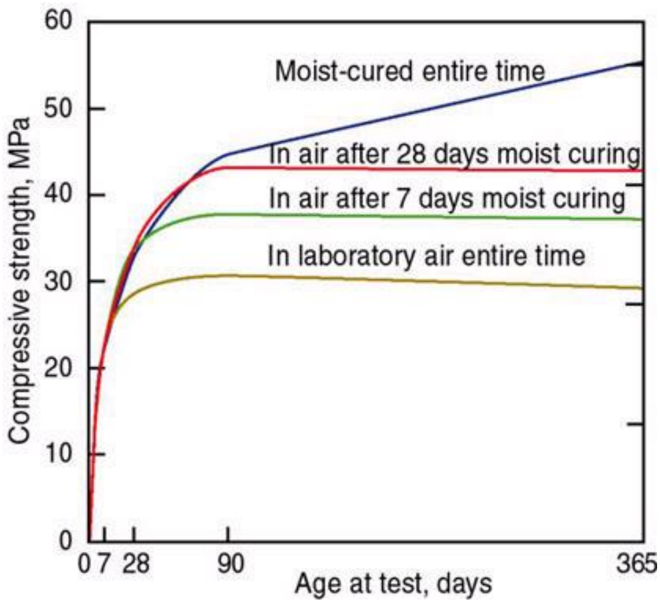

Figure 2.6: Effect of moist curing (Zemajtis, 2013)

Processes that ensure that the concrete does not dry out include (Newman & Choo, 2003):

- Ponding: Used for flat surfaces.
- Spraying: Used when ambient humidity is low.
- Saturated wet coverings: Used after concrete has hardened enough- this is to prevent surface damage.
- Covering with plastic sheets: Used to trap existing moisture.

- Steam curing: Used to increase temperature and relative humidity.

- **Temperature history**

The temperature of concrete during curing influences the strength gain rate of concrete. Low temperatures can lead to the cement not hydrating. The temperature at which the hydration reaction no longer occurs, is referred to as the datum temperature. High temperatures, in turn, can lead to accelerated curing.

Accelerated curing increases the rate at which concrete gains strength but can cause an increase in porosity. It is believed that this is brought about by the hydration products that form too close to the original cement particles and not spreading uniformly throughout the cement paste. Accelerated curing can lead to an ultimate strength reduction of up to 30%, depending on the maximum temperature reached during curing. The effect of accelerated curing is described by the cross-over effect. Cross-over behaviour is exhibited when higher early age strength concrete leads to lower ultimate strength (McIntosh, 1949). This is illustrated in Figure 2.7 where different curing temperatures lead to different ultimate strengths.

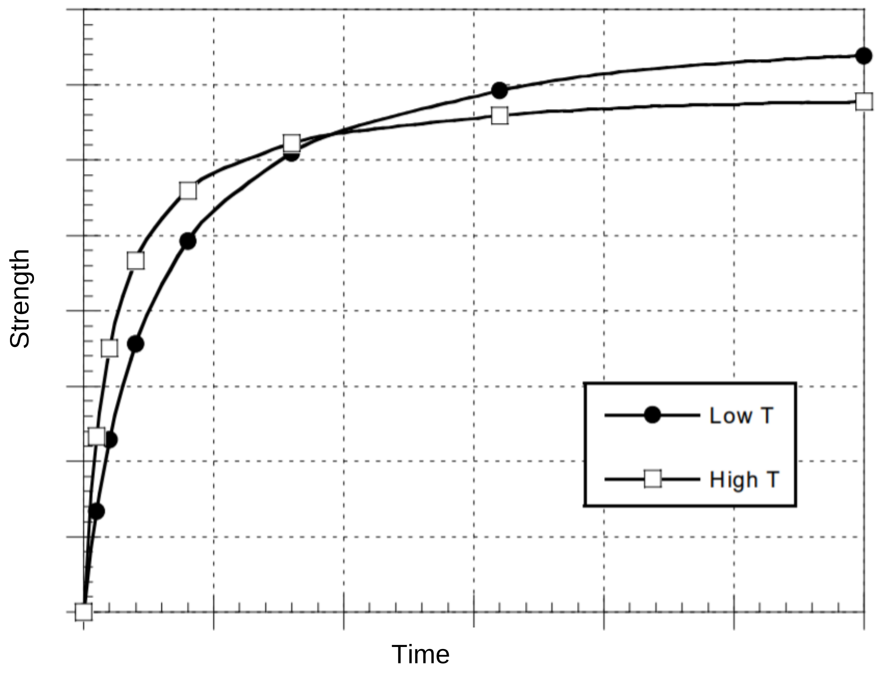

Figure 2.7: Cross-over effect (Carino & Lew, 2001)

2.3 In-situ strength estimation of concrete

Various techniques have been developed to estimate the in-situ strength of concrete. These tests range from simple tests that are easy to apply, to tests that require specialized equipment. These tests have varying degrees of accuracy.

a) Concrete cube specimens

The use of concrete cube specimens is the most common estimation technique used in the South African construction industry. It is prescribed by the South African National Standard (SANS) 5863. The testing of cube specimens measures the uniaxial compressive strength of the concrete. The test involves sampling concrete from the batch that is used on site and casting concrete cubes. These cubes are then transported to a laboratory, cured under controlled conditions and tested at certain ages, for example 3, 7 and 28 days (PPC, 2018).

The concrete cube test is an arbitrary test method and measures the in-situ strength of concrete in terms of one property (compressive strength) and does not measure the strength of concrete in any unique way. This test is mainly used for quality control. It should be noted that a factor is incorporated into the design of concrete structures to account for the difference in strength that is developed by a concrete cube and the strength that is developed by in-situ concrete (SABS 0100-1, 2000).

The factor is incorporated such that:

$$f_c = 0.67 f_{cu} \qquad \text{[Eq. 1]}$$

where:

f_c = design concrete strength and

f_{cu} = concrete cube strength, known as characteristic strength.

The factor of 0.67 takes into account a factor of 0.85 for the difference between in-situ flexural strength of concrete and cylinder sample strength, whilst also including a factor of

0.80 to account for the difference between cylinder and cube strength (SABS 0100-1, 2000).

The sampling of concrete for cube testing is prescribed by SANS 861-2:2004. The samples should be taken from the discharge stream of the ready-mix truck. The first and last 10% of the load should not be sampled. The concrete should also not be allowed to fall for more than 500 mm into the sampling scoop. Furthermore, nine samples should be taken at equally spaced intervals, and mixed to ensure overall uniformity of the sample.

The making and curing of concrete cube specimens is prescribed by SANS 861-3:2004. The moulds used for casting the cubes should be either 100 mm or 150 mm in size and made from a non-absorbent material. The mould should be lubricated with a mould release agent to ensure that the cube is not damaged when it is demoulded.

Each mould should be filled in three layers with each layer being compacted by tamping the layer with a rod. 100 mm cubes should be tamped 20 times between each layer and a 150 mm cube should be tamped 45 times between each layer. After each layer is tamped, two sides of the mould should be tapped five times with a rubber mallet, to ensure any remaining voids are collapsed.

After the cube is cast, the sample must be covered with a damp cloth and stored in the shade until it has hardened enough to be demoulded without damaging the cube. After a cube is demoulded, it must be stored in a curing tank, which is controlled between 22 ℃ and 25 ℃.

Four cube samples can be taken to test one sample at 7 days, and three at 28 days, but ideally, three cubes should be tested at each of the two ages. SANS 2001-CC1 specifies that a sample (consisting of four or six cubes) should be taken for each 50 m^3 (or part thereof) of a specific concrete mix that is poured.

b) Pull-out test

The pull-out test involves a metal insert that is cast into fresh concrete. Once the concrete has hardened sufficiently, the insert is pulled from the concrete with a jack that reacts against bearing pads. Figure 2.8 shows the setup of the pull-out test

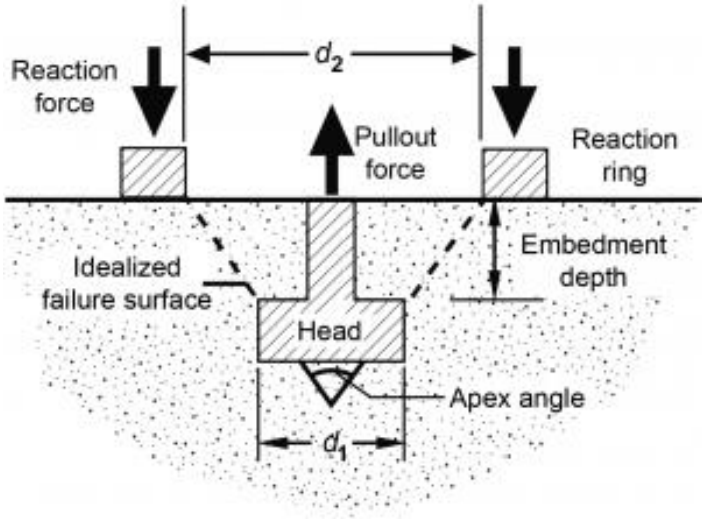

Figure 2.8: Pullout test setup (Giatec Scientific, 2018)

The pullout test is semi destructive as there is some surface damage, but it is easily repairable. The conical failure results from the concrete failing in tension and in shear, but the pullout force can, however, be correlated to the compressive strength of the concrete. Careful planning is necessary to embed the inserts at the correct position in relation to the steel reinforcement and to allow for voids in formwork (Telisak, et al., 1991). This test is not commonly used in South-Africa.

c) Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity test involves measuring pulse velocity by recording a pulse at certain frequencies over a given distance. Apparatus required for this test include a transducer that is in contact with the concrete, a pulse generator, amplifier and time measurement display. The Young's Modulus of the concrete can then be estimated, from which the compressive strength is then obtained. This test is also used to verify the homogeneity of concrete, to detect the presence of voids or cracks in hardened concrete and to check if any changes have occurred in the concrete with time (Telisak, et al., 1991).

d) Concrete core specimens

Testing concrete cores as a means of estimating in-situ concrete strength involves drilling cylindrical specimens from concrete that has hardened sufficiently. American standards (ASTM C42) states that the concrete should be hard enough such that the drilling of the specimen does not damage the cement paste-aggregate bond. These standards recommend that the concrete be at least 14 days old (Telisak, et al., 1991). This test method can also be used to verify the results from concrete cube specimens or to determine the concrete compressive strength in existing structures.

e) Rebound hammer

This test uses the Schmidt hammer which utilizes the principle of an elastic mass that rebounds of a hard surface. The varying surface densities affect impact and stress wave propagation. The impact and wave propagation are measured and is recorded as rebound numbers. The rebound numbers can be converted to compressive strength (Telisak, et al., 1991). Figure 2.9 shows a schematic of a rebound hammer and an example of a chart to convert rebound numbers to compressive strengths.

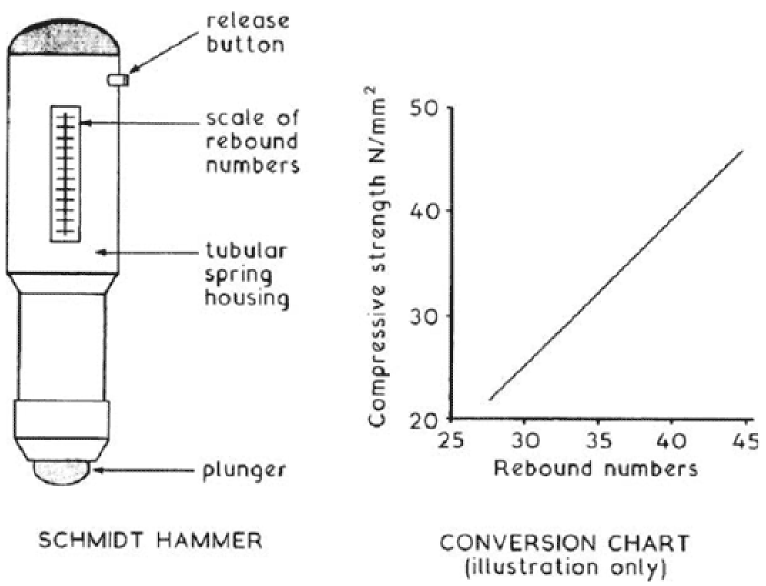

Figure 2.9: Schmidt hammer and rebound hammer conversion chart (O'Brien, 2013)

This test is limited to smooth surfaces and false results may occur where large aggregates influences the uniformity of the concrete.

f) Penetration resistance

The penetration resistance is measured with the Windsor Probe test. Variations of this test exist, but in general, it measures the penetration resistance of the concrete against a steel rod, that is pushed with a predetermined force into the concrete. The compressive strength of the concrete is then inversely proportional to the penetration depth. Several penetration tests are necessary to obtain an accurate assessment of the concrete strength- this allows for when the steel rod potentially cannot penetrate dense aggregates. The main advantage of this test is that it can estimate concrete strengths at greater depths than the pull-out test and the rebound hammer (Telisak, et al., 1991). Figure 2.10 shows the setup of the penetration test.

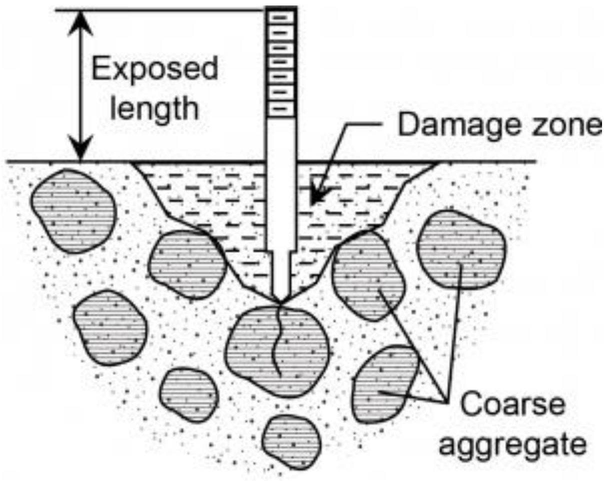

Figure 2.10: Penetration test setup

It can be seen that all of these test methods have some sort of limitation, whether it is potential inaccurate results or the need for specialized equipment. The testing of concrete cube specimens has been widely adopted and is mainly used in South Africa for in-situ strength estimations. This is due to its simplicity and over time, the construction industry has developed confidence in this estimation technique. Logistics can, however, sometimes be a problem as the cubes need to be transported to a laboratory for curing and testing. It can easily happen that track is lost over which concrete cubes was cast from which site- this compromises the accuracy of the results. Another issue that can arise, is when the site is far from the laboratory and that the cubes are not placed under controlled environments soon enough after casting. Furthermore, it is unknown to what extent the fairly rigorous process of sampling and casting the concrete cubes, is adhered to.

2.4 Strength estimation using the maturity method

The Maturity Method is a non-destructive technique used to estimate the early age strength of concrete. The maturity concept had its origins in England in the 1950's when researchers investigated accelerated curing methods and consequently the combined effects of temperature and time on concrete strength development. It has been widely adopted in North America in the field of Pavement Engineering in the construction of rigid concrete pavements (Nixon, et al., 2008).

As discussed earlier, the temperature of the concrete during curing, greatly affects concrete strength development. It is therefore difficult to estimate the in-situ concrete strength using samples cured under controlled conditions- as is the case with the Cube Test. Consequently, it is necessary to take the temperature history of the in-situ concrete into account when in-situ strength is estimated (Carino, 1991). The Maturity Method takes the age and temperature history of concrete into account when estimating compressive strength and the application thereof is standardized by the American Society for Testing and Materials (ASTM).

Various functions exist that quantify the extent of maturity that has developed in the concrete. The functions that were investigated in this study, are the Nurse-Saul maturity function and the Arrhenius maturity function. These two functions are also recommended by the ASTM C 1074 standard and is discussed in the next section. Figure 2.11 shows a simplification of the relationship between time, temperature, maturity and the estimated compressive cube strength of concrete (f_{cu}').

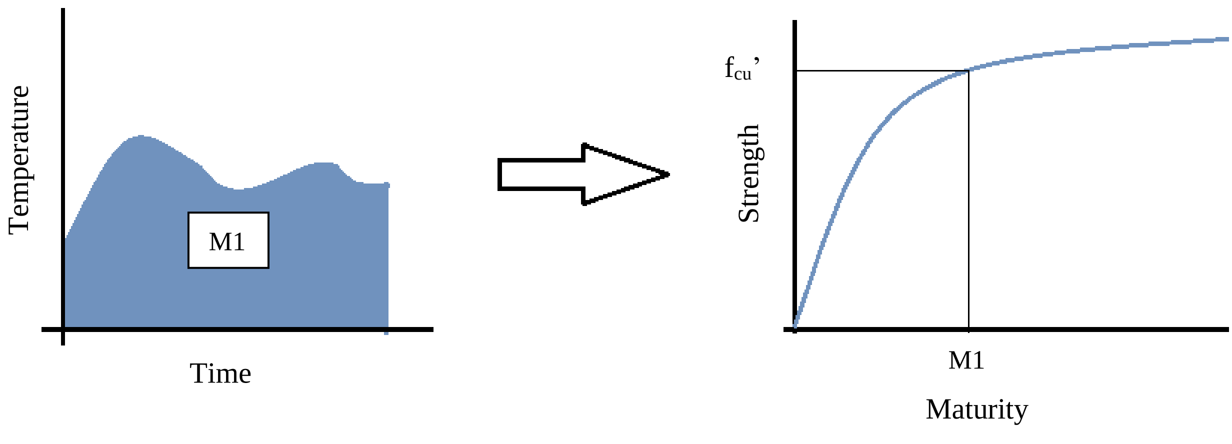

Figure 2.11: Simplified maturity method

Saul formulated the maturity rule to read:

"*Concrete of the same mix at the same maturity (reckoned in temperature time) has approximately the same strength whatever combination of temperature and time go to make up that maturity*." (Saul, 1951)

Carino further stated that:

"*The strength of a given concrete mix which has been properly placed, consolidated and cured is a function of its age and temperature history*." (Carino, 1991)

The maturity method consequently considers the time and the temperature history of in-situ concrete to estimate strength. Concrete cured under different conditions can therefore reach the same maturity and hence, the same strength, provided that it has been placed correctly and adequately consolidated and cured. This level of maturity (and strength) will however be reached at different ages. Concrete cured at lower temperatures will take longer to reach the maturity than that of concrete cured at higher temperatures. Figure 2.12 arbitrarily shows the temperature history of the same concrete mix being cured at different temperatures and the effect of the combination of time and temperature being considered when estimating concrete strength.

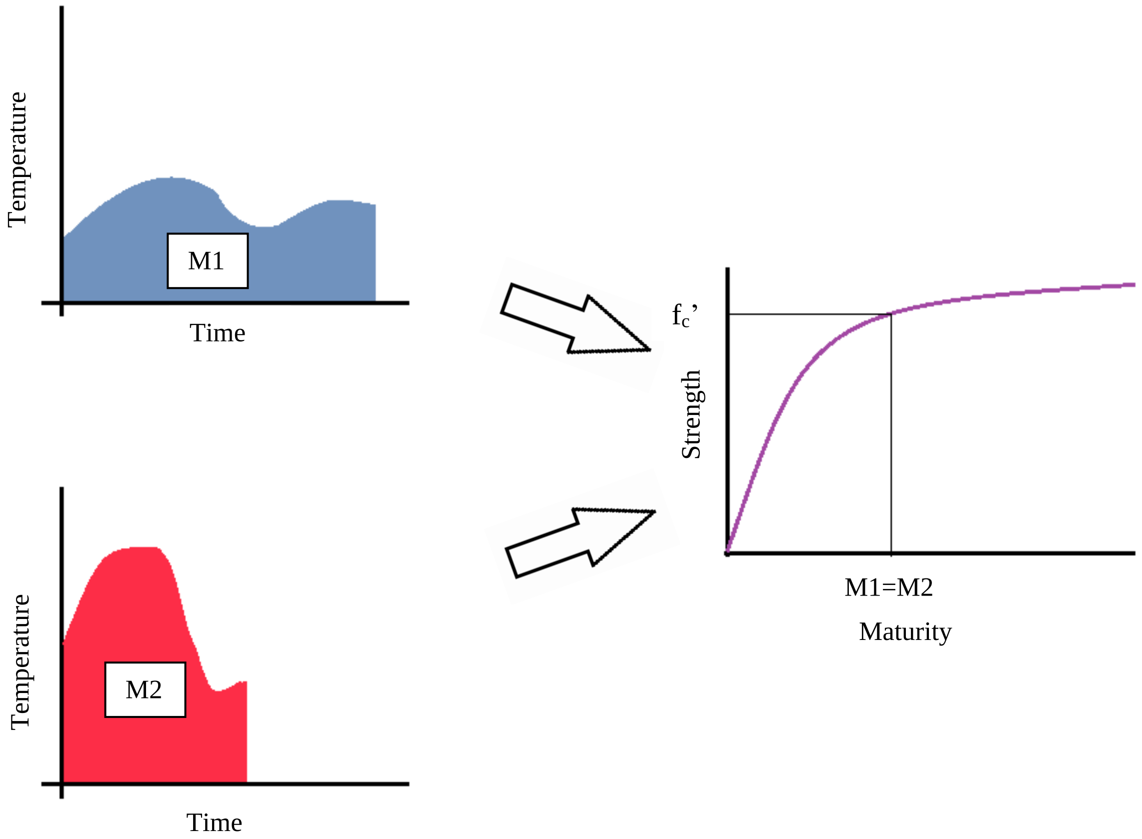

Figure 2.12: Effect of time and temperature on concrete strength (Adapted from Nixon, et al., 2008)

2.5 Maturity functions

2.5.1 Nurse-Saul maturity function

McIntosh (1949) was the first researcher to notice that concrete strength gain can be described by the combination of time and temperature. He was also the first to introduce the concept of a "datum temperature". He defined this temperature as the "no-hardening temperature" and that if the concrete temperature dropped below this temperature, it will not develop strength. He found that using the product of time and temperature, the concrete strength development could be adequately modelled. At different curing temperatures, this simplified method was however not accurate anymore (McIntosh, 1949). He attributed this to the cross-over effect discussed earlier.

Nurse (1949) was one of the researchers that studied accelerated curing techniques. Whilst investigating steam curing, he tested samples that were cured at various temperatures at various ages.

Nurse plotted the concrete strengths against the time-temperature products and noticed that this relationship followed a curve. Saul (1951) continued with the work of Nurse and defined the Temperature-Time factor as “maturity”. Saul also incorporated the idea of the datum temperature proposed by McIntosh (1949) and developed a mathematical function for the maturity concept. The Nurse-Saul maturity function is defined as (ASTM C 1074, 2011):

$$M(t) = \sum_{t=0}^{t^*} (T_a - T_0) \cdot \Delta t \qquad \text{[Eq. 2]}$$

where:

$M(t)$ = Maturity as the time-temperature product at age t^* (°C·hrs)

Δt = Time interval (hrs)

t^* = Concrete age at time of strength estimation (hrs)

T_a = Average concrete temperature during Δt (°C)

T_0 = Datum temperature (°C)

Figure 2.13 shows a diagram illustrating the application of the Nurse-Saul maturity function as well as the parameters used in the function. The blue line indicates the temperature history, whilst the grey shaded area represents the maturity (temperature time factor) that is calculated by the Nurse-Saul maturity function. The datum temperature (T_0) is also included in this figure and it can be seen that time-temperature products below this temperature is ignored.

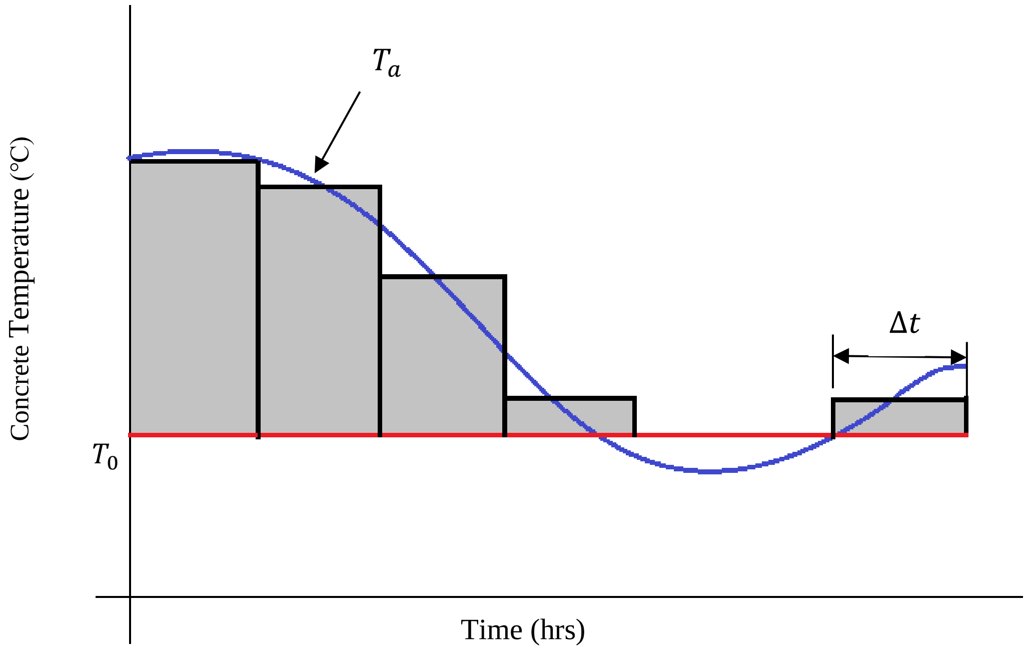

Figure 2.13: Application of the Nurse-Saul maturity function (Adapted from Nixon, et al., 2008)

In the formulation of the Nurse-Saul maturity function, Saul (1951) incorporated the datum temperature in the function, He proposed that -10.5°C be used as the temperature at which concrete will no longer develop strength. A datum temperature of -10°C was generally used in the past (Carino, 1991), but the ASTM C 1074 (2011) now allows for the experimental determination of the datum temperature and also provides a procedure for this. The procedure that the ASTM standards adopted was developed by Carino and Tank (1992) when they experimentally determined the datum temperature for two w/c ratio and various cement types. Their findings are summarized in Table 2.1. Datum temperatures are given in °C

Table 2.1: Experimentally determined datum temperatures (Carino & Tank, 1992)

Cement Type	w/c = 0.45	w/c = 0.60
Type I	11	9
Type II	9	6
Type III	7	7
Type I + 20% Fly Ash	-5	0
Type I + 50% Slag	8	10
Type I + Retarder	5	5
Type I + Accelerator	8	9

It can be seen from the results of Carino and Tank (1992) that the datum temperature originally proposed by Saul is inaccurate and that most of the datum temperatures are above 0 °C. For Type I and Type II cement, the datum temperature reduced for a higher w/c ratio but remained the same for Type III cement. When cement replacement materials were used, the datum temperature increased with the increased w/c ratio. The datum temperature remained constant when retarder was used, whilst it increased slightly when accelerator was used.

2.5.2 Arrhenius maturity function

The Arrhenius equation was first incorporated into concrete strength development when it was observed that the influence of temperature on rate of cement hydration can accurately be expressed by the Arrhenius equation in the range of 4.4℃ to 110℃. (Copeland, et al., 1960). This research was continued when a function, based on the Arrhenius equation, was proposed to calculate the Maturity as Equivalent Age. This calculation was based on the apparent activation energy of concrete (Freiesleben Hansen & Pederson, 1977).

The Arrhenius maturity function is given by:

$$t_e = \sum_{t=0}^{t^*} e^{-Q\left[\frac{1}{T_a}-\frac{1}{T_s}\right]} \cdot \Delta t \qquad \text{[Eq. 3]}$$

where:

t_e = Maturity given as Equivalent Age (hrs)

Δt = Time interval (hrs)

t^* = Concrete age at time of strength estimation (hrs)

T_a = Average concrete temperature during Δt (K)

T_s = Specified temperature (K)

Q = Activation energy (E) divided by the universal gas constant (R)

ASTM C 1074 (2011) specifies a typical value of 20 °C to be used for T_s. This equates to 293 K. The value to use for the universal gas constant (R) is specified as 8.3144 J/mol·K. The activation energy (E) can be obtained in several ways. The three methods that are investigated in this study are:

1. **Equation relating concrete temperature and activation energy:**

   This method was recommended by Freiesleben Hansen and Pederson (1977) when they first developed the Arrhenius Maturity function and introduced the concept of activation energy. The equation is defined as:

$$E = \begin{cases} 33\,500 + 1.47(20 - T_a)\; J/mol, & T_a < 20°\mathrm{C} \\ 33\,500\; J/mol, & T_a \geq 20°\mathrm{C} \end{cases} \qquad \text{[Eq. 4]}$$

2. **Estimating activation energy from typical values:**

   Various researchers proposed activation energies for different cementitious systems, that were experimentally determined. Carino (1991) summarized these values and is shown in Table 2.2

Table 2.2: Typical activation energies (Carino, 1991)

Cement type	Activation energy (J/mol)
Type I	41 000
OPC (Paste)	42 000-47 000
OPC + 70% GGBS	56 000
Type I/II (Paste)	44 000
Type I/II + 50% GGBS (Paste)	49 000

3. **Calculating activation energy experimentally:**

   ASTM C 1074 (2011) recommends an activation energy of between 40000 J/mol and 45000 J/mol for a Type I cement with no admixtures, but does not provide further guidelines when other cementitious systems are used. As is the case with the datum temperature in the Nurse-Saul maturity function, ASTM C 1074 (2011) provides an experimental procedure for the determination of activation energies. This procedure was also developed by Carino and Tank (1992). In the same study where they determined datum temperatures, they also determined activation energies. These values are summarized in Table 2.3. Activation energies are given in J/mol.

Table 2.3: Experimentally determined activation energies (Carino & Tank, 1992)

Cement Type	w/c = 0.45	w/c = 0.60
Type I	63 000	48 000
Type II	51 100	42 700
Type III	43 000	44 000
Type I + 20% Fly Ash	30 000	31 200
Type I + 50% Slag	44 700	56 000
Type I + Retarder	44 600	50 200
Type I + Accelerator	38 700	38 700

It can be seen that a range of activation energies are proposed by various researchers and through various methods. All of the applicable activation energies are tested to verify their accuracy. This will account for the various combinations of w/c ratios, concrete temperatures and cementitious systems that are investigated in this study.

2.5.3 Nurse-Saul – Arrhenius interrelationship

The Temperature-Time factor of the Nurse-Saul maturity function can be expressed as Equivalent Age using the Age Conversion Factor (Carino, 1991). Equivalent age is then calculated with:

$$t_e = \sum_{t=0}^{t^*} \alpha \cdot \Delta t \qquad \text{[Eq. 5]}$$

where:

t_e = Equivalent age (hrs)

Δt = Time interval (hrs)

t^* = Concrete age at time of strength estimation (hrs)

α = Age Conversion Factor

The Age Conversion Factor for the Nurse-Saul maturity function is defined as:

$$\alpha = \frac{T_a - T_0}{T_s - T_0} \qquad \text{[Eq. 6]}$$

where:

T_a = Average concrete temperature during Δt (°C)

T_0 = Datum temperature (°C)

T_s = Specified temperature (°C)

Equivalent age is calculated with the Arrhenius equation with the Age Conversion factor given as:

$$\alpha = e^{-Q\left[\frac{1}{T_a}-\frac{1}{T_s}\right]} \quad \text{[Eq. 7]}$$

where:

T_a = Average concrete temperature during Δt (K)

T_s = Specified temperature (K)

Q = Activation energy (E) divided by the universal gas constant (R)

Plotting the Age Conversion Factors against the concrete temperature for the Nurse-Saul maturity function as well as the Arrhenius maturity function, the mathematical differences can be seen. The datum temperature and activation energy that are used, are the values obtained by Carino and Tank (1992) for a Type I cement with a w/c ratio of 0.60. 20°C is used as the Specified Temperature. The comparison between the Age Conversion Factors for the two maturity functions can be seen in Figure 2.14.

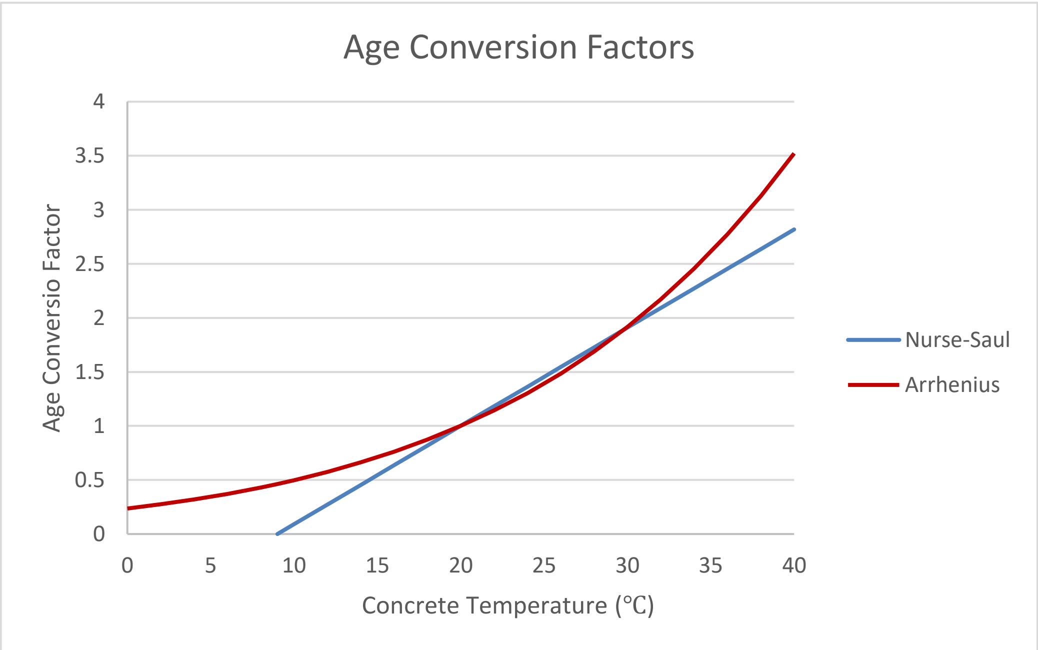

Figure 2.14: Age Conversion Factor comparison (by author)

The two maturity functions give varying results at extreme temperatures. The Nurse-Saul and Arrhenius functions do, however give similar results in the range of 18 °C - 32 °C. This range will always contain the Specified Temperature that is chosen. In this example, the Specified Temperature was chosen as 20 °C.

Many researchers prefer the Arrhenius maturity function due to the similarities between the exponential function's shape and the non-linear trend of the strength development of concrete over time. The Arrhenius function does, however, predict strength development of concrete at very low temperatures. Plowman (1956) found that concrete can still gain strength at -12 °C and in a more recent study this was confirmed to be valid, as it was found that concrete can still gain strength at temperatures as low as -5 °C (Liu, et al., 2017). Lower temperatures than -5 °C was not investigated in this study. The Nurse-Saul maturity function, on the other hand, assumes the strength development of concrete ceases below the datum temperature.

Existing literature therefore shows that the Arrhenius maturity function yields more accurate results, but the simpler Nurse-Saul function, is easy to apply and may yield sufficiently accurate results. The accuracy of the Nurse-Saul and Arrhenius maturity functions are investigated to determine the most applicable maturity functions for estimating in-situ concrete strength.

2.6 Practical application of the Maturity Method

2.6.1 Mix calibration

The American Society for Testing and Materials C 1074 standard provides a "Standard Practice for Estimating Concrete Strength by the Maturity Method". The relationship between strength and maturity is unique for each concrete mixture and hence the relationship should be calibrated for each mix. This is done with laboratory tests. The ASTM standard recommends cylindrical test specimens to be used in the calibration. Cube specimens (100 mm) are however used in this study, as the use of concrete cubes is more common in South Africa. The concrete cube strength is also used in design as a reference strength. The following procedure should be followed to determine the maturity functions (ASTM C 1074, 2011):

1. Prepare 15 cube specimens. The specimens should be prepared from a similar mix to the concrete which strength needs to be estimated.
2. Temperature sensors need to be embedded into two specimens to within ±15 mm from the centers of the specimens.

3. The temperature sensors should log temperature every 30 minutes for the first 48 hours after casting, and every hour for the remaining 26 days of the test. The sensors should be accurate to within 1 °C.
4. Perform cube compression tests at ages of 1, 3, 7, 14 and 28 days on two specimens and calculate the average strength. If the strength of the two specimens vary by more than 10%, a third specimen should be tested. The compressive strength is then calculated as the average of the three specimen’s strength. Outliers may be disregarded.
5. Calculate the Temperature-Time factor (in the case of the Nurse-Saul maturity function) or the Equivalent Age (in the case of the Arrhenius maturity function) at each test age from the temperature history that is recorded by the temperature sensors.
6. Plot the compressive strength obtained from the tests against the maturity. Determine the best-fitting curve through the data- this strength-maturity relationship is the mix calibration that will be used to estimate in-situ strength.

Three curves proposed by Carino (1991) for the strength-maturity relationship are investigated in this study. Hyperbolic (Carino, 1991), logarithmic (Plowman, 1956) and exponential (Freiesleben Hansen & Pederson, 1977) functions are proposed and defined as:

- **Hyperbolic:**

$$S = S_u \cdot \frac{k(M - M_0)}{1 + k(M - M_0)} \qquad \text{[Eq. 8]}$$

where:

S = Compressive strength (MPa)

S_u = Ultimate compressive strength (MPa)

M = Maturity given as the Temperature time factor (°C·hrs) or the Equivalent Age (hrs)

M_0 = Maturity when concrete strength development commences.

k = Rate constant (1/°C·hrs or hrs)

- **Logarithmic:**

$$S = a + b \log M \qquad \text{[Eq. 9]}$$

where:

a = Strength constant (MPa)

b = Maturity rate constant (MPa/°C·hrs or MPa/hrs)

- **Exponential:**

$$S = S_u \cdot e^{-\left[\frac{\tau}{M}\right]^{\beta}} \qquad \text{[Eq. 10]}$$

where:

τ = Characteristic time constant (hrs)

β = Shape parameter

The ASTM 1074 recommends the use of the exponential or hyperbolic functions. This is based on the work of Carino (1991) when he concluded that the logarithmic function has its limitations as it predicts continuous strength gain with maturity and that the near linear relationship at low maturities is not sufficiently accurate.

2.6.2 SmartRock

The SmartRock is a waterproof wireless concrete temperature and maturity sensor that is investigated in this study. It utilizes Bluetooth technology to wirelessly measure, log and transmit the temperature history of concrete in real-time (Giatec Scientific, 2018). The sensors connect to smartphones running the Android or iOS platforms through an application provided by the manufacturers of the sensors. Figure 2.15 shows an example of a SmartRock.

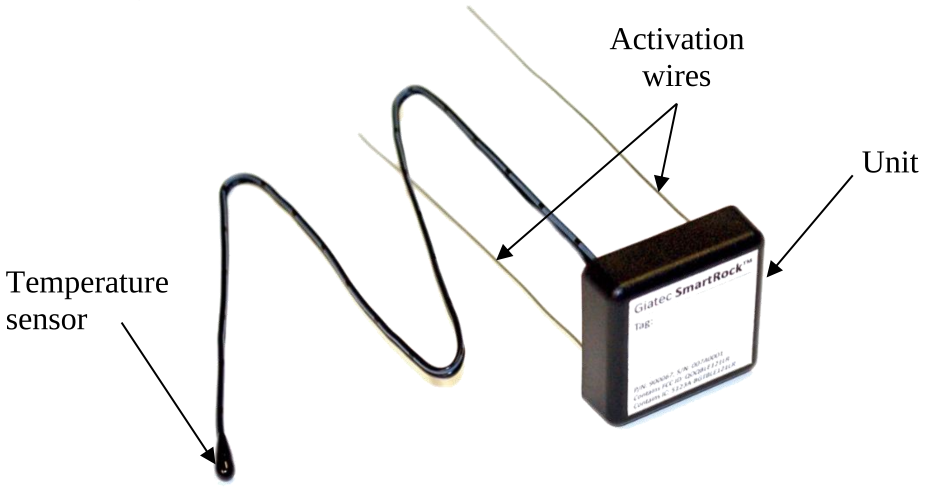

Figure 2.15: SmartRock (Giatec Scientific, 2018)

The square body of the SmartRock unit pictured in Figure 2.15 measures 40 mm x 40 mm. This is where the data is stored, and from where it is transmitted. The unit should be fixed to the steel reinforcement bars in the concrete and this is done with the two metal wires protruding from the body of the SmartRock. These wires also serve as activation wires and complete the electrical circuit of the sensor when they come in contact with each other. This starts the measuring and logging of concrete temperature. The battery-life of the SmartRock is estimated at approximately 4 months. The battery-life is therefore sufficient to estimate the early-age strength of concrete. The black wire protruding from the SmartRock is the temperature sensor.

The reading range of the SmartRock is between -30℃ and 80℃. It has an accuracy of ±1℃ with a resolution of 0.5℃. It is recommended that the unit not be installed deeper than 5 cm from the surface of the concrete. At this depth, the unit can still easily communicate with the smartphone it is connected to, up to a distance of 8 meters. The 40 cm temperature sensor extension cable can be placed where the temperature reading is deemed to be necessary. The temperature is recorded every 30 minutes for the first 48 hours after pouring, after which temperatures are logged every hour.

Figure 2.16 shows screenshots of the SmartRock iOS application interface. The temperature can be read in real-time, whilst the minimum and maximum temperatures are also given. The application calculates the maturity using the chosen maturity function. Strength is estimated by setting a concrete pouring time and using the logarithmic function discussed earlier. The app is calibrated for each mix by inputting the a and b constants present in Equation 9. All the sensors in use on a project is allocated to the particular project on the app and managed from there. Multiple projects' sensors can also be managed on the app.

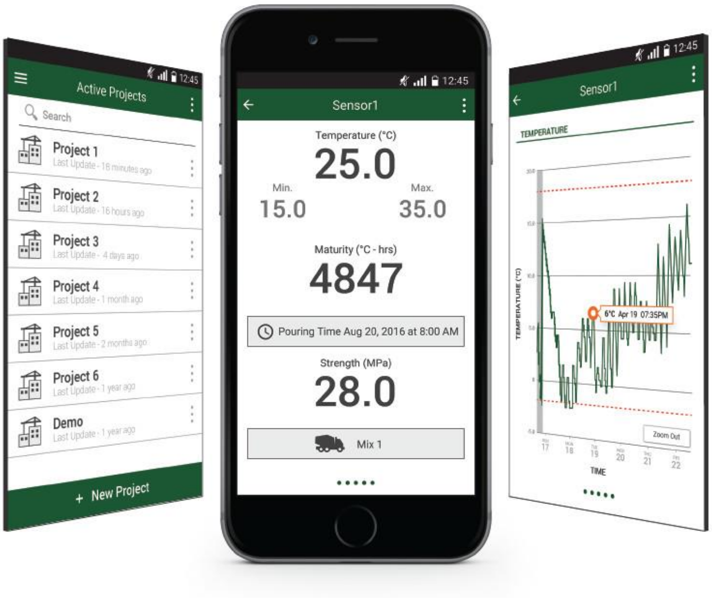

Figure 2.16: SmartRock iOS Application interface (Giatec Scientific, 2018)

The real-time strength estimation of the SmartRock is convenient and it has the potential to become a necessary tool in the construction industry. The need for concrete cube tests can potentially be minimized and the stripping of formwork can be optimized. This is investigated in this study.

2.7 Early formwork removal

2.7.1 Current guidelines

The removal of formwork is currently governed by the SANS 2001 – CC1: 2007. This standard specifies procedures for structural concrete construction works. This standard states that formwork should be kept in place until such time that the concrete has attained the necessary strength to prevent any surface damage when the formwork is removed, Further to this, the concrete should be able to support its own mass, as well as any loads imposed on it. For construction projects where no qualitative data is available on the compressive strength of concrete, the SANS 2001 – CC1: 2007 gives a table containing minimum periods of time before the formwork to various structural members can be removed. Table 2.4 shows the minimum time before removal formwork as given in SANS 2001 – CC1: 2007.

Table 2.4: Minimum time for formwork removal (South Afican National Standards, 2007)

1	2	3	4	5	6	7	8	9	10
Formwork to structural member	**Strength class of cement**								
	42,5 R or higher			**CEM I and CEM II A-S, D, P, Q, V, A, W, T, L, LL, M and blends of CEM I with 20 % or less ground granulated blast-furnace slag or fly ash**			**CEM II B-S,P, Q, V, W, T, L, LL, M; CEM III, CEMIV and CEM V and blends of CEM I with more than 20 % ground granulated blast-furnace slag or fly ash**		
	Minimum time before removal of formwork d								
	Weather								
	Hot or normal	**Cool**	**Cold**	**Hot or normal**	**Cool**	**Cold**	**Hot or normal**	**Cool**	**Cold**
Beam sides, walls and unloaded columns	0,5	0,75	1	0,75	1,25	1,5	2	3	4
Slabs with props left underneath	2	3	4	4	5,5	7	6	8	10
Beam soffits with props left underneath and ribs with a ribbed floor construction	3	4	5	7	9,5	12	10	13,5	17
Slab props including cantilevers	5	7	9	10	13,5	17	10	13,5	17
Beam props including cantilevers	7	9,5	12	14	17,5	21	14	17,5	21
NOTE In cool weather stripping times may be determined by interpolation between the periods specified for normal and cold weather.									
[a] A day is taken as 24 h.									

Table 2.4 shows that the SANS standard gives minimum formwork removal times for various strength classes of cement. Column 5 through 7 gives values for cementitious systems commonly used for slabs. Table 2.4 also gives values for various weather conditions, for which a definition is given earlier in SANS 2001 – CC1: 2007. This definition is given for the minimum ambient temperature values (T_{amb}), and these values are summarized in Table 2.5.

Table 2.5: Minimum ambient temperature values for weather classification

Hot or Normal	Cool	Cold
$T_{amb} > 15$ ℃	5 ℃ $< T_{amb} < 15$ ℃	$T_{amb} < 5$ ℃

It should be noted that SANS 2001 – CC1: 2007 allows for formwork to be removed earlier if the early-age strength of the concrete is evaluated. This evaluation can be done on cubes tested that have reached the same maturity. This can be done by curing the cubes in the same conditions as the in-situ concrete.

The concept of equal maturity is the main principle upon which the Maturity Method is based. The SmartRock and the associated use of the Maturity Method is an effective and convenient way to obtain a strength estimation based on equal maturity, as it not always possible to impose similar curing condition, than what is experienced by the in-situ concrete, onto concrete cubes. External temperatures and moisture can be easily simulated, but the internal hydration heat is neglected. The hydration heat in thin elements such as slabs are often ignored, but it can aid the rate of early age strength development to some extent (Nguyen & Nguyen, 2017). Taking the hydration heat into account by using the SmartRock can potentially lead to the optimization of formwork removal.

2.7.2 Effects of early formwork removal

- **Cost saving**

The early removal of formwork can have significant cost savings as a result. The turnaround time for a set of formwork can be much quicker, resulting in less formwork that has to be used. Secondary to this, the formwork can be returned to the supplier earlier.

From a project prospective, project completion can be achieved quicker, resulting in earlier site handover. A reduction in project time, also reduces the amount of Preliminary and General costs of the contractor.

- **Risk of increased deflection**

In the event that formwork is prematurely removed with the concrete not achieving sufficient strength, cracking can occur in the concrete section. The degree to which the cracking capacity of the concrete section is exceeded determines the extent of the cracking and this is closely linked with the severity of the deflection.

Pallet (2003) has published a determination with which the required concrete compressive strength can be estimated before a slab can be loaded. This loading implies the removal of formwork, as the slab needs to carry its self-weight. This determination can be used for in-situ reinforced concrete slabs of less than 350 mm in thickness. The determination is given by Equation 11 (Pallet, 2003):.

$$f_c \geq f_{cu}\left(\frac{w}{w_{ser}}\right)^{1.67} \qquad \text{[Eq. 11]}$$

where:

f_c = required concrete strength

f_{cu} = concrete design strength

w = total unfactored construction load

w_{ser} = total unfactored design service load

During the European Concrete Building Project, a seven-storey concrete frame with flat slabs were constructed and tested over an extended period of time. It was found that provided the determination given by Equation 11 is adhered to, there is no significant effect on deflections.

SANS 0100-1 provides a method to determine the immediate deflection at the midspan of a member due to an applied characteristic load. The only parameter in this method that is dependent on the concrete strength at the time of loading is the static Modulus of Elasticity (E_s) at the time of loading. The immediate deflection is inversely proportional to E_s. E_s is approximated from the concrete characteristic strength and this relationship is given in Table 2.6.

Table 2.6: Modulus of Elasticity approximation (SABS 0100-1, 2000)

1	2	3	4	5
Characteristic strength $f_{cu,}$ MPa	**Static modulus $E_{c,}$** GPa		**Dynamic modulus $E_{cq,}$** GPa	
	Mean value	**Typical range**	**Mean value**	**Typical range**
20	25	21-29	35	31-39
25	26	22-30	36	32-40
30	28	23-33	38	33-43
40	31	26-36	40	35-45
50	34	28-40	42	36-48
60	36	30-42	44	38-50

Table 2.6 shows that for a specific characteristic strength, a range of typical values for the Modulus of Elasticity can be assumed. However, the mean value is commonly used. It can further be shown that changes in the characteristic strength will not influence the E_s value significantly. For example, a change in the characteristic strength of the concrete from 20 MPa to 25 MPa (which is a 25% change) will result in a change in E_s from 25 GPa to 26 GPa (which is a 4%) change. It is at these lower strengths that formwork removal will most likely take place.

From the small changes in E_s brought about by lower characteristic strengths, it can be assumed that early removal of formwork will not influence the immediate deflection significantly. This approach of calculating and controlling deflections can, however, be supplemented by simply controlling the ratio of span to effective depth of a concrete member. The South African standards does not directly take concrete strength into account in this process (SABS 0100-1, 2000).

2.8 Limitations of the Maturity Method

2.8.1 Cross-over behaviour

Accelerated curing, and the associated cross-over effect, was discussed earlier in this chapter. Higher curing temperatures often lead to higher early age strength but lower ultimate strength, whilst lower curing temperature often lead to lower early age strength but a higher ultimate strength (McIntosh, 1949). Carino (1991) concluded that the Maturity Method does not account for substandard curing of concrete. Figure 2.17 arbitrarily shows the results obtained by Carino (1991) when he investigated the effect of different curing temperatures on compressive strength.

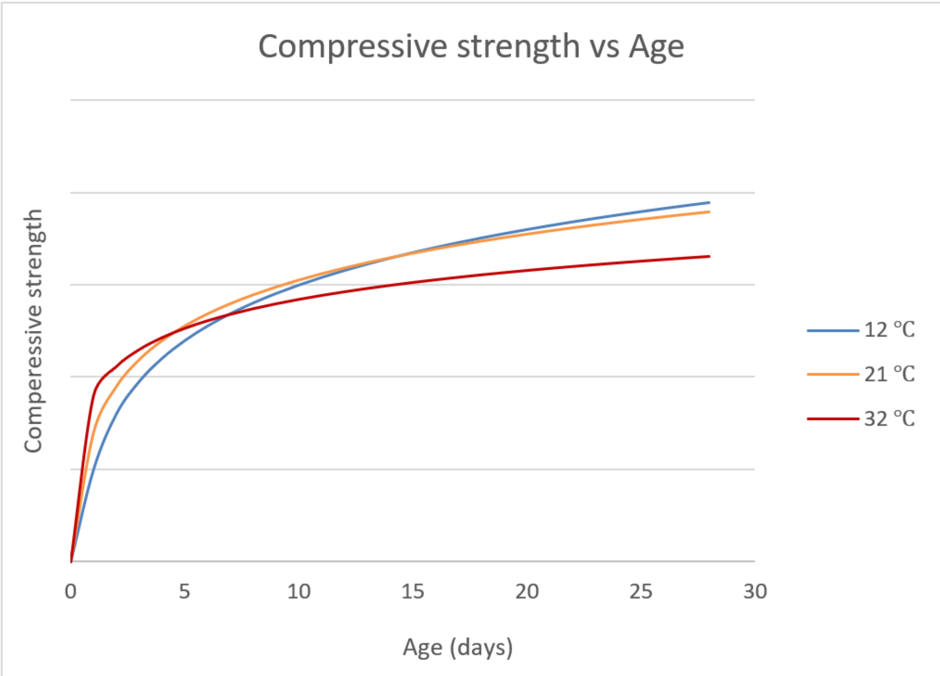

Figure 2.17: Effect of different curing temperatures on compressive strength (Adapted from Carino, 1991)

The data illustrated in Figure 2.17 was converted to equivalent ages and is shown in Figure 2.18.

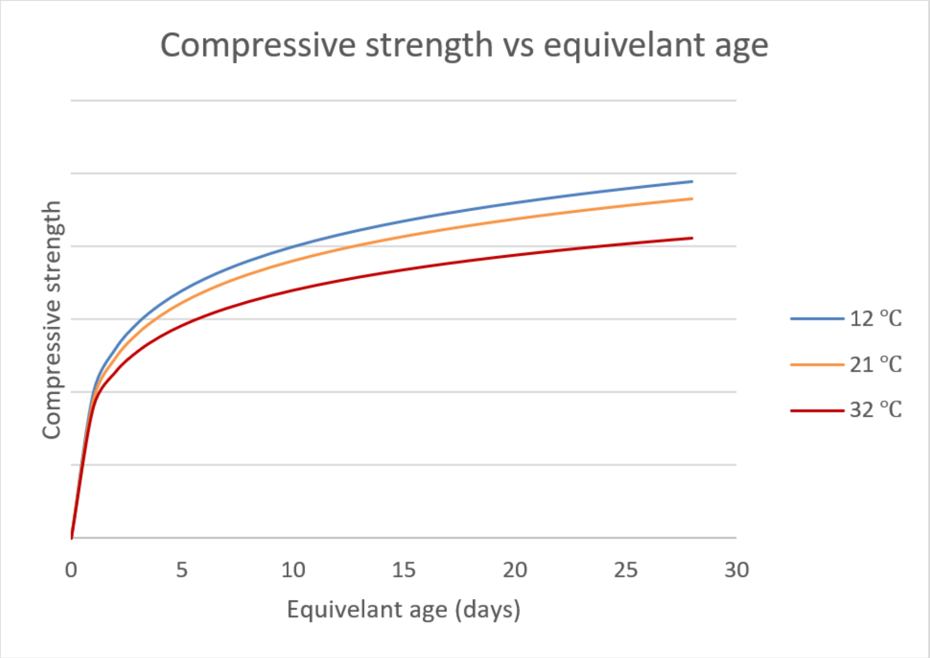

Figure 2.18: Effect of different curing temperatures on equivalent age (Adapted from Carino, 1991)

Figure 2.17 shows that different curing temperatures result in different strength development profiles. Figure 2.18 shows the strength-maturity relationships developed with the Arrhenius maturity function. Since the Maturity Method takes the combined effect of temperature and time into account, the different curing temperatures should theoretically have the same compressive strengths at the same maturities. Figure 2.18 shows that this is, however, not the case. The three different curing temperatures result in three different Strength-Maturity relationships. The three relationships do, however predict similar compressive strengths at early ages (up to approximately 2 days). The Maturity Method does not take this variability into account, since the mix calibration is done with concrete specimens cured only at one temperature.

A study was conducted on the later-age strength prediction of concrete (Kjellsen & Detwiller, 1993). This study found that the Maturity Method provides accurate strength estimations only up to 40% of the 28-day strength. They attributed the inaccuracies to the effect of high early age temperature and, again confirming McInstosh's findings on the cross-over effect. They modified the maturity function, but the modification is deemed to be too difficult, and not practical to apply (Nixon, et al., 2008).

2.8.2 Strength-Maturity relationship is unique for each mix

Strength-Maturity relationships should be determined for every unique concrete mix. The ASTM C 1074 (2011) standard states that the strength estimations accuracy is greatly dependent on a properly developed Strength-Maturity relationship. This relationship is unique for each concrete mix as the temperature sensitivity varies with different constituents of the concrete mixture. This standard allows for small changes in the mix design after the mix calibration is conducted, but the extent of these changes is not defined explicitly.

2.8.3 Moisture during curing

As discussed earlier, a sufficient amount of moisture is required for cement hydration to be sustained. Since the Maturity Method uses the in-situ temperature history to estimate the concrete's in-situ strength, this strength estimation will not be accurate if insufficient moisture is available to sustain cement hydration. Even if the concrete dries out, hydration stops and the strength gain ceases, the maturity value will still increase.

During construction, water is lost from the concrete through evaporation and due to absorption by the formwork and aggregates. Hydration will stop if the internal humidity of the concrete reduces below a level of 80% (Mindess, et al., 2003). This will dramatically affect the strength development of the concrete, but the Maturity Method does not account for this lack of curing. It is, however, unlikely that this will have an effect during the early phases of concrete setting and hardening and will therefore not influence early-age strength estimations. It should be noted that the current practice of cube tests, also does not take this into account.

2.8.4 Variability in void content

Concrete strength decreases with an increase in void content. As mentioned earlier, an accepted rule is that the compressive strength decreases by approximately 5% with a 1% increase in void content. (Mindess, et al., 2003). This, however, does not change the maturity of the concrete mixtures. Variability in the void content may therefore cause the in-situ Strength-Maturity relationship to deviate from the Strength-Maturity relationship developed in the laboratory during mixture calibration.

When calibrating the concrete mixture, the void content of the mixture should be similar to the void content that will be obtained on site. The void content on site should be carefully monitored and controlled through sufficient compaction. It should be noted that the current practice of cube tests, also does not take this into account.

2.8 Conclusion

With the theory discussed in this chapter, it is possible to verify the accuracy of the Maturity Method as an in-situ strength estimation technique. The Maturity Method has various advantages as it is a non-destructive estimation technique and with the use of SmartRocks, the estimation can be made in real-time on site. The Maturity Method has limitations, but the applicability thereof will be determined for use in South-Africa.

It should be noted that various limitations of the Maturity Method are also apparent in the testing of concrete cubes which is currently adopted in South Africa as an in-situ strength estimation technique. These limitations are that the Maturity Method, and the testing of concrete cubes do not account for insufficient compaction of the in-situ concrete. These methods also do not consider the moisture availability during curing.

Factors that influence the accuracy of the strength estimation provided by the SmartRocks that need to be carefully controlled are firstly, the mix calibration. The quality of the strength estimations provided by the SmartRocks, is directly influenced by the quality of the mix calibration. Therefore, the mix calibration should be carefully controlled. Secondly, the mix calibration should be an accurate representation of the strength development of the in-situ concrete. Thus, no major changes can be made to the mix design of the in-situ concrete after mix has been calibrated. Lastly, high temperatures experienced by concrete on site, may lead to cross-over behaviour, which is not taken into account by the Maturity Method.

Chapter 3

Laboratory Test Phase

3.1 Introduction

This chapter explains the methodology of the laboratory test phase as well as the results that were obtained from this phase. The test design is given, explaining the objectives of the tests, as well as the different concrete mixes and curing temperatures that were investigated. The process that was undertaken for temperature measurements and cube compression tests is also given. Furthermore, the regression procedure is explained and regression equations for the different strength prediction models that were tested, are given.

The results of this phase will be explained based on the objectives given in this chapter.

3.2 Test Design

3.2.1 Objectives

The main objective of the laboratory test phase is to verify the accuracy of the Maturity Method in order to ensure that it can be easily applied on site and achieve good quality in-situ strength estimations. To verify the accuracy of the Maturity Method, comparisons are made between various parameters that can be selected during several stages of implementing the Maturity Method. These comparisons are between curing temperatures for the mix calibration, two maturity functions and three strength prediction models.

a) Maturity Functions

The ASTM C 1074 (2011) specifies that two functions can be used to calculate the maturity value from the measured concrete temperatures. These two functions are the Nurse-Saul Maturity Function and the Arrhenius Maturity Function.

The Nurse-Saul Maturity Function calculates the temperature-time factor as the maturity value (Nurse, 1949). It is simple and essentially only calculates the area underneath the temperature-time graph. The Nurse-Saul Maturity Function incorporates the Datum

Temperature. This is defined as the temperature at which concrete no longer develops strength. Time intervals where the concrete falls below this temperature, are ignored from the maturity calculation. As discussed earlier, various values for the Datum Temperature have been proposed by researchers. These values are trialled to determine the applicable value. It should be noted that the choice of Datum Temperature value does not have a significant influence under South-African conditions, as sub-zero temperatures are not as common as in the Northern Hemisphere, where the Maturity Method was developed.

The Arrhenius Maturity Function calculates the equivalent age as the maturity value. The equivalent age of the concrete is the age that the concrete would have been, if it was cured at a specified temperature based on the maturity it has already attained, by being cured at another temperature. For this calculation, the apparent activation energy of the concrete has to be assumed. As is the case with the Nurse-Saul various researchers have proposed values for the activation energy and these values are trialled to determine an applicable value.

The two functions are compared to each other to determine their relative accuracy. This enabled the proposal of a maturity function to be used in the concrete mix calibration, along with the appropriate input values to accurately estimate the concrete compressive strength.

b) Strength prediction models

Strength prediction models are fitted to the strength-maturity data. Three strength prediction models are investigated in this study- Logarithmic, Hyperbolic and Exponential models. These models are fitted with a regression analysis and the most appropriate model is proposed.

The Logarithmic model is the simplest model and is the only model that is incorporated into the SmartRock application. Existing literature has shown that this model underestimates early-age strength and overestimates later-age strength (Carino, 1991).

Due to the limitations of the Logarithmic model, the Hyperbolic (Carino, 1991) and Exponential (Freiesleben Hansen & Pederson, 1977) models were developed. Carino (1991) proposed that any of the latter two models should be used for strength prediction.

Regardless of the limitations of the Logarithmic model, it is still investigated as it can prove to be sufficiently accurate. As mentioned earlier, an appealing feature of the Logarithmic model is that it is incorporated into the SmartRock application. Therefore, a real-time strength estimation can be obtained from the application.

c) Curing temperatures

The ASTM C 1074 (2011) specifies that a single temperature can be used to calibrate a mix and to develop a strength-maturity relationship. As discussed earlier, the cross-over effect was identified when concrete was cured at a higher temperature. It is intuitive that the temperature developed in a slab will be higher than the temperature developed in a 100 mm cube. Curing the concrete cubes at a lower temperature, may result in no cross-over behaviour, and therefore not taking the higher temperatures experienced by larger concrete volumes into account, whilst curing the cubes at a high temperature, may result in exaggerated cross-over behaviour. Three curing temperatures were investigated to determine if cubes from these three curing regimes accurately predict each other's strengths and what the extent of cross-over behaviour is over the three different curing temperatures

3.2.2 Concrete mixes

Three different concrete mixes were tested to evaluate the use of the Maturity Method. As it was decided to focus this study on strength estimation of suspended concrete slabs, three mixes were tested that are commonly used for slabs.

Table 3.1 shows the relevant design characteristics of each mix that are needed to estimate Datum Temperature and Activation Energy values for the Nurse-Saul and Arrhenius maturity functions respectively. Other mix design parameters cannot be explicitly given in this study, as the mix design was obtained from a commercial concrete ready-mix supplier.

Table 3.1: Relevant mix design information

Characteristic	Mix 1	Mix 2	Mix 3
Design strength	25 MPa	25 MPa	30 MPa
CEM II/A-S	100%	85%	85%
Fly-Ash	-	15%	15%
w/c	~ 0.75	~ 0.65	~ 0.60

CEM II/A-S cement has between 6% and 20% Corex slag as an extender, but as discussed earlier, Corex slag exhibits the same hydration behaviour as Ordinary Portland Cement. Curing temperatures

As mentioned earlier, tests were conducted on concrete cubes cured at three different temperatures. The laboratory where the concrete cubes was cast, cured and tested has limited apparatus available to produce variable curing temperatures. A standard curing tank which maintains water temperature at 24 °C is available, along with a single, smaller tank that can be heated to 80 °C. Figure 3.1 shows the heated tank that was used for curing concrete cubes at higher temperatures.

Figure 3.1: Heated curing tank

The water temperature in the heated curing tank fluctuates between the temperature that the thermostat is set to, and 4 °C below this specified temperature. The chamber used for cold curing was not in operation at the time of the tests.

The three curing temperatures that was selected for the laboratory test phase are:

- 24 ℃ (cured in standard curing tank)
- 34 ℃ (cured in heated curing tank)
- 44 ℃ (cured in heated curing tank)

The tests conducted on the cubes cured at 24 ℃ and 34 ℃ could be performed simultaneously in the standard and heated tank respectively, and since only a single heated curing tank is available, the cubes cured at 44 ℃ were tested in a separate round of tests

Limited variable curing conditions were also available for the cubes during the first 24 hours after casting during which the concrete cubes were still in the moulds. To distinguish the curing conditions from each other, it was decided to cure the cubes that were ultimately cured at 24 ℃, at room temperature (~ 22 ℃) for the first 24 hours, with the moulds wrapped in plastic, to prevent the concrete from drying out. The cubes that were ultimately cured at 34 ℃ and 44 ℃ was placed in a humidified room that is kept at 26 ℃ for the first 24 hours after casting.

3.2.3 Concrete cube specimens

The ASTM C 1074 (2011) specifies that two cubes need to be tested at the ages of 1, 3, 7, 14 and 28 days and that a third cube needs to be tested if the results from the cube compression test differs by more than 10 %. Therefore, 16 cubes were cast from each mix, for each curing temperature, with SmartRock sensors being installed in two concrete cubes. The ASTM C 1074 (2011) further specifies that the temperature sensor be installed within 15 mm of the centre of the cube. Figure 3.2 shows the installation of the SmartRock sensor in the concrete cube. The probe was pushed into the cube, to within 15 mm of the centre of the cube sample (as ASTM C 1074 specifies) under the stiffness of the wire. It is this stiffness that also held the probe in place in the cube sample.

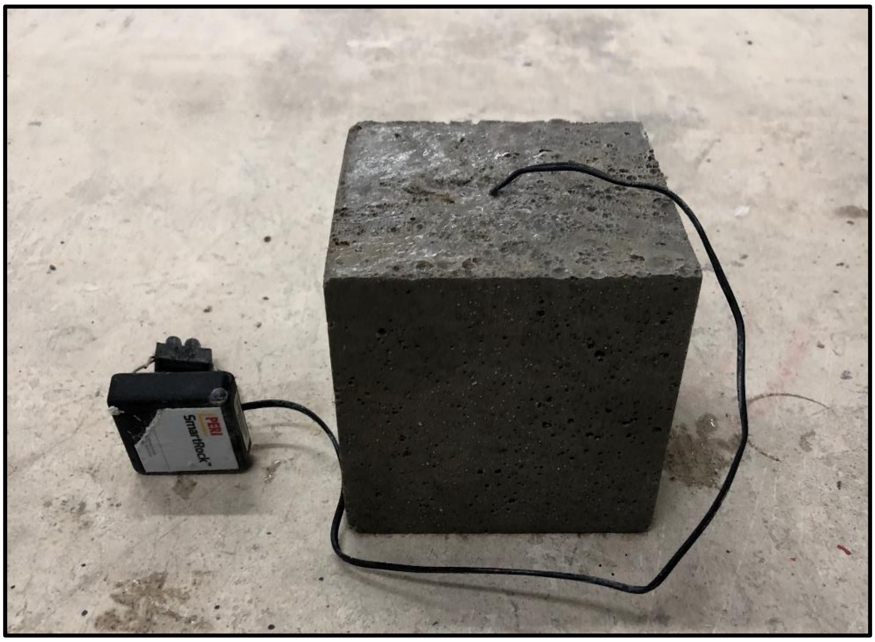

Figure 3.2: SmartRock sensor installed in concrete cube

To ensure that the activation wires did not lose contact with each other and that the sensor stopped measuring, logging and transmitting the data, the activation wires were fixed to each other using strip connectors. Figure 3.3 shows how the activation wires were connected.

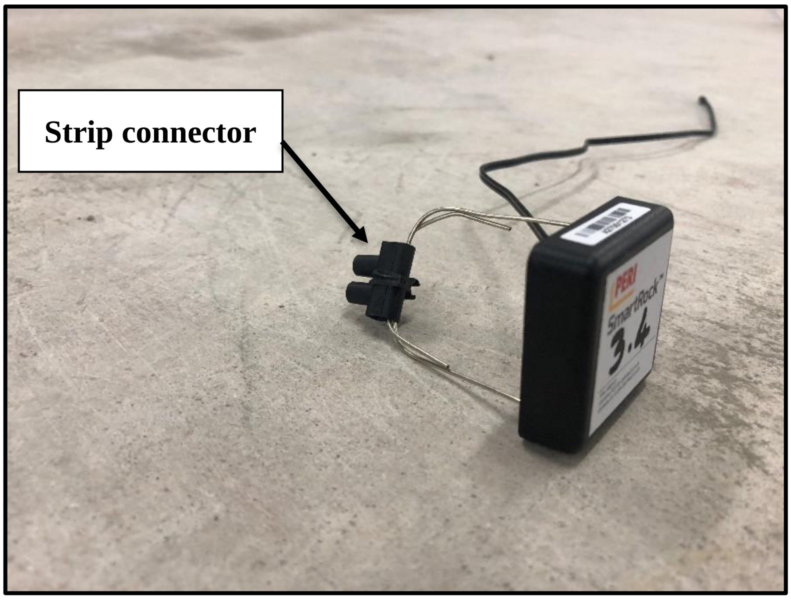

Figure 3.3: Connection of activation wires

3.2.4 Compression test

The cube compression tests on the concrete cubes were conducted in accordance with SANS 5863 which specifies the compressive strength tests of hardened concrete. This standard specifies a test method for concrete cubes and cylinders.

Each specimen was tested immediately after it was removed from the curing bath to ensure that it is tested in a saturated condition. Any surface water or grit was removed prior to testing. Figure 3.4 shows the cubes after it has been prepared for testing. All cubes were weighed to ensure that the densities of the cubes from the same mix were similar. This was to ensure that there was a similar degree of compaction for all cubes.

Figure 3.4: Cubes prepared for testing

Each test specimen was loaded into the compression testing machine with the top face of the cube facing outward. This was done to ensure that the loading direction was perpendicular to the casting direction- as specified by SANS 5863. Figure 3.5 shows the concrete cube after it had been placed into the compression testing machine.

Figure 3.5: Cube prior to testing

The test specimens were all loaded at a rate of 0.3 MPa/s until it reached the maximum load. This maximum load was recorded. Figure 3.6 shows the typical failure pattern that was observed on all of the test specimens.

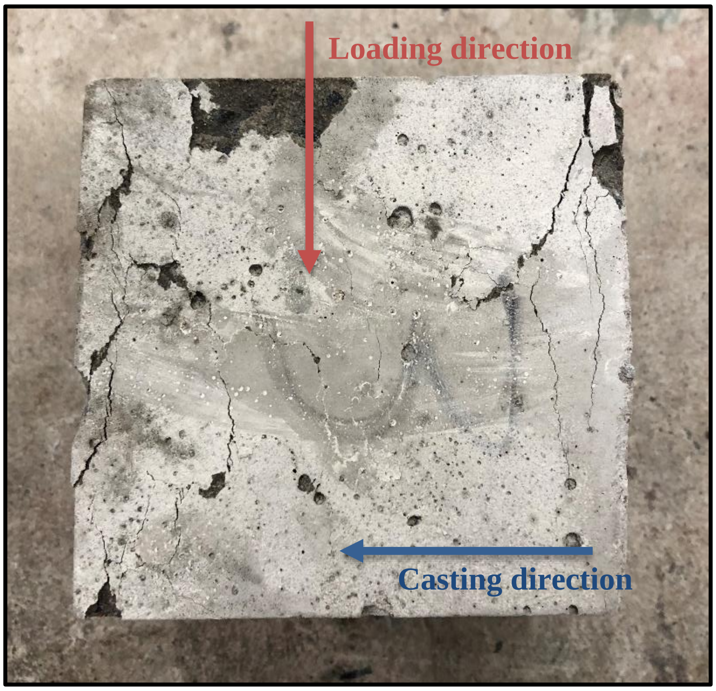

Figure 3.6: Typical failure pattern

3.3 Regression analysis

The different models which describe the relationship between maturity and concrete compressive strength that were identified in Chapter 2, were fitted to the data obtained from the laboratory tests. These three models follow a logarithmic, hyperbolic and exponential trend respectively. The models were fitted to the data by means of a linear regression analysis, whilst least squares fitting was utilized in order to minimize the errors in the analysis.

3.3.1 Regression procedure

The measured strengths and the maturities, that were calculated from the measured temperature histories, should be plotted on a scatter plot. The maturities should be modelled as the independent variable, whilst the compressive strength should represent the dependant, or response variable.

Least squares fitting was used in this regression analysis to fit the models to the data. Least squares fitting minimizes the sum of squares of the vertical residual of each response variable data point (Montgomery & Runger, 2011). The vertical residual is the difference between the measured value and the value predicted by the model and can therefore be defined as the error in the estimation at each data point. The residual is defined as:

$$\epsilon_i = y_i - \hat{y}_i \qquad \text{[Eq. 12]}$$

where:

ϵ_i = residual of the ith estimation

y_i = ith measured value

$\hat{y}_i$ = ith estimated value

If the ϵ_i value has a small value, it is an indication that the model provides a good estimation of the measured value. To ensure that the model provides a good fit to the measured data and that extremes of positive and negative residual values falsely indicate a good fit, the sum of squares of all residuals were used.

The total squares of the vertical residual is calculated with:

$$Res^2 = \sum_{i=1}^{n} \epsilon_i{}^2 = \sum_{i=1}^{n} (y_i - \widehat{y_i})^2 \qquad \text{[Eq. 13]}$$

The expression for Res^2 is minimized through differentiation to ensure the best possible fit, with the equation for the particular model being substituted for $\widehat{y_i}$.

The coefficient of determination (R^2) will be used to evaluate the overall capability of the model to accurately predict the response variable. The R^2 value is a measure of the total amount of variability that can be accounted for by the model relative to the total variability.

SS_E indicates the total variability that cannot be explained by the model. This variability is attributed to the error of the model in predicting values. SS_E is defined as:

$$SS_E = Res^2 = \sum_{i=1}^{n} (y_i - \widehat{y_i})^2 \qquad \text{[Eq. 14]}$$

The total variability consists of another component. This variability (SS_R) can however be accounted for by the model. SS_R is defined as:

$$SS_R = \sum_{i=1}^{n} (\widehat{y_i} - \bar{y})^2 \qquad \text{[Eq. 15]}$$

where:

$\bar{y}$ = mean of the dataset

The total variability can therefore be calculated with:

$$SS_{TOT} = SS_E + SS_R \qquad \text{[Eq. 16]}$$

A model that provides a good fit to the measured data has a small amount of unexplained variability relative to the variability that can be accounted for. The coefficient of determination takes both these variabilities into account and is defined as:

$$R^2 = \frac{SS_R}{SS_{TOT}} \qquad \text{[Eq. 17]}$$

The range of the coefficient of determination is given as $0 \leq R^2 \leq 1$ and the closer the value of R^2 is to 1, the better the accuracy of the model in predicting values.

3.3.2 Regression equations

The regression equations for the Logarithmic, Hyperbolic and Exponential models were calculated from first principles using Equation 13. Each model was substituted for $\hat{y}_i$.

a) Logarithmic

The logarithmic model is a simple model that describes the strength development of concrete. The model is defined with Equation 9, given here again:

$$S = a + b \log M$$

It should be noted that this model is intrinsically linear. This made the attainment of equations to calculate the constants a and b possible. As mentioned earlier, this model was substituted for $\hat{y}_i$ in Equation 13. This expression was differentiated with respect to a and b and set equal to zero in order to minimize the error of the model in predicting values. Matrix algebra was applied to ultimately determine the equations for a and b. These equations are given by:

$$a = \frac{\sum_{i=1}^{n} y_i \cdot \sum_{i=1}^{n} (\log x_i)^2 - \sum_{i=1}^{n} \log x_i \cdot \sum_{i=1}^{n} (\log x_i \cdot y_i)}{n \cdot \sum_{i=1}^{n} (\log x_i)^2 - (\sum_{i=1}^{n} \log x_i)^2} \qquad \text{[Eq. 18]}$$

$$b = \frac{n \cdot \sum_{i=1}^{n} (\log x_i \cdot y_i) - \sum_{i=1}^{n} \log x_i \cdot \sum_{i=1}^{n} y_i}{n \cdot \sum_{i=1}^{n} (\log x_i)^2 - (\sum_{i=1}^{n} \log x_i)^2} \qquad \text{[Eq. 19]}$$

where:

$x_i = i$th maturity value

$y_i = i$th strength value

b) Hyperbolic

Carino (1991) proposed that a hyperbolic function be used to model the strength development of concrete. This model is defined with Equation 8, given here again:

$$S = S_u \cdot \frac{k(M - M_0)}{1 + k(M - M_0)}$$

The parameter M_0 is defined as the value of the maturity where strength gain commences. It is assumed that this value is small and can therefore be ignored. This simplifies the Hyperbolic Model to:

$$S = S_u \cdot \frac{k \cdot M}{1 + k \cdot M} \qquad \text{[Eq. 20]}$$

It is not possible to linearize this function in order to convert it to a function that is intrinsically linear. Therefore, it was decided to only develop an equation for k and to determine the optimum value for S_u using trial and error.

This function was also substituted for $\hat{y}_i$ in Equation 13, but it was only differentiated with respect to k. An equation was obtained for k in terms of S_u and is given as:

$$k = \frac{\sum_{i=1}^{n} y_i}{S_u \cdot \sum_{i=1}^{n} x_i - \sum_{i=1}^{n}(x_i \cdot y_i)} \qquad \text{[Eq. 21]}$$

S_u was calculated using the Solver function in Excel in order to maximize R^2.

c) Exponential

Freiesleben Hansen & Pederson (1977) proposed that an exponential function be used to model the strength development of concrete over time. It is given by Equation 10, given here again:

$$S = S_u \cdot e^{-\left[\frac{\tau}{M}\right]^{\beta}}$$

Setting $a = \frac{1}{\tau}$, $b = -\beta$, $\hat{y}_i = S$, $x_i = M$ and also taking the natural logarithm of each side gives:

$$\ln \hat{y}_i = \ln S_u + (a \cdot x_i)^b \qquad \text{[Eq. 22]}$$

The three constants in the exponential function make it impossible to linearize the expression. One constant, therefore, has to be chosen and optimized through trial and error-this constant was chosen as b. Consequently, only two constants have to be calculated and it is now possible to linearize the equation.

Setting c $= \ln S_u$, $a' = a^b$ and $z_i = x_i^b$ gives:

$$\ln \hat{y}_i = c + a' \cdot z_i \qquad \text{[Eq. 23]}$$

This function is intrinsically linear and therefore, after substituting $\hat{y}_i$ into Equation 12, could be differentiated with respect to a' and c to develop equations for the two unknown constants. Following the same procedure as for the logarithmic function, results in:

$$a' = \frac{n \cdot \sum_{i=1}^{n} (\ln y_i \cdot z_i) - \sum_{i=1}^{n} z_i \cdot \sum_{i=1}^{n} \ln y_i}{n \cdot \sum_{i=1}^{n} z_i^2 - (\sum_{i=1}^{n} z_i)^2} \quad \text{[Eq. 24]}$$

$$c = \frac{\sum_{i=1}^{n} z_i^2 \cdot \sum_{i=1}^{n} \ln y_i - \sum_{i=1}^{n} z_i \cdot \sum_{i=1}^{n} (\ln y_i \cdot z_i)}{n \cdot \sum_{i=1}^{n} z_i^2 - (\sum_{i=1}^{n} z_i)^2} \quad \text{[Eq. 25]}$$

b was calculated using the Solver function in Excel in order to maximize R^2.

3.4 Results

3.4.1 Maturity functions

As mentioned earlier, three mixes were tested to verify the use of the Maturity Method.

a) Mix 1

Various values of the Datum Temperature have been proposed by researchers for use in the Nurse-Saul Maturity Function. The ASTM C 1074 (2011) proposes that a value of 10 °C be used for a Type I cement. The American classification of Type I is similar to the cement that was used in this study. The w/c ratio of Mix 1 is not within the range for the Datum Temperatures that Carino & Tank (1992) experimentally determined.

The Datum Temperature was defined as the temperature at which concrete will no longer develop strength, with research showing that this temperature can be as low as -10,5 °C (Saul, 1951). In this study, the lowest temperature at which concrete could be cured, was 24 °C. Thus, the strength gain of the concrete was never interrupted by low temperatures. The choice of a Datum Temperature, therefore, has a minimal impact on the Strength-Maturity relationship. This is deemed to be the case for the application of the Maturity Method on site as well, since sub-zero ambient temperatures are not that common in South-Africa.

To illustrate the effect of different Datum Temperatures, Strength-Maturity relationships were developed for a Datum Temperature of 10 °C as well as for 0 °C. These relationships are shown in Figure 3.7 for concrete cured at 34 °C

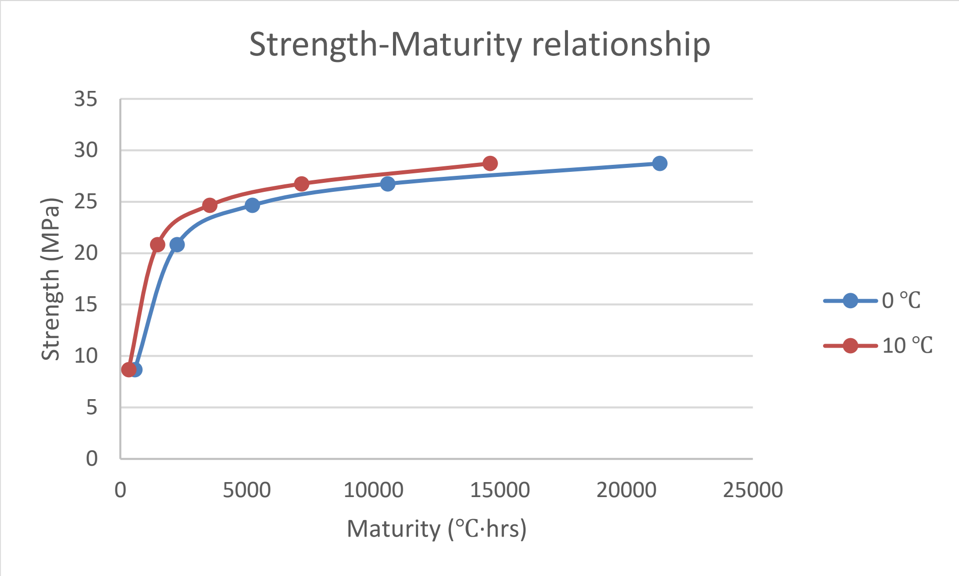

Figure 3.7: Strength-Maturity relationship for different Datum Tempratures

Figure 3.7 shows that different Datum Temperatures result in Strength-Maturity relationships with similar shapes. It may seem that it is more conservative to use a Datum Temperature of 0 °C, but the only implication of using a lower Datum Temperature, is that a constantly larger maturity will be calculated during the calibration and strength estimation on site. In reality, it is more conservative to use a higher Datum Temperature to ensure that strength gain is not erroneously assumed under low temperatures.

The Arrhenius Maturity Function requires an assumed value for the Apparent Activation Energy of the concrete. As is the case with the Nurse-Saul Maturity Function, various values have been proposed for the Activation Energy. Freiesleben Hansen and Pederson (1977) proposed a value of 33 500 J/mol for a concrete temperature of more than 20 °C. Another typical value for the activation energy is given as 41 000 J/mol for Type I cement (Carino, 1991). The ASTM C 1074 (2011) proposes a value of between 40 000 and 45 000 J/mol for a Type I cement. The w/c ratio of Mix 1 is not within the range for the Activation Energies that Carino & Tank (1992) experimentally determined.

Strength-Maturity relationships were developed for the various applicable Activation Energies for Mix 1 using the Arrhenius Maturity Function. These Activation Energies are chosen as 33 500 and 41 000 J/mol respectively and the relationships are shown in Figure 3.8.

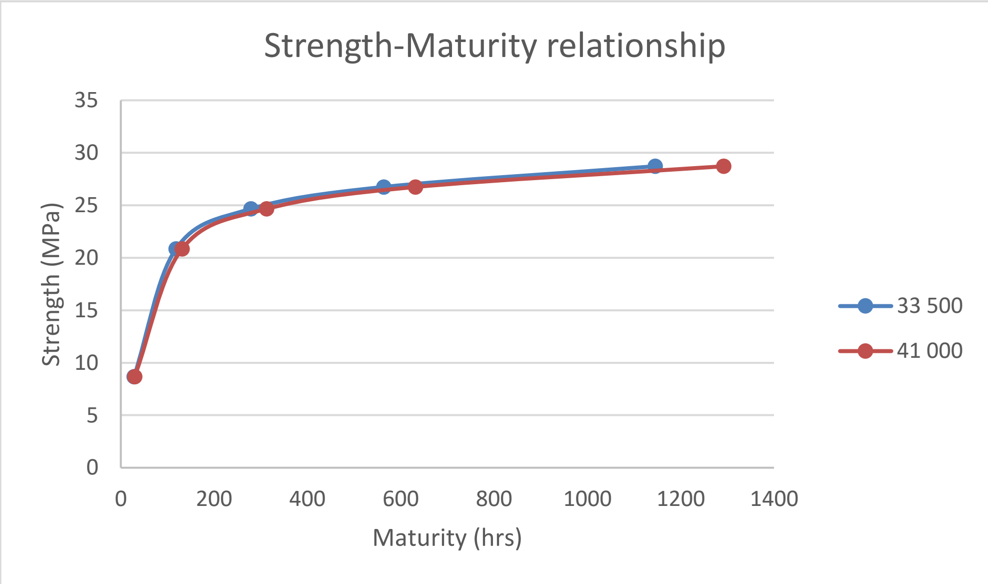

Figure 3.8: Strength-Maturity relationship for different Activation Energies

Figure 3.8 shows that there is no significant difference between the Strength-Maturity relationships developed by using an Activation Energy of 33 500 or 41 000 J/mol even though these values differ considerably. It is for this reason, that it was not deemed necessary to determine Activation Energy values experimentally.

The maturities calculated by the Nurse-Saul Maturity Function was converted to an equivalent age using the Age Conversion factor given by Equation 6. The percentage difference between the equivalent age calculated from the Nurse-Saul and Arrhenius Maturity Functions are shown in Figure 3.9. A Datum Temperature of 10 °C was used in the comparison whilst values for both previously discussed Activation Energies are shown for a concrete temperature in the range of 20 °C to 45 °C.

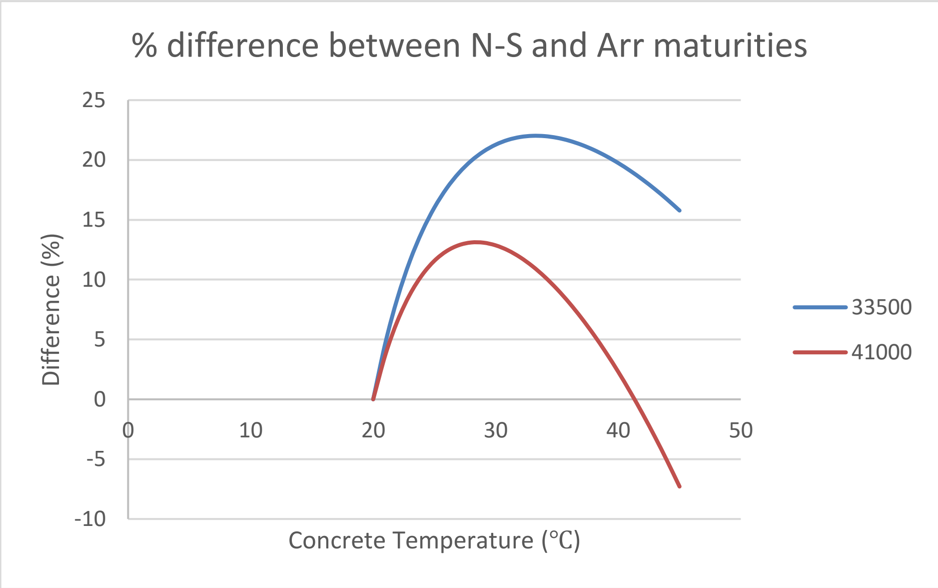

Figure 3.9: % difference between maturities calculated from the Nurse-Saul and Arrhenius Maturity Functions

Although the two Strength-Maturity relationships developed from the applicable Activation Energies are similar, Figure 3.9 shows that there is a significant difference in the actual maturity values. The difference between the maturity values calculated with the Nurse-Saul Maturity Function and the Arrhenius Maturity Function, is however less when an Activation Energy of 41 000 J/mol is used. Furthermore, this value is within the range that is proposed by the ASTM C 1074 (2011).

b) Mix 2

The ASTM C 1074 (2011) does not provide a value for the Datum Temperature for a mix containing additives or admixtures that affect the hydration heat, but allows this value to be experimentally determined. Mix 2 contains Fly-Ash and therefore a value that was experimentally determined by Carino and Tank (1992) can be used. These values are given in Table 2.1. Carino and Tank (1992) experimentally determined Datum Temperatures for a Type I cement with 20% Fly-Ash for w/c ratios of 0.45 and 0.6. This is deemed to be sufficiently similar to the constituents of Mix 2. Mix 2, however has a w/c ratio of approximately 0.65. Therefore, the Datum Temperature for Mix 2 was extrapolated from the known values to be 2 °C.

The ASTM C 1074 (2011), again, does not provide a value for the Activation Energy if a mix contains admixtures or additives. The Activation Energy can therefore also be estimated from the values that Carino and Tank (1992) experimentally determined. These values are given in Table 2.3. The Activation Energy for Mix 2 was extrapolated from the known values to be 31 600 J/mol.

The maturities calculated with the Nurse-Saul Maturity Function were also converted to equivalent age using the Datum Temperature of 2 °C, whilst the maturities were calculated from the Arrhenius Maturity function using an Activation Energy of 31 600J/mol. The percentage differences between the two calculated maturities are given in Figure 3.10 for a range of concrete temperature between 20 °C and 45 °C.

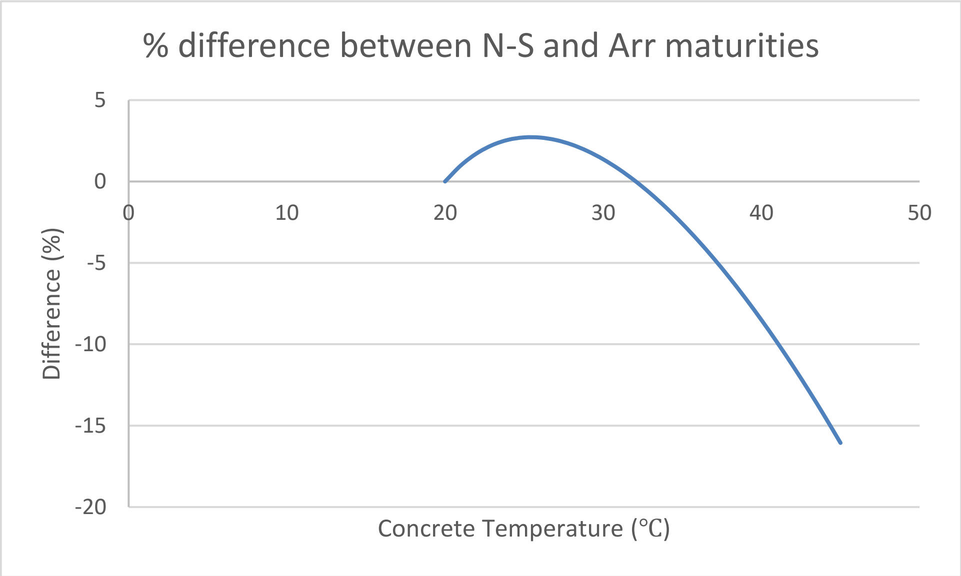

Figure 3.10: % difference between maturities calculated from the Nurse-Saul and Arrhenius Maturity Functions

Figure 3.10 shows that there is less than 5% difference between the maturities calculated from the two Maturity Functions between a concrete temperature of 20 °C and 37 °C.

c) Mix 3

Mix 3 had similar constituents to Mix 2 but had a w/c ratio of approximately 0.6. Therefore, values for the Datum Temperature and Activation Energy could be used directly from Table 2.1 and Table 2.3 respectively, without extrapolation. A Datum Temperature of 0 °C and an Activation Energy of 31 200 J/mol was used. The difference between the Maturities calculated from the Nurse-Saul and Arrhenius Maturity Functions were similar to that of Mix 2 and is shown in Figure 3.11.

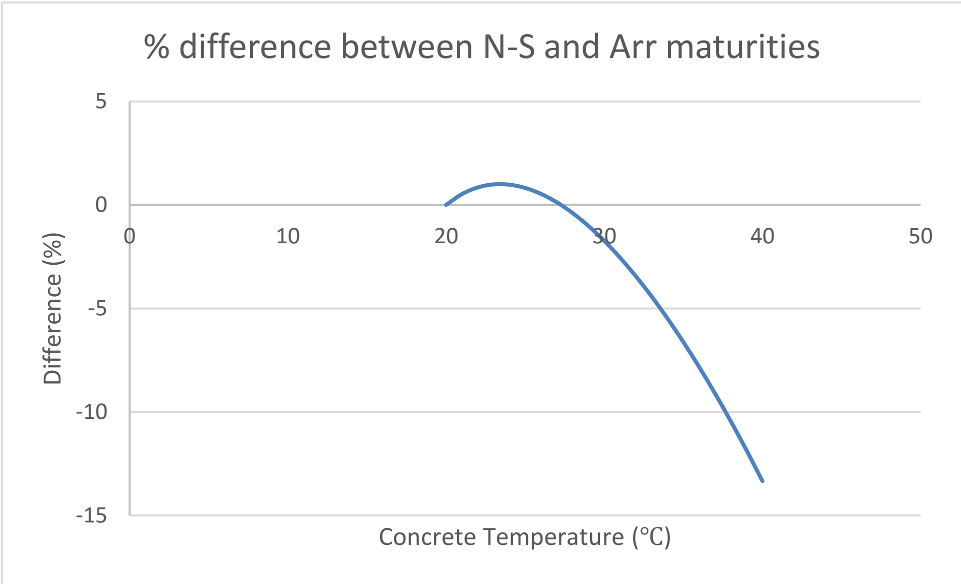

Figure 3.11: % difference between maturities calculated from the Nurse-Saul and Arrhenius Maturity Function3

To determine which of the Maturity Functions is the most accurate to calculate maturities, the Strength-Maturity relationship was developed for the Nurse-Saul Maturity Function by converting the Temperature-Time Factor to Equivalent Age and comparing these values with the Strength-Maturity relationship developed from the Arrhenius Maturity Function. Mix 1 showed the biggest difference between the two Maturity Functions. Hence, the Strength-Maturity relationship for Mix 1 at a curing temperature of 34 °C is shown in Figure 3.13.

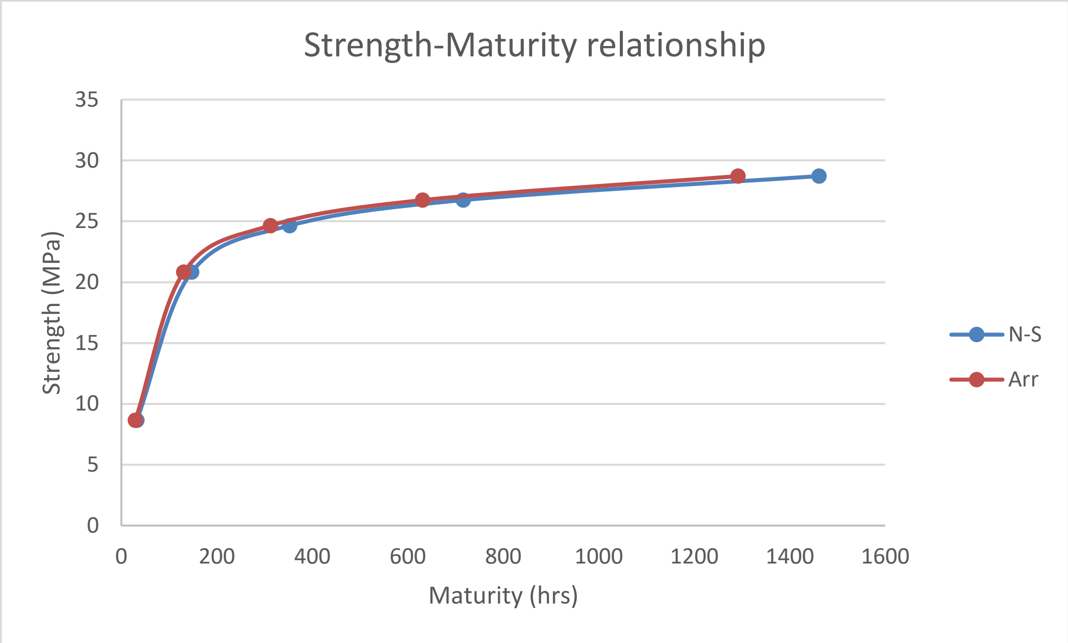

Figure 3.12: Mix 1 Strength-Maturity relationship of Nurse-Saul and Arrhenius Maturities

Figure 3.12 shows that there is not a significant difference between the Strength-Maturity relationships developed from the Nurse-Saul and Arrhenius Maturity Functions. As a verification to this, the Strength-Maturity relationship of Mix 2 was also developed and is shown in Figure 3.13.

Figure 3.13: Mix 2 Strength-Maturity relationship of Nurse-Saul and Arrhenius Maturities

Figure 3.12 and Figure 3.13 show that there is no significant difference between the Strength-Maturity relationship when it is calculated using either the Nurse-Saul or Arrhenius Maturity Functions. It is therefore decided to use the Nurse-Saul Maturity Function for this study as it is deemed to be easier to apply. Further to this, for the practical application of the Maturity Method, it is easier to visualize and understand the concept of a Datum Temperature, than it is to understand the Activation Energy.

3.4.2 Strength prediction models

Three strength predictions models were fitted to the Strength-Maturity relationships. These models are logarithmic, hyperbolic and exponential models respectively.

a) Mix 1

Mix 1 consisted of Ordinary Portland Cement and a small proportion of Corex slag and had a design strength of 25 MPa. A rapid strength gain was therefore expected after which the strength gain plateaued. The three models were fitted to the data and is shown in Figure 3.14, Figure 3.15 and Figure 3.16. Data is shown for a curing temperature of 24 °C by the green dots, whilst the model is shown by the solid blue line.

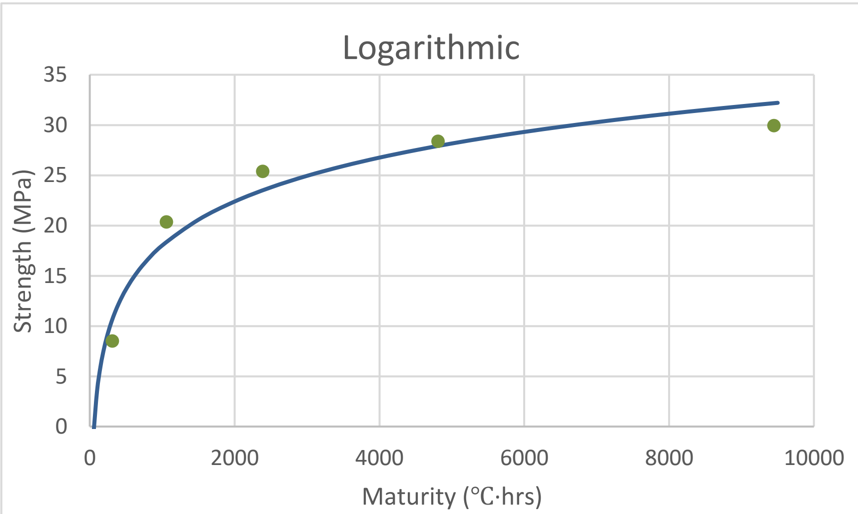

Figure 3.14: Logarithmic fit to Mix 1

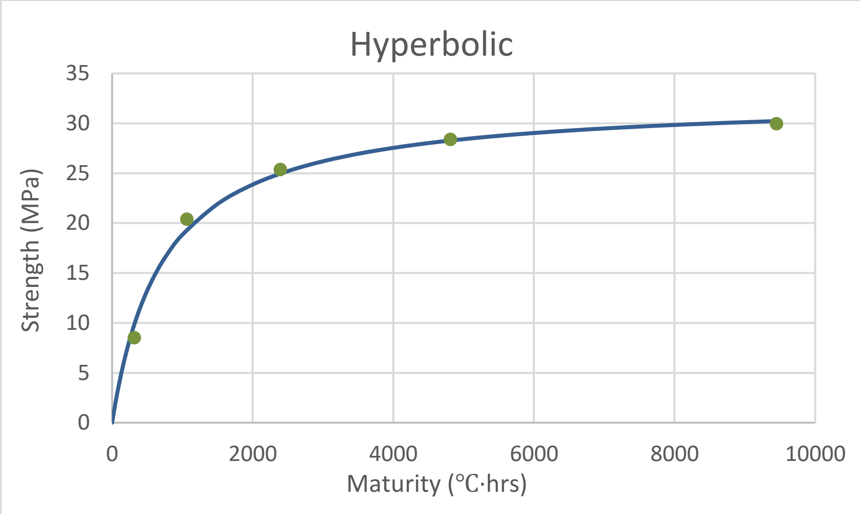

Figure 3.15: Hyperbolic fit to Mix 1

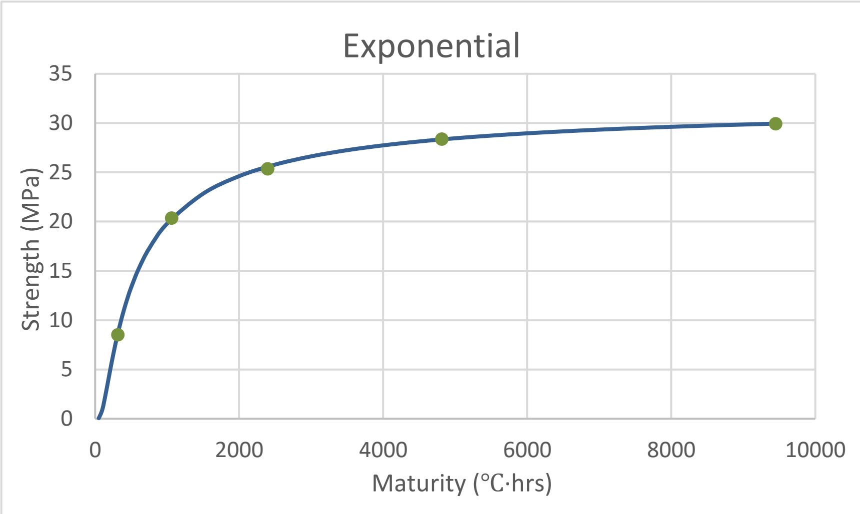

Figure 3.16: Exponential fit to Mix 1

The logarithmic model underestimates the rapid early age strength gain of Mix 1 and overestimates the compressive strength above the age of 14 days. This model also predicts continuous strength development at later ages.

The hyperbolic model predicts the rapid initial strength gain better than the logarithmic model and incorporates a limiting compressive strength as an asymptote to the strength gain of the concrete. As discussed earlier, the limiting compressive strength was chosen to maximize the R^2 value. The limiting compressive strength was chosen as 32.5 MPa, through trial and error.

The exponential model predicted the initial strength even better than the hyperbolic model and similar to the hyperbolic model, also incorporated a limiting compressive strength. The limiting compressive strength was again, chosen through trial and error as 32.1 MPa. Figure 3.17 shows the comparison of the three strength prediction models.

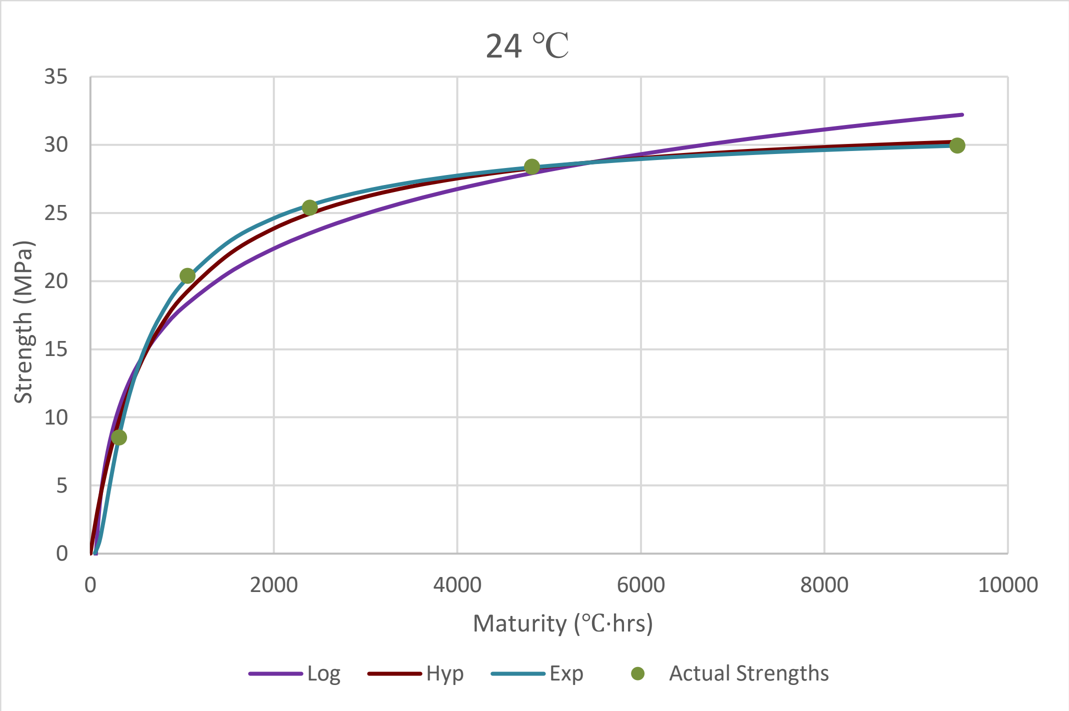

Figure 3.17: Mix 1 strength prediction models for 24 °C curing temperature

Figure 3.18 and Figure 3.19 shows the comparison of the three strength prediction models for the 34 °C and 44 °C curing temperatures respectively.

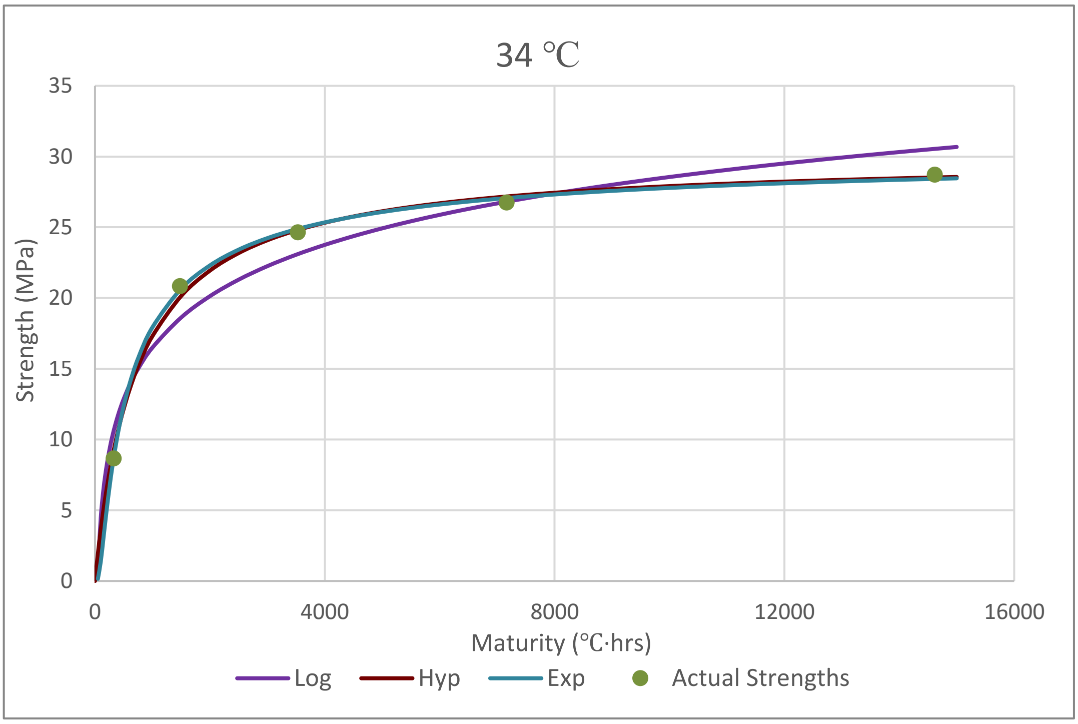

Figure 3.18: Mix 1 strength prediction models for 34 °C curing temperature

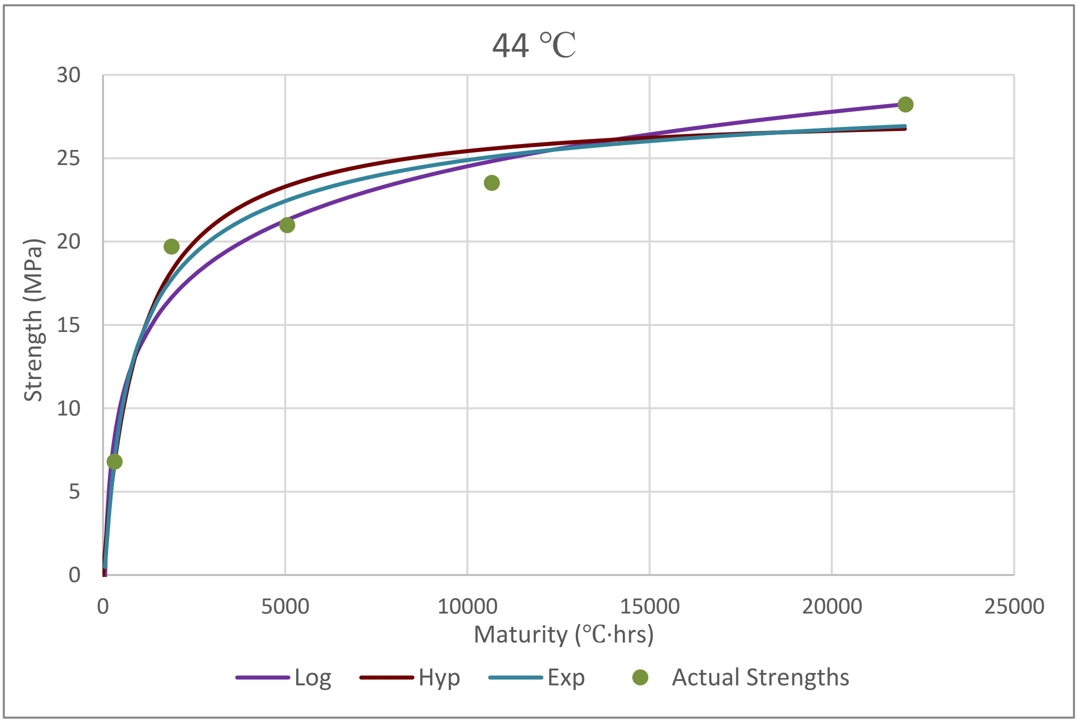

Figure 3.19: Mix 1 strength prediction models for 44 °C curing temperature

b) Mix 2

Mix 2 also had a design strength of 25 MPa and consisted of cement and Fly-Ash. The strength gain was therefore less rapid and delayed to an extent with a larger portion of the strength gain occurring between 3 and 28 days when comparing the strength development of Mix 2 with Mix 1. The three strength development models were, again, fitted to the data and is shown in Figure 3.20, Figure 3.21 and Figure 3.22. Data is shown for a curing temperature of 24 °C.

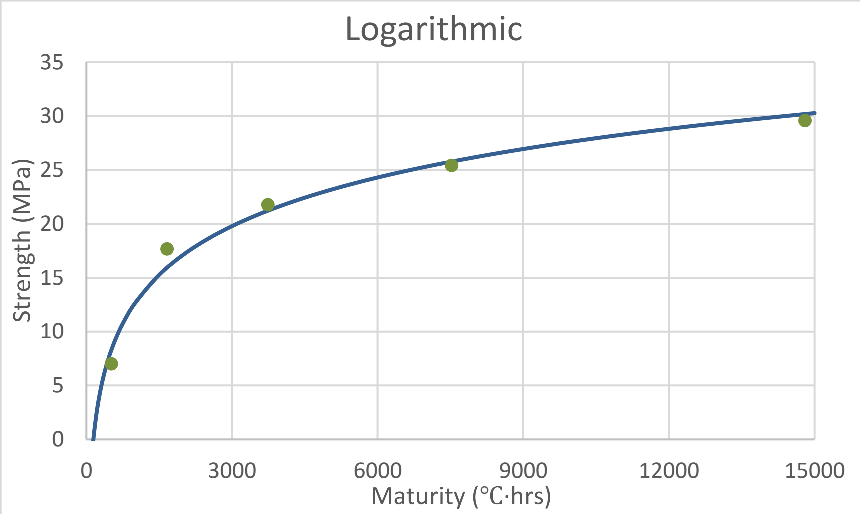

Figure 3.20: Logarithmic fit to Mix 2

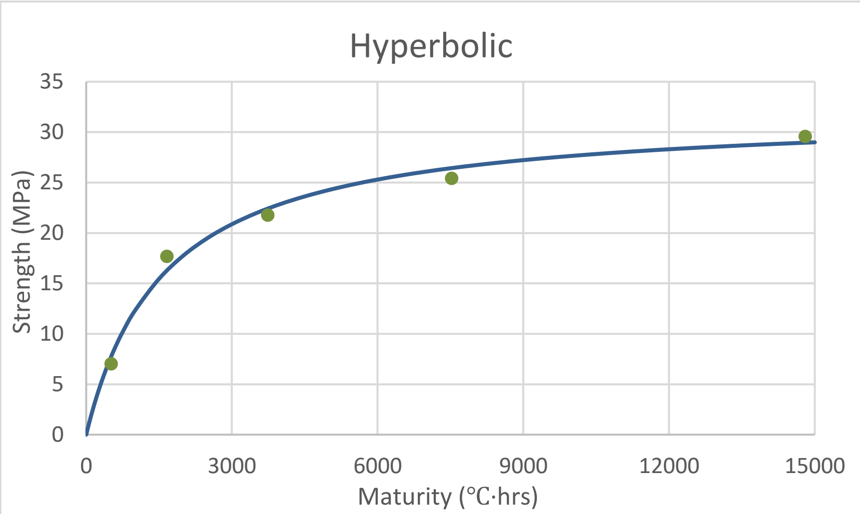

Figure 3.21: Hyperbolic fit to Mix 2

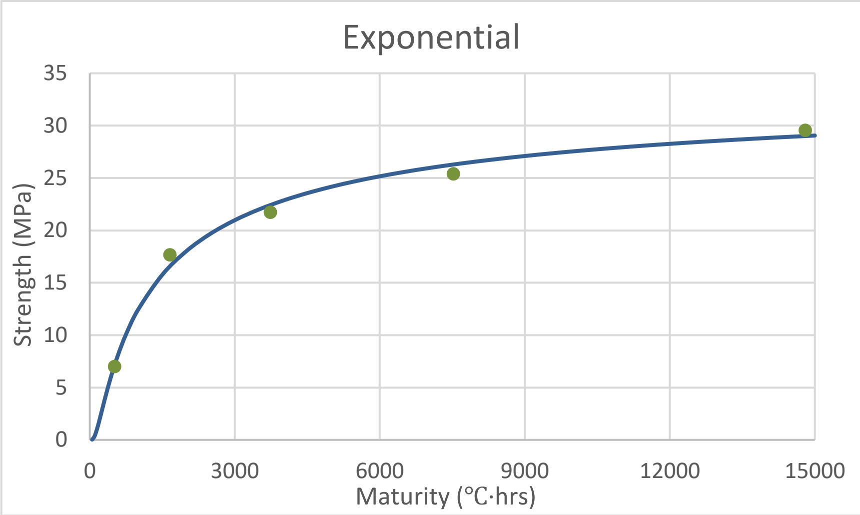

Figure 3.22: Exponential fit to Mix 2

As was the case with Mix 1, the logarithmic model underestimated the early strength gain, despite the Fly-Ash contained in the mix and, again, predicted continuous strength development at later ages.

The hyperbolic and exponential models predicted the strength gain of Mix 2 more accurately. The hyperbolic model predicted a limiting compressive strength of 32.1 MPa, whilst the exponential model predicted a limiting compressive strength of 34.7 MPa. Figure 3.23 shows the comparison of the three strength prediction models.

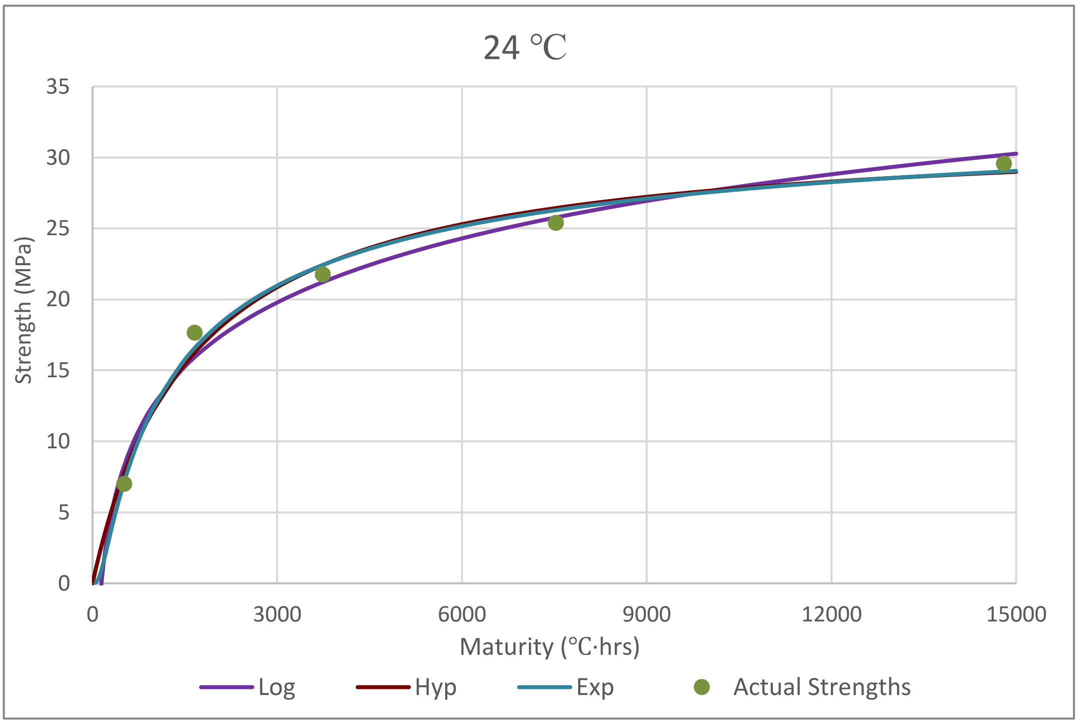

Figure 3.23: Mix 2 strength prediction models for 24 °C curing temperature

Figure 3.24 and Figure 3.25 show the combination of the three strength prediction models for the 34 °C and 44 °C curing temperatures respectively.

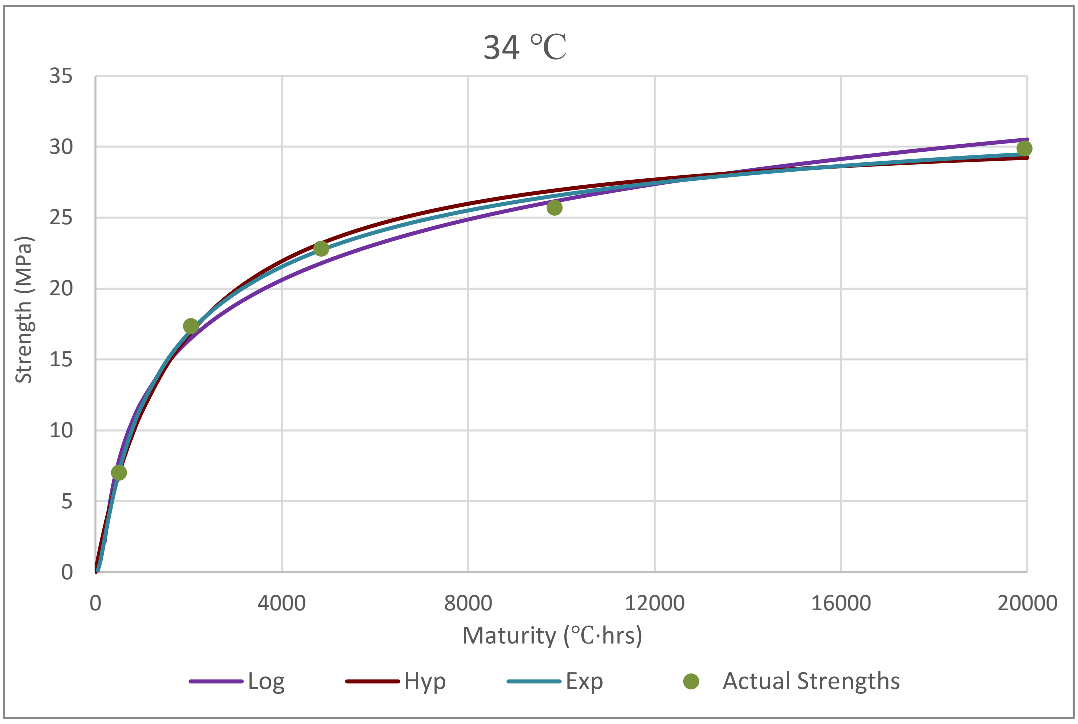

Figure 3.24: Mix 2 strength prediction models for 34 °C curing temperature

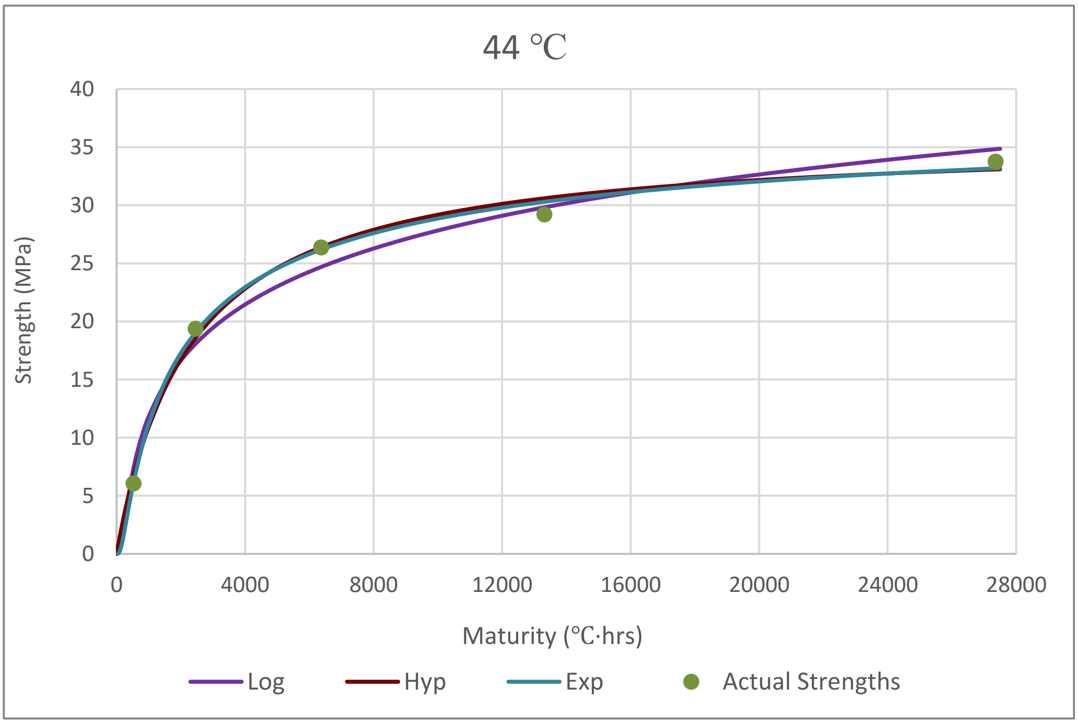

Figure 3.25: Mix 2 strength prediction models for 44 °C curing temperature

c) Mix 3

Mix 3 had the same OPC to Fly-Ash ratio than Mix 2, but had a design strength of 30 MPa at the age of 28 days. A similar strength development profile to Mix 2 was therefore observed. The three strength development models were fitted to the data and are shown in Figure 3.26, Figure 3.27 and Figure 3.28. Data is shown for a curing temperature of 24 °C.

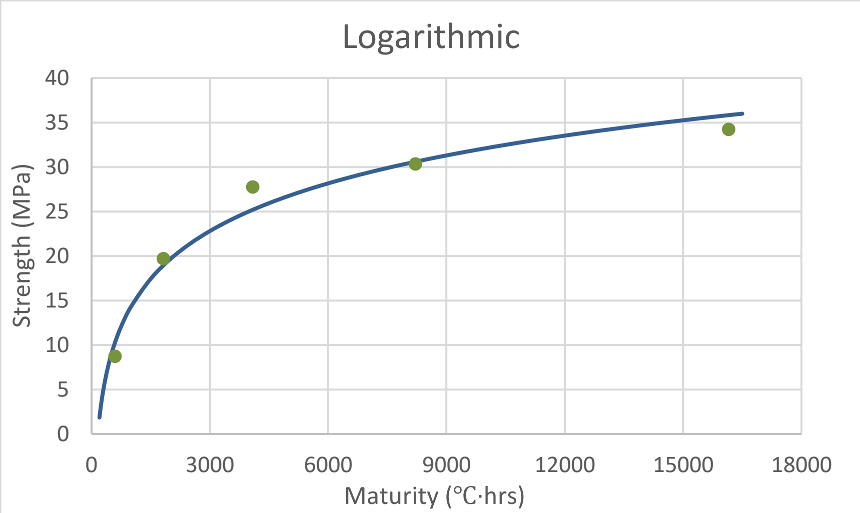

Figure 3.26: Logarithmic fit to Mix 3

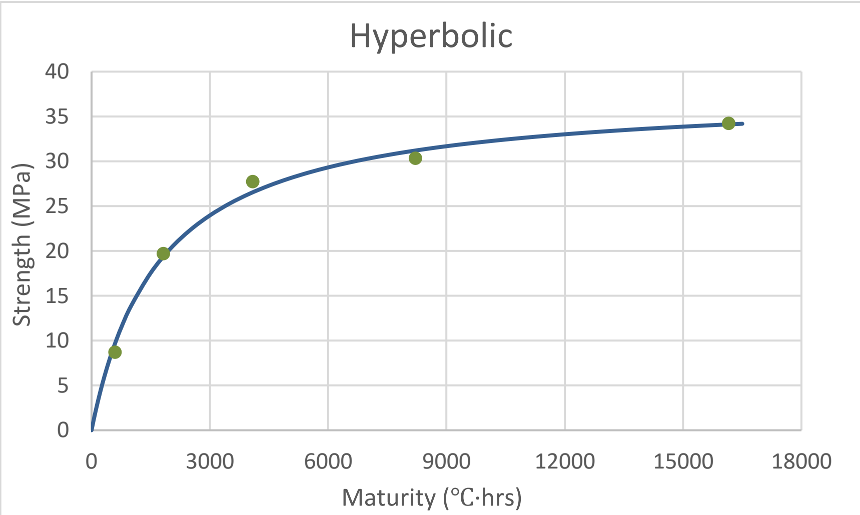

Figure 3.27: Hyperbolic fit to Mix 3

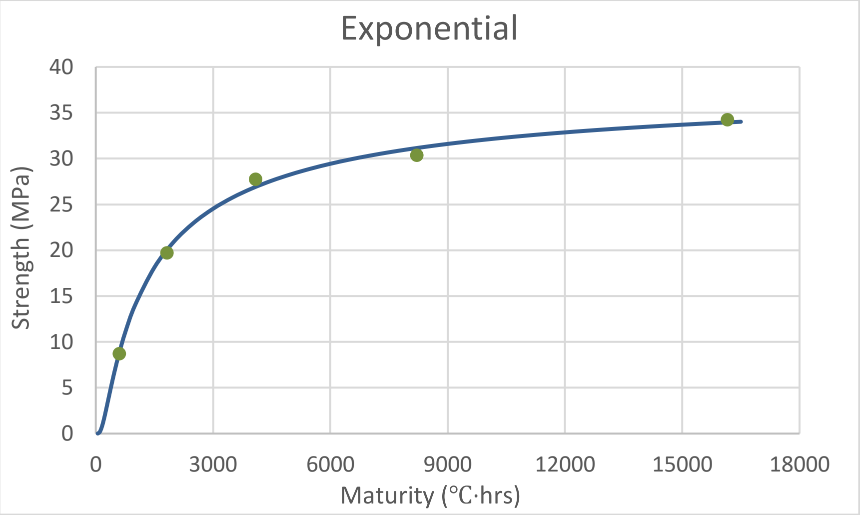

Figure 3.28: Exponential fit to Mix 3

The logarithmic model fits the data for Mix 3 better than for the other two mixes. Nevertheless, it still predicts continuous strength development at later ages. The hyperbolic and exponential models are more sensitive to changes in strength development profiles. The hyperbolic model predicts a limiting compressive strength of 37.8 MPa, whilst the exponential model predicts a limiting compressive strength of 38.9 MPa. Figure 3.29 shows the comparison of the three strength prediction models.

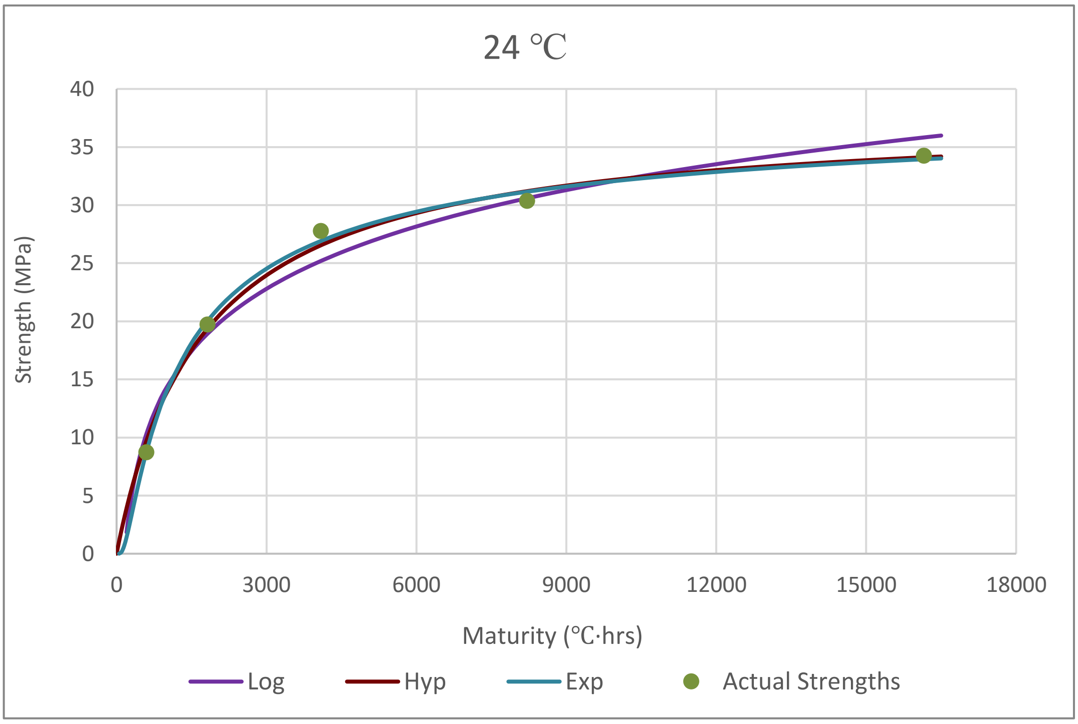

Figure 3.29: Mix 3 strength prediction models for 24 ℃ curing temperature

Figure 3.30, and Figure 3.31 show the comparison of the three strength prediction models for the 34 °C and 44 °C curing temperatures respectively.

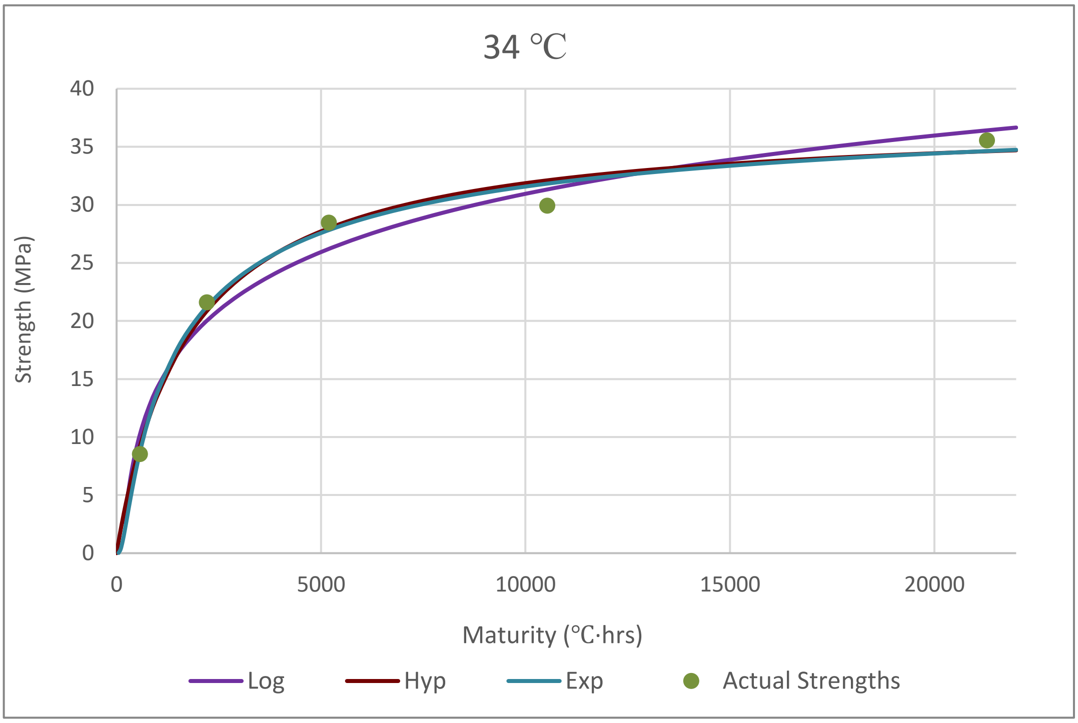

Figure 3.30: Mix 3 strength prediction models for 34 °C curing temperature

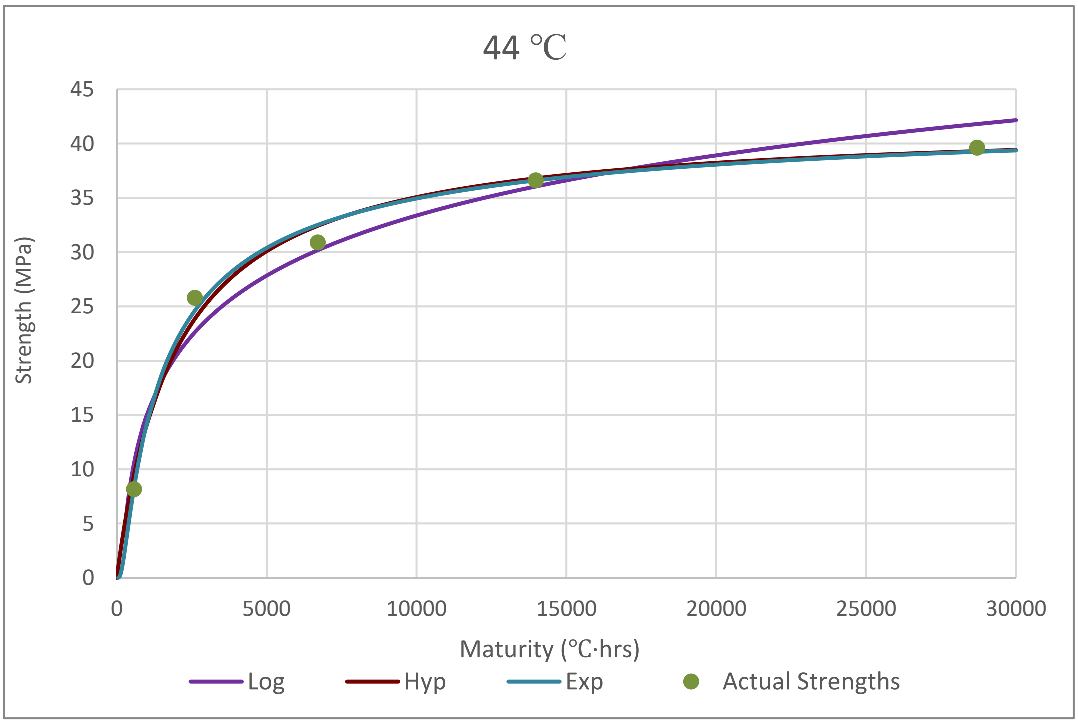

Figure 3.31: Mix 3 strength prediction models for 44 °C curing temperature

Table 3.2 presents a summary of the values for the coefficient of determination of the various scenarios analysed.

Table 3.2: Coefficient of determination for scenarios analyzed

Mix	Curing temperature	Logarithmic	Hyperbolic	Exponential
Mix 1	24 °C	0.942	0.991	1
	34 °C	0.942	0.996	0.999
	44 °C	0.948	0.959	0.96
Mix 2	24 °C	0.982	0.988	0.991
	34 °C	0.990	0.994	0.997
	44 °C	0.983	0.994	0.996
Mix 3	24 °C	0.970	0.993	0.996
	34 °C	0.970	0.987	0.988
	44 °C	0.965	0.989	0.993

Table 3.2 shows that high values were obtained for the coefficient of determination. In each of the scenarios tested, the logarithmic model did not fit the data as well as the other two models and although the lowest value for the coefficient of determination was 0.942, the fit of the logarithmic model to the measured data, was not necessarily good. The logarithmic model had an average value for the coefficient of determination of 0.966 over the 9 analysis scenarios.

The hyperbolic model had a good fit to the measured data and provided an accurate estimation for the compressive strength. The average value for the coefficient of determination was 0.988. The exponential model provided the best fit for all but one of the analysis scenarios with an average value for the coefficient of determination of 0.991. The exponential model was more sensitive to variations in the initial strength gain rate and modelled the strength gain accurately at later ages.

3.4.3 Curing temperatures

Three different curing temperatures were investigated to verify the accuracy of the Maturity Method in estimating the strength of concrete. Curing the concrete cubes at three different temperatures also allowed for the identification of cross-over behaviour and to determine the extent thereof in the three concrete mixes. The cubes were cured at 24 °C, 34 °C and 44 °C and the accuracy of the Maturity Method can be verified by determining if the strength-maturity relationship developed from the three curing temperature accurately predict the results of each other.

a) Mix 1

The OPC/Corex slag composition of Mix 1 had rapid hydration and strength gain in the first three days as a result. The temperature sensitivity of OPC and Corex Slag was discussed in Chapter 2 and therefore, significant cross-over behaviour could be expected. Figure 3.32 shows the strength development of Mix 1.

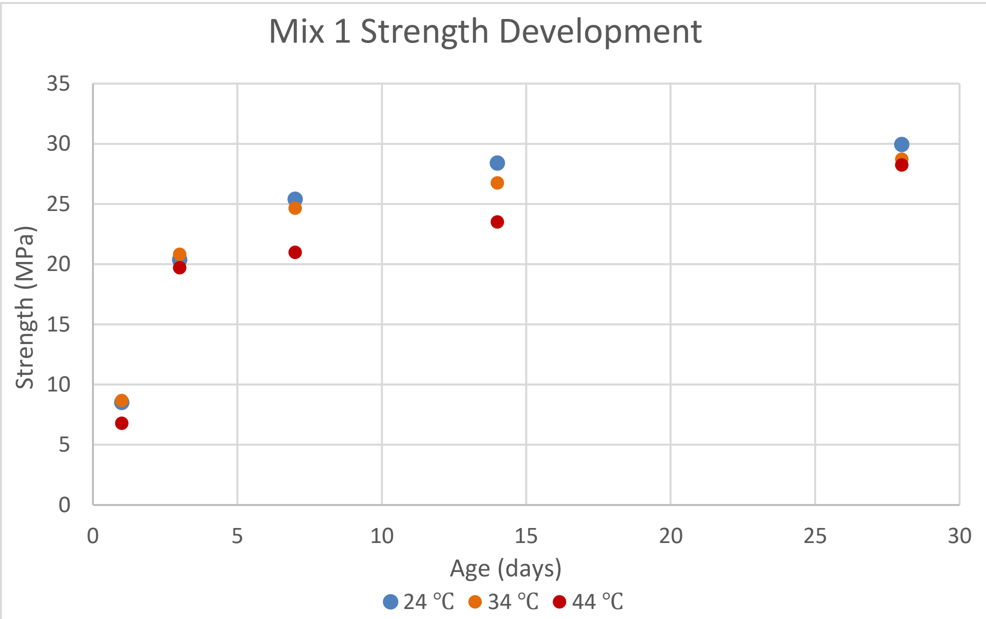

Figure 3.32: Mix 1 strength development

Rapid early strength gain can be observed for the first three days after casting with a 20 MPa compressive strength already reached at 3 days. After 7 days the strength gain plateaued. The concrete cubes cured at 44 °C did not develop significant strength between 3 and 7 days and was much weaker at 7 days than the concrete cured at 24 °C and 34 °C. The concrete cubes cured at 44 °C did however, gain more strength between 7 and 28 days than the cubes cured at lower temperatures. At 28 days the cubes cured at 24 °C had a strength of 27 MPa, whilst the cubes cured at 44 °C had a strength of 25 MPa.

Cross-over behaviour can be seen between the concrete cured at the three temperatures. For the cubes cured at 24 °C and 34 °C respectively, the cross-over occurred between 3 and 7 days, whilst the cubes cured at 44 °C were weaker throughout the curing period.

The data shown in Figure 3.32 was converted to a Strength-Maturity relationship using the Nurse-Saul Maturity function with a Datum Temperature of 10 °C. The exponential strength prediction model was fitted to the data. The Strength-Maturity relationship for the three curing temperatures is shown in Figure 3.33.

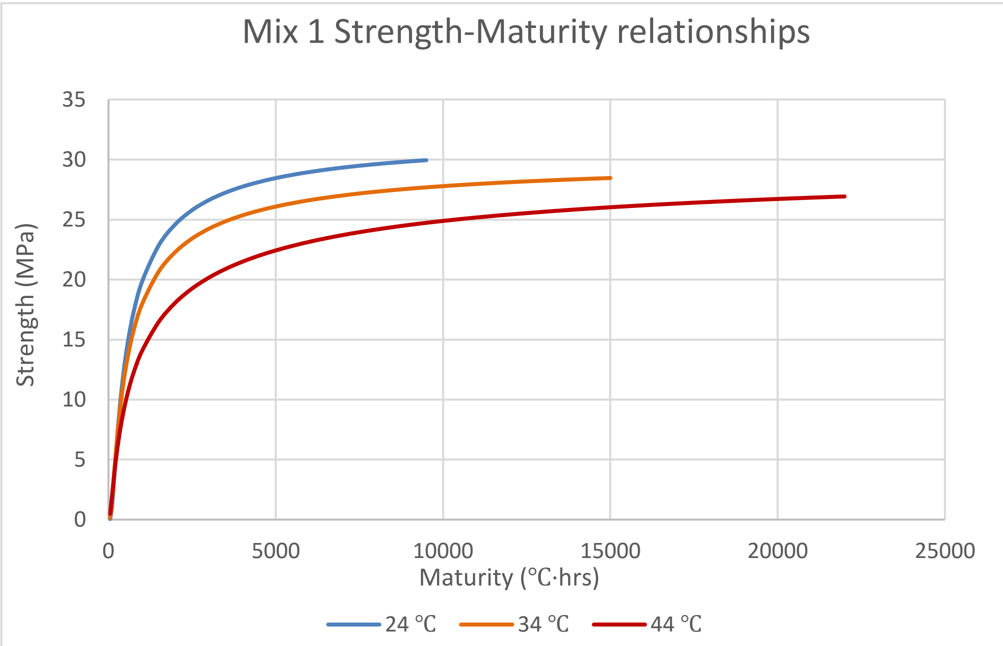

Figure 3.33: Mix 1 strength-maturity relationship for various curing temperatures

If the Maturity Method proved to be perfectly accurate for Mix 1, the strength-maturity relationships developed from the three curing temperature would be identical. Contrary to this, cross-over behaviour is evident from the three relationships shown in Figure 3.33, as higher maturities resulted in lower strengths for higher curing temperatures. It will therefore be more conservative to use a Strength-Maturity relationship (as a mix calibration) developed from a higher curing temperature than using a mix calibration developed from a lower temperature. This is because potential cross-over behaviour that can be exhibited by in-situ concrete will be taken into account.

It should be noted that a curing temperature of 44 °C proved to be over conservative with regards to cross-over behaviour. Concrete may reach high temperatures at very early ages due to the hydration heat of the cement, but this hydration heat dissipates quickly, and it is not likely that in-situ concrete suspended slabs will maintain such a high temperature over long periods of time. This was verified in the site test phase and is discussed later. Figure 3.34 shows the percentage difference between the Strength-Maturity relationships developed from the 24 °C and 34 °C as well as 34 °C and 44 °C curing temperatures respectively.

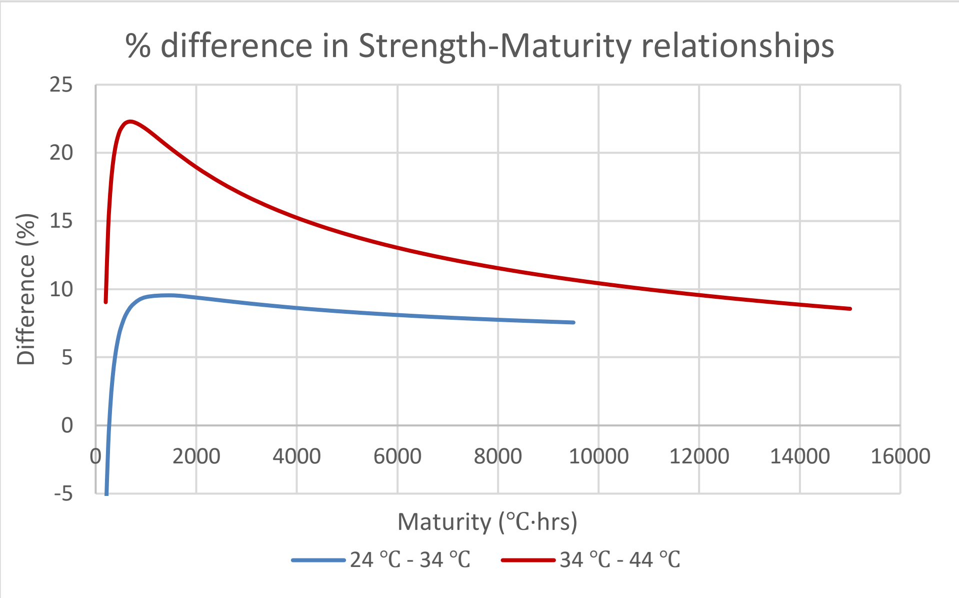

Figure 3.34: Mix 1 % difference in Strength-Maturity relationships developed from various curing temperatures

Figure 3.34 shows that there is 7%-8% difference between the Strength-Maturity relationships developed from the 24 °C and 34 °C curing temperatures. This difference is significantly larger between the relationship developed from the 34 °C and 44 °C curing temperatures. As discussed earlier, the temperature reached by suspended slabs on site will not be as high as 44 °C. Such high temperatures are therefore deemed not to be applicable to the accuracy of the Maturity Method for the majority of South African conditions.

b) Mix 2

With the fly-ash content of Mix 2, a less rapid strength development at very early ages and significant strength gain between 3 and 28 days could be expected. Figure 3.35 shows the strength development of Mix 2.

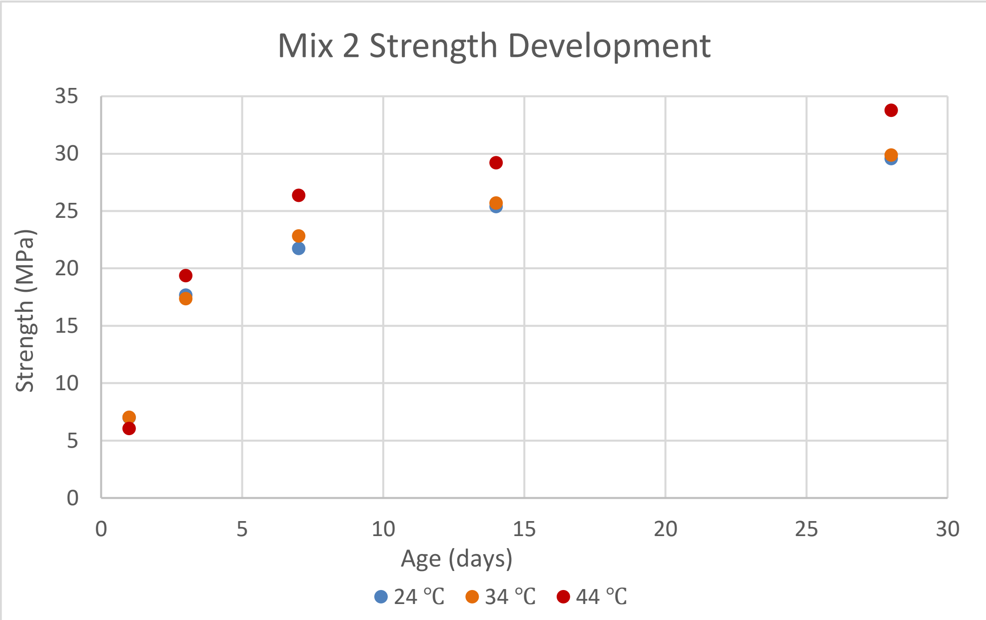

Figure 3.35: Mix 2 strength development

Figure 3.35 shows that Mix 2 responded well to the higher temperatures and no significant cross-over behaviour can be observed. As expected, the strength gain was not as rapid as in the case of Mix 1, with a large part of the strength gain still occurring after 3 days.

Figure 3.36 shows the Strength-Maturity relationships developed from the measured strength and temperature data.

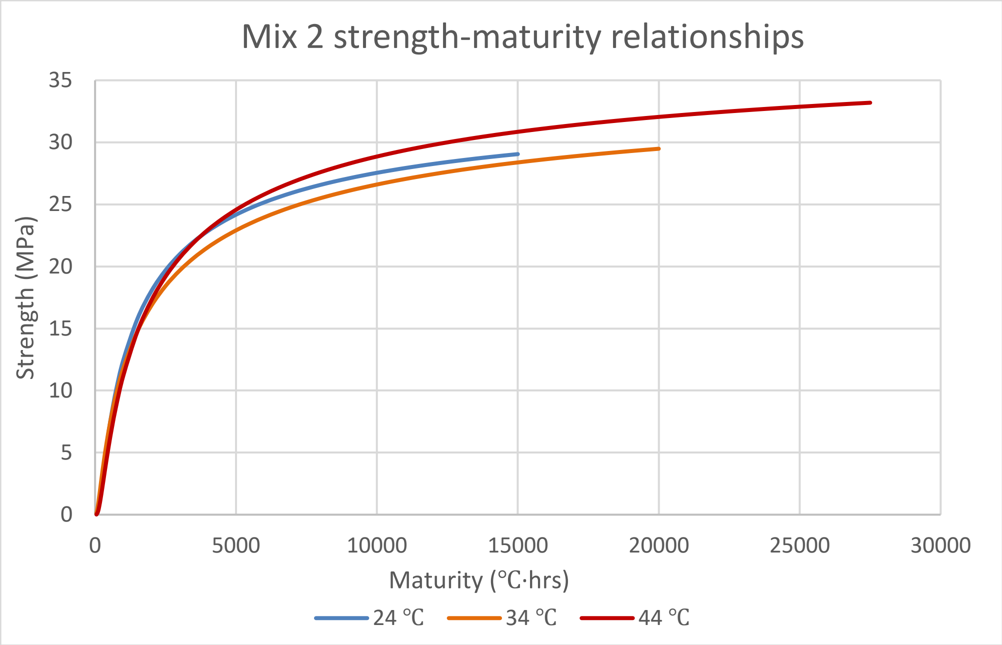

Figure 3.36: Mix 2 Strength-Maturity relationship for various curing temperatures

Figure 3.36 shows the three Strength-Maturity relationships developed from the various curing temperatures. These relationships do not differ as much as for Mix 1 and therefore predict each other well. Figure 3.37 shows the percentage difference between the Strength-Maturity relationships developed from the 24 °C and 34 °C as well as 34 °C and 44 °C curing temperatures respectively.

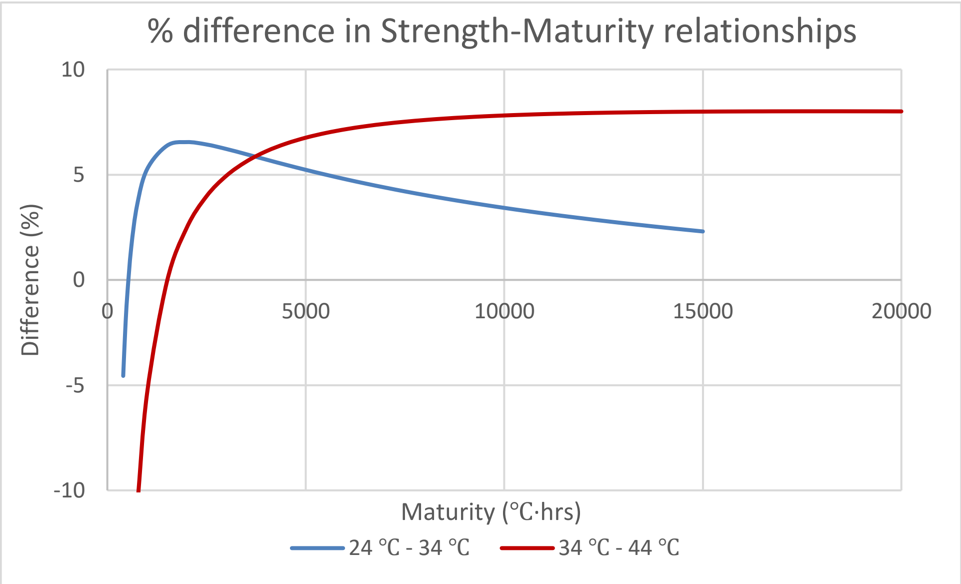

Figure 3.37: Mix 2 % difference in Strength-Maturity relationships developed from various curing temperatures

Figure 3.37 shows that the percentage difference between the Strength-Maturity relationship developed from the 24 °C and 34 °C does not differ significantly. The relationships developed from the 34 °C and 44 °C curing temperatures differ more, but never differ by more than 8 %.

c) Mix 3

The similar constituents of Mix 3 to Mix 2 resulted in a comparable strength gain rate. Figure 3.38 shows the strength development of Mix 3.

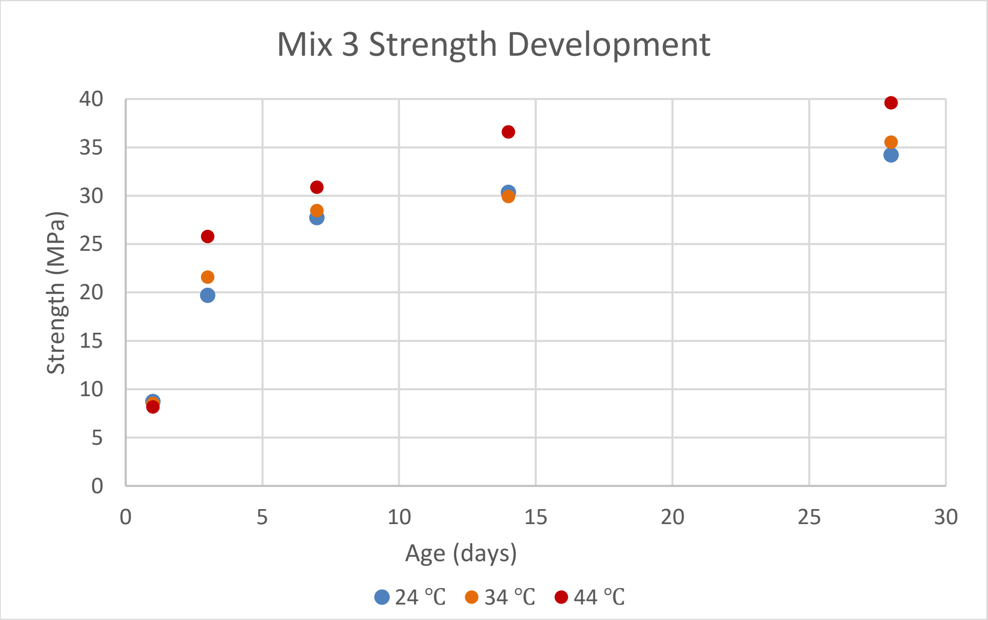

Figure 3.38: Mix 3 strength development

Figure 3.38 shows that Mix 3 also responded well to higher temperatures and that a significant portion of the strength gain also occurred after 3 days. No cross-over behaviour can be observed for Mix 3. Figure 3.39 shows the Strength-Maturity relationships developed from the measured strength and temperature data for Mix 3.

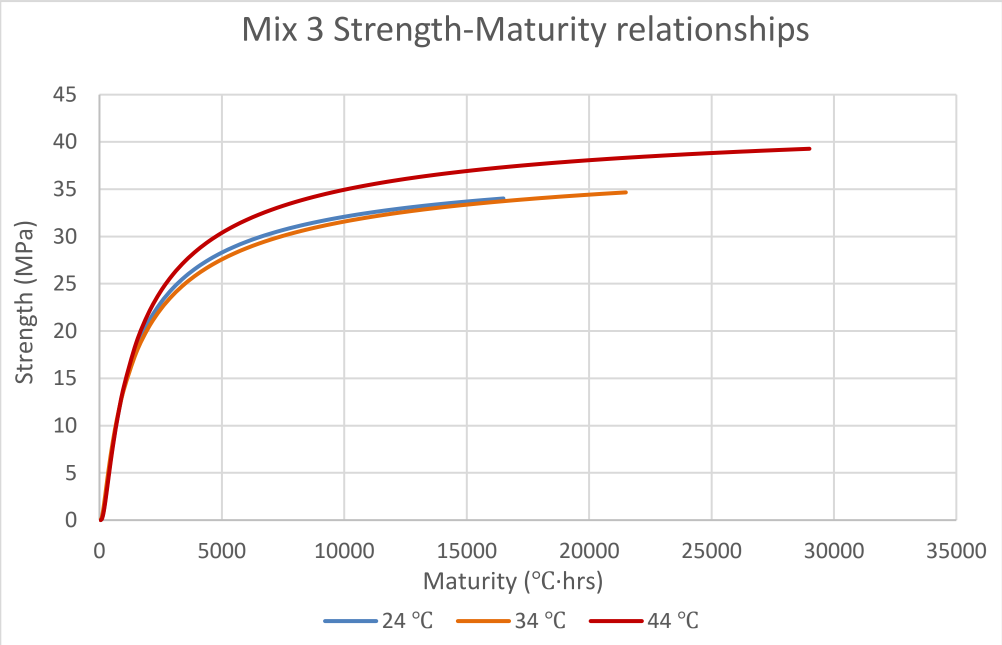

Figure 3.39: Mix 3 Strength-Maturity relationship for various curing temperatures

Figure 3.39 shows that there is a good correlation between the Strength-Maturity relationships developed from the 24 °C and the 34 °C curing temperatures. The Strength-Maturity relationship developed from the 44 °C curing temperature differed from the other relationships, as was the case with Mix 2. Figure 3.40 shows the percentage difference between the Strength-Maturity relationships developed from the 24 °C and 34 °C as well as the 34 °C and 44 °C curing temperatures respectively.

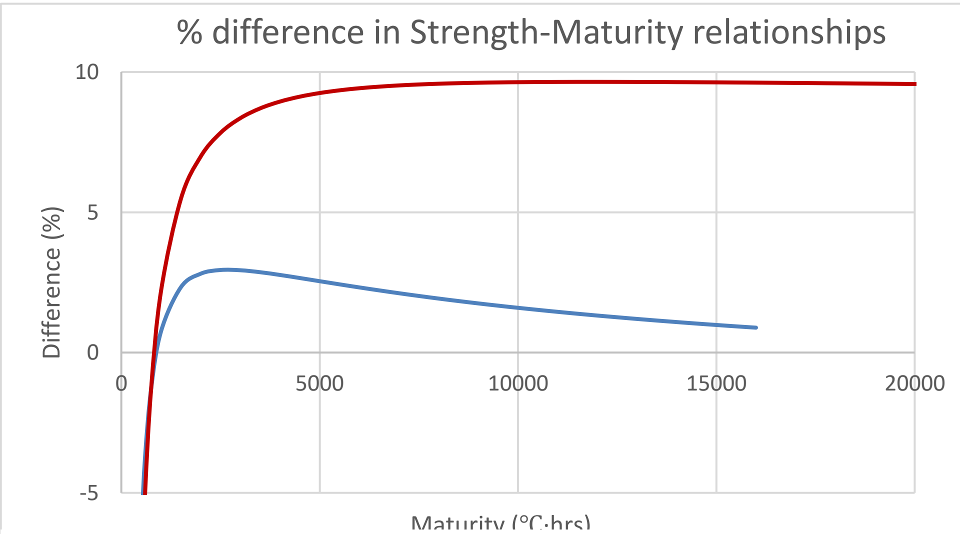

Figure 3.40: Mix 3 % difference in Strength-Maturity relationships developed from various curing temperatures

Figure 3.40 shows that there is not a significant difference between the Strength-Maturity relationships developed from the 24 °C and 34 °C curing temperatures respectively, whilst the relationships developed from the 34 °C and 44 °C curing temperatures differed more, but never more than 10 %.

It was discussed in Chapter 2 that Fly-Ash is much less temperature sensitive than OPC and Corex Slag. The Fly-Ash content of Mix 2 and Mix 3 can be given as the reason why these mixes responded well to higher temperatures and did not exhibited cross-over behaviour.

3.4.4 Sensitivity of mix calibration

ASTM C 1074 (2011) states that similar mix constituents has to be used for mix calibration as what is used in the in-situ concrete of which the strength estimation has to be obtained. Thus, these standards allow for small changes in the mix design after calibration. However, the extent of these changes is not quantified. To visualize this, the mix calibrations of Mix 2 and Mix 3 were plotted on the same graph and is shown in Figure 3.41. Mix 2 has a w/c ratio 0.65 whilst Mix 3 has a w/c ratio of 0.6. Both mixes have the same proportion of cement to Fly-Ash. Mix 2 has a design strength of 25 MPa and Mix 3 has a design strength of 30 MPa. The mix calibration of Mix 3 was therefore scaled by a factor of $\frac{25}{30}$.

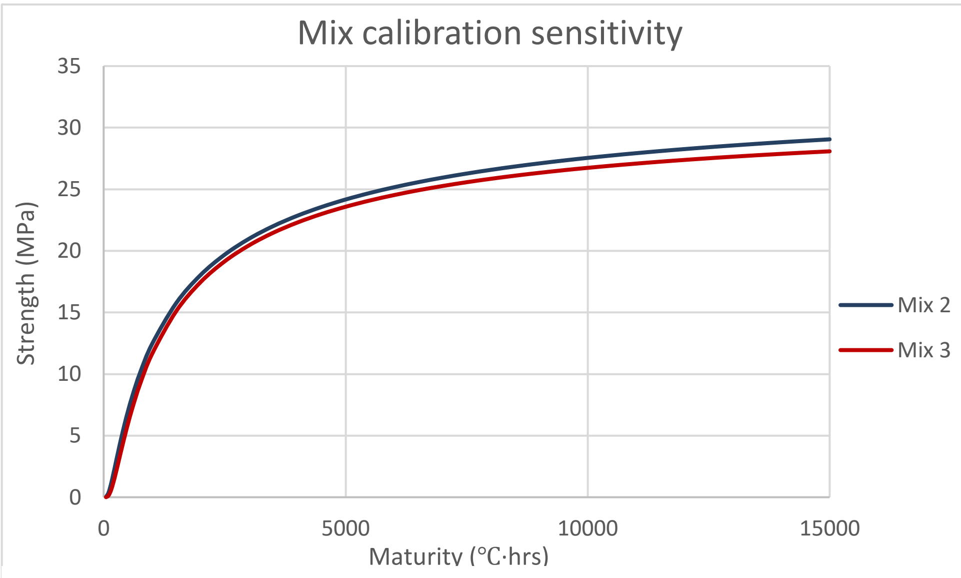

Figure 3.41: Mix calibration sensitivity

Figure 3.41 shows that there is no significant difference between the mix calibrations of Mix 2 and Mix 3 when the mix calibration of Mix 3 is scaled to represent a mix with a design strength of 25 MPa. Even though the two mixes were calibrated by using maturities calculated from different Datum Temperatures values, a good correlation exist between the two mix calibration curves. This indicates that the mix calibration is not very sensitive to changes in the w/c ratio and that at low maturity values, the two mix calibrations describe each other well.

3.5 Conclusion

This chapter explains the methodology that was followed during the laboratory test phase and the results that were obtained. It can be concluded that the Nurse-Saul Maturity function is an easy way to apply the Maturity Method and also yields sufficiently accurate results, especially at early ages. Furthermore, the accuracy of the strength estimation is not greatly influenced by the choice of Datum Temperature.

The exponential model predicted the Strength-Maturity relationship most accurately of the three models that were tested. The logarithmic model was not accurate enough to justify using it in the SmartRock application, as it underestimated early-age strength and overestimated later-age strength.

The results obtained from curing the concrete at three temperatures showed promising results regarding the accuracy of the Maturity Method. The Strength-Maturity relationships developed from the three curing temperatures were sufficiently similar and this implies that the Maturity Method is accurate enough to obtain quality in-situ strength estimations.

Chapter 4

Site Test & Interview Phase

4.1 Introduction

This chapter outlines the process that was undertaken during the site test phase, and the results that were obtained. The test design is given, explaining the objectives of the tests, as well as background on the construction site where the tests were conducted. An explanation is given on installation guidelines that were followed in order to propose best practices for the use of SmartRocks.

4.2 Test design

4.2.1 Objectives

The overarching objective of this phase is to verify the applicability of the use of SmartRocks, and the subsequent use of the Maturity Method, to estimate the early age strength of concrete. To verify the applicability of SmartRocks, the accuracy of the strength predictions provided by the SmartRocks as well as the willingness of individuals in the industry to use SmartRocks in the South African construction industry were investigated.

a) Accuracy verification

The accuracy of the strength predictions provided by the SmartRocks was verified by comparing it to current in-situ concrete strength estimation practices. Cube compressive strengths are widely used in South-Africa to estimate the strength of concrete. Cube tests are commonly done at the ages of 7 and 28 days, but in some instances, the tests are also conducted at 3 days.

The SmartRock sensors were embedded into a slab on a construction site to measure the temperature history of the concrete. A strength prediction was obtained, and this was compared to the results of cube tests performed on the same mix at 3, 7 and 28 days.

b) Applicability of SmartRocks in South Africa

Sufficient accuracy of the SmartRocks to predict in-situ concrete strength will not necessarily ensure that it is widely adopted in the industry in South-Africa. Opinions from individuals in the engineering industry were obtained to determine if the SmartRocks can be applied in the South African engineering industry.

4.2.2 Construction site background

The construction site where the SmartRocks were installed, is for a 11-storey upper income residential development. SmartRocks were already, independent of this research, used by the contractor during the construction of the post-tensioned slabs. The SmartRocks were used to obtain a strength estimation to verify that tensioning could commence.

Various difficulties have been experienced on the site of the 11-storey development. Access to the site was restricted and it was, therefore not possible to use a crane for construction. All the steel reinforcement and formwork had to be carried by the construction workers. Furthermore, the formwork used for casting columns and lift shafts had to be disassembled each time when it was stripped. When a crane is available on site, this formwork only needs to be unclamped from the concrete that has been cast, keeping its form, and then lifted to the next level with the crane. With each of these panels weighing around 80 kg, along with the steel reinforcement that had to carried by hand, many delays were experienced. These delays were however partly absorbed by using the SmartRock sensors and tensioning that could commence earlier (Marais, 2019).

At the time of testing for this research, the slab for the 10th level was being cast. The same concrete mix was used for the steel reinforced slabs, than had been used for the post-tensioned slabs. A mix calibration was, subsequently, available but this mix calibration was verified by further tests. Figure 4.1 shows a view from ground level of the construction site.

Figure 4.1: View of construction site

4.2.3 SmartRock installation

One advantage of the SmartRock sensor is its ease of use brought about by the wireless data logging and transmitting. As discussed earlier, other maturity sensors are dependent on wired thermocouples and data loggers that can be easily damaged during the construction process. Once the SmartRock is cast into concrete and the concrete has been consolidated, it is unlikely that the sensor can be damaged. The SmartRock, however, needs to be protected, to some extent, during casting and compaction.

To ensure that the activation wires of the SmartRocks do not loose contact with each other, the wires are twisted together on both sides of the reinforcing steel. It can happen that concrete seeps in between the wires but twisting the wires multiple times will minimize the chance of the wires losing contact. Figure 4.2 shows the connection of the activation wires and how the SmartRock is installed on the reinforcing steel to hold it in place.

Figure 4.2: Activation wires connection and SmartRock installation

Regardless of how well the activation wires are connected, they can loose contact during compaction, or the sensor's body can be damaged by the concrete vibrator. The sensors were therefore installed close to a column so that the location is known after casting and the compaction close to the sensors be carefully controlled, with the chance of the sensor being damaged minimized. Figure 4.3 shows the proximity of the SmartRock installation location near a column.

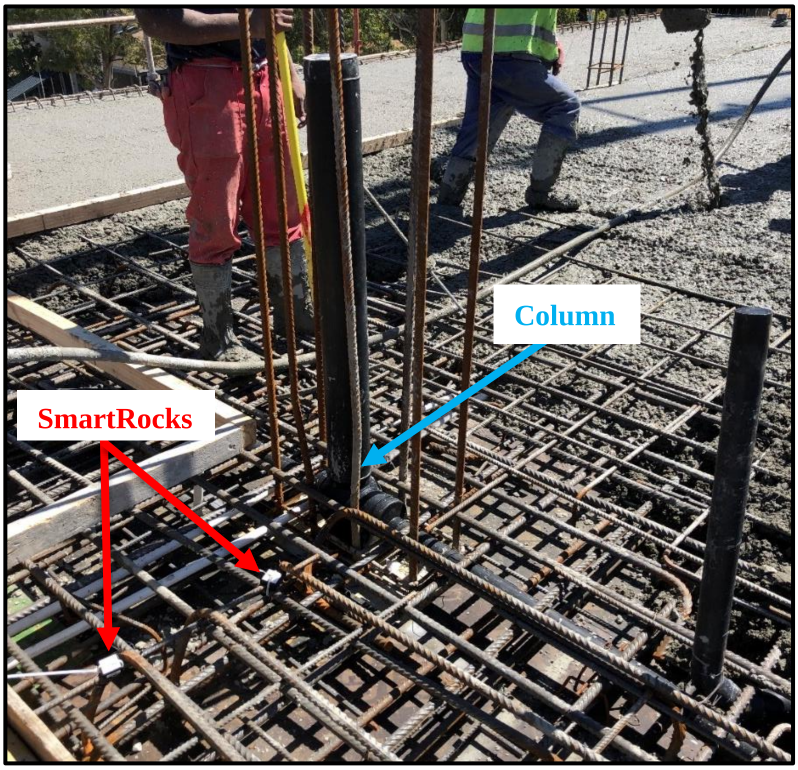

Figure 4.3: SmartRock installation location

To ensure that the sensor is not damaged after it had been fixed to the steel reinforcement and before the concrete has been poured, the sensor was not fixed to the uppermost level of top steel. This minimized the chance of construction workers stepping on the SmartRock before the concrete has been poured. Figure 4.4 shows the installation position of the SmartRock relative to the steel reinforcement. It should be noted, that the installation guidelines issued by the manufacturers of the SmartRock regarding the depth of the sensor was still adhered to. As mentioned earlier, the SmartRock unit should not be installed deeper than 50 mm from the top surface of the concrete. This is to ensure that the sensor can be easily connected to via Bluetooth.

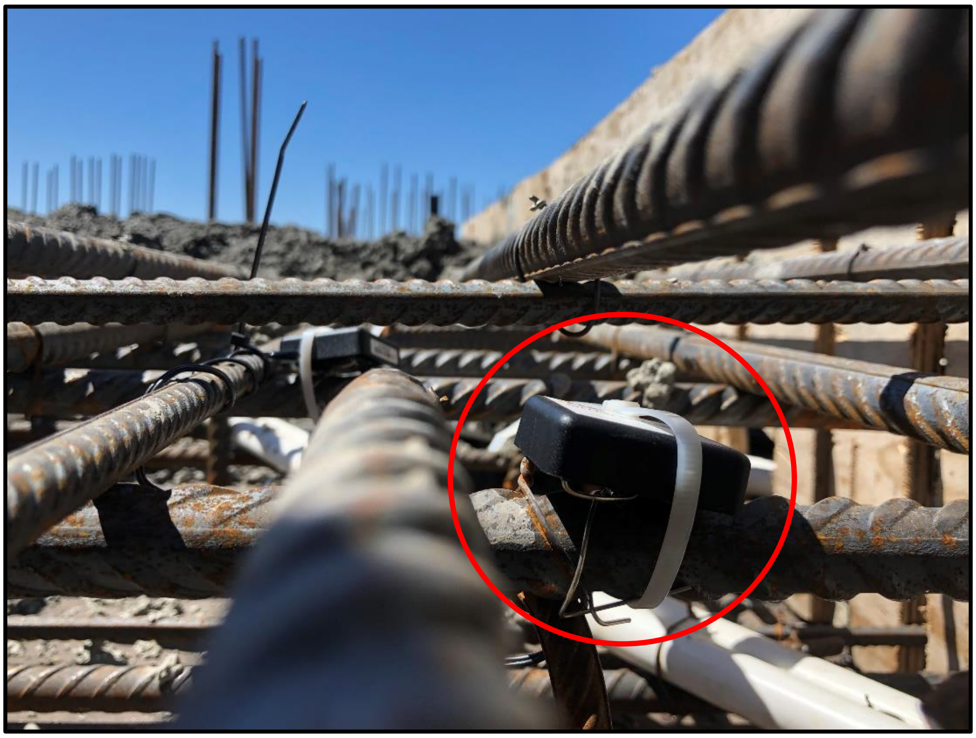

Figure 4.4: Position of SmartRock relative to top steel

Two SmartRocks were fixed in proximity to each other, with the temperature sensors being installed at the top and bottom of the slab respectively, at the same position in plan. This was done to determine the difference in maturity values when it is calculated for the bottom and top of the slab. The depths of the temperature sensors were controlled by fixing the sensor to the top and bottom steel respectively, with cable ties. Figure 4.5 shows how the sensor was fixed to the bottom steel, whilst Figure 4.6 shows how the sensor was fixed to the top steel, but firstly wrapped around the steel to ensure that the wire is not caught on something else during the pouring process.

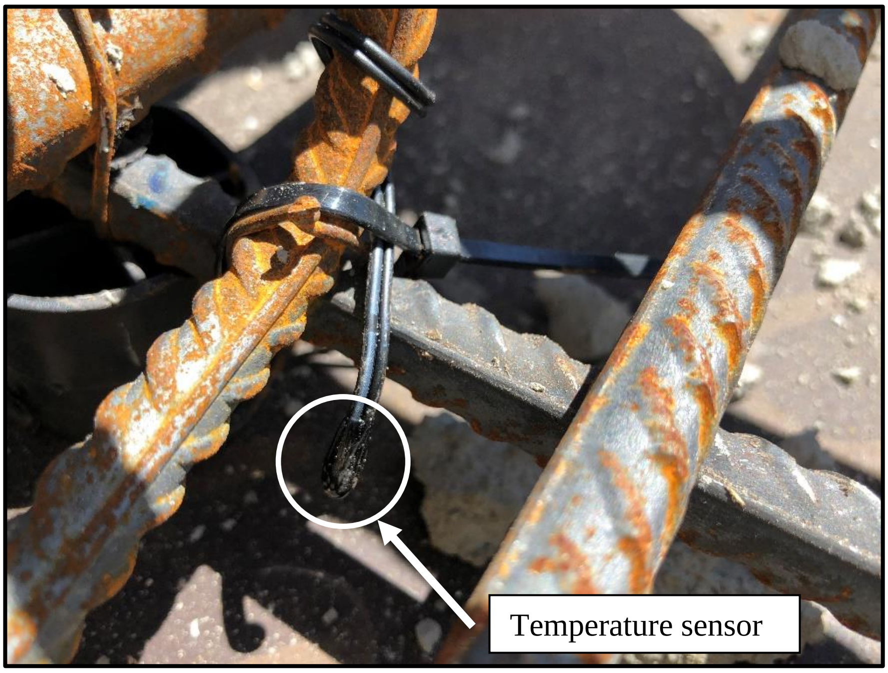

Figure 4.5: Temperature sensor fixed to bottom steel

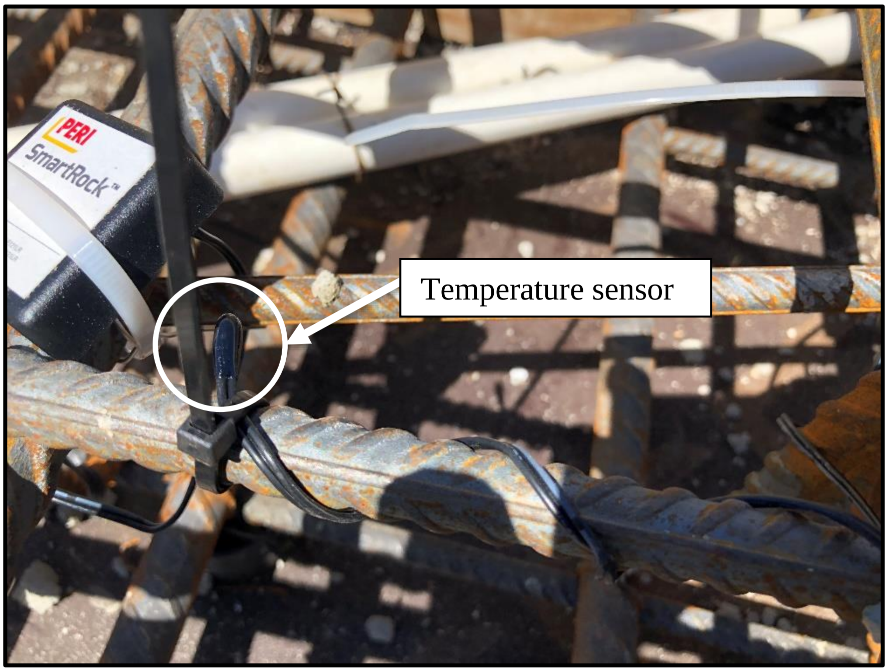

Figure 4.6: Temperature sensor fixed to top steel

4.3 Accuracy verification

To verify the accuracy of the strength estimation provided by the SmartRock, this estimation was compared to strength estimations provided by current techniques. As discussed earlier, the cube compression test is widely used in South Africa as an in-situ concrete strength estimation technique.

Cube tests are performed at 7 days, and 28 days after casting. An additional test at 3 days was be done to compare the 3-day strength with the strength estimation obtained from the SmartRock.

4.3.1 Temperature measurement depths

As discussed earlier, SmartRock sensors were installed at the top and bottom of the suspended slabs to compare the calculated maturity values from the different sensor installation depths. Figure 4.7 presents the percentage difference between the maturity values at the top and bottom of the slab.

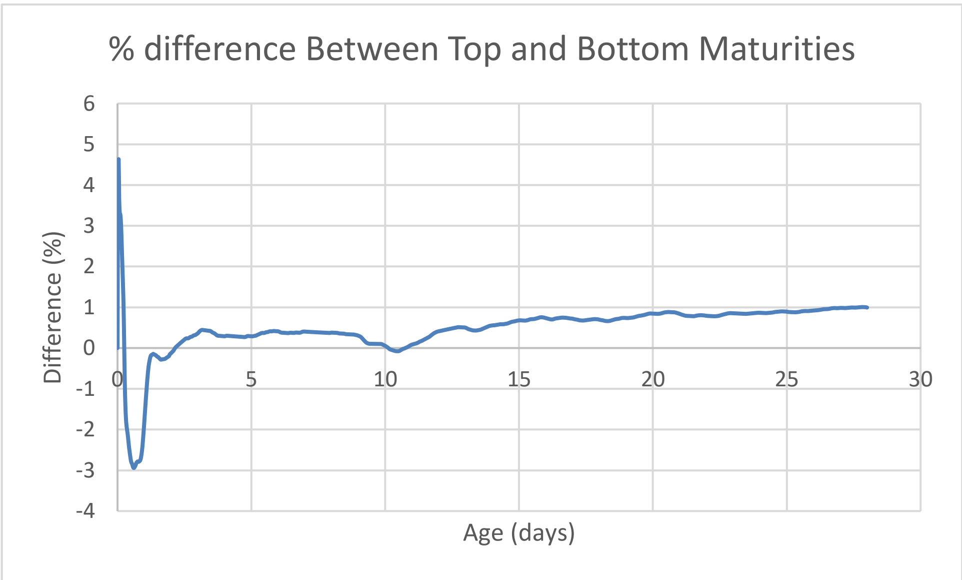

Figure 4.7: % difference between maturities at top and bottom of slab

Figure 4.7 shows that there is no significant difference between the maturities calculated from temperatures measured at the top or bottom of the slab. As an explanation of this finding, the measured temperatures were plotted for the first four days after casting and is shown in Figure 4.8. It should be noted that the concrete casting time (concrete age of zero) was at 14:00.

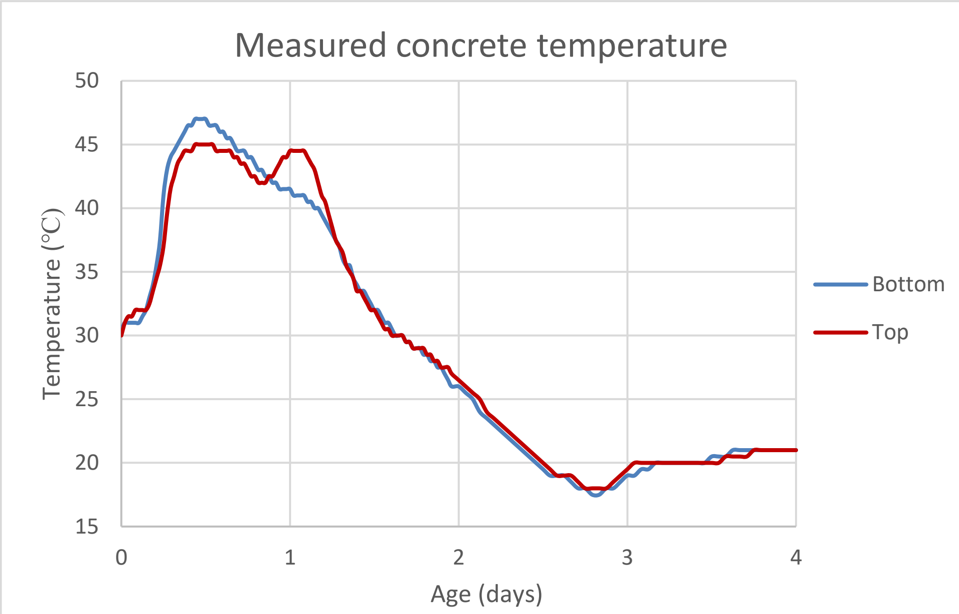

Figure 4.8: Measured concrete temperatures

The first temperature peak was approximately 12 hours after casting (at an age of 0.5 days), at 02:00 in the morning. This could be attributed to the hydration heat of the cement. The bottom of the slab experienced a higher temperature peak due to the insulation effect of the formwork. The initial hydration heat dissipated evenly through the thickness of the slab. One day after casting, the top of the slab experienced a second temperature peak and this could be attributed to the direct sunlight and ambient temperature the top of the slab was exposed to. This heat, again, dissipated quickly through the thickness of the slab. Thus, the temperatures at the top and bottom of the thin slab element, never differed much and this is why the maturities developed at the top and bottom of the slab did not differ significantly

4.3.2 Mix calibration accuracy

A mix calibration had earlier been developed by the contractor when the SmartRocks were implemented during the casting of the post-tensioned slabs. During the research project, another mix calibration was developed on the same concrete mix, with the same process as was followed in the Laboratory Test Phase of this research project. This was done as a verification of the calibration developed by the contractor. The calibration curve is shown for the contractor's data and the verification data in Figure 4.9. The exponential model was fitted to the data.

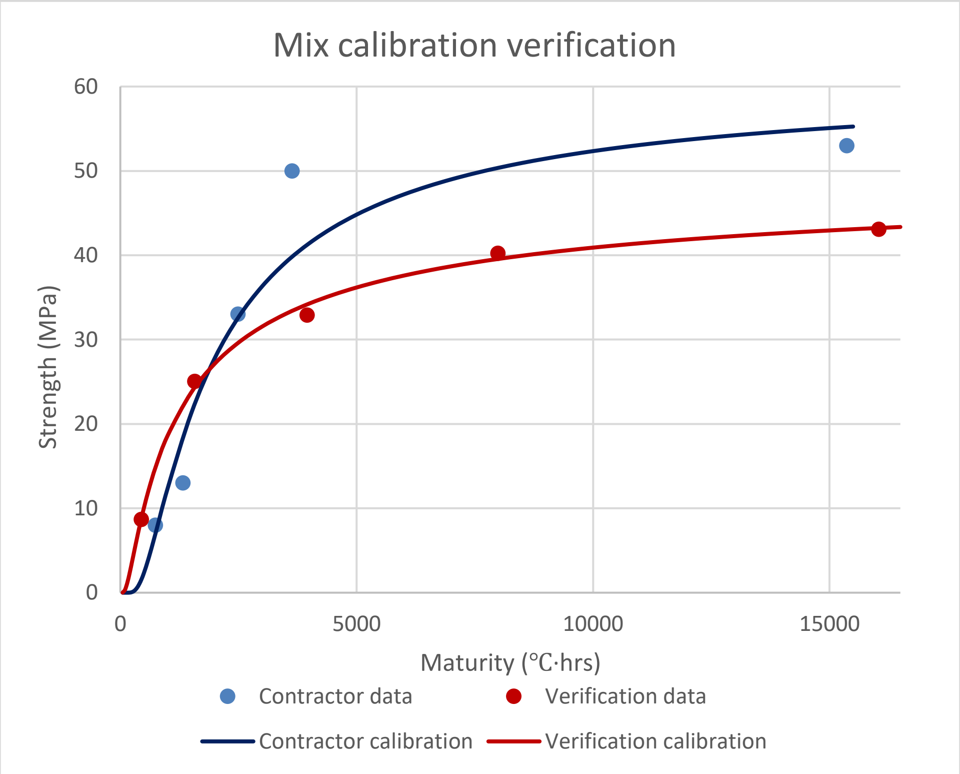

Figure 4.9: Mix calibration verification

Figure 4.9 shows that there is a significant difference between the data provided by the contractor and the verification data developed for this research. It should be noted that the conditions under which the contractor's mix calibration had been developed is not known. The concrete cubes used to develop the verification mix calibration was mixed, cast and cured under controlled conditions, conforming to the standards prescribed in SANS 5863.

When considering the maturity values of the contractor's and verification data, it can be seen that there is a variation in the values. This could potentially be attributed to the cubes that were either not cured at controlled temperatures by the contractor or that the cubes were tested at inconsistent ages. The design strength of the concrete was given as 30 MPa. It is more likely that a 28-day strength of 43 MPa will be obtained, as the verification calibration predicts, than the 53 MPa which the contractor's calibration gives.

An accurate mix calibration is a prerequisite for accurate in-situ strength predictions. From Figure 4.9 it can be concluded that there had not been sufficient control in the development of the contractor's mix calibration and that an accurate mix calibration was not obtained. Thus, there has to be stringent control over the mix calibration process.

Compressive strength tests on cubes are commonly done at 7 and 28 days and when early age strength of concrete is of concern, a test at 3 days is also done. It might seem attractive to do the mix calibration with only these three data points. A regression analysis was done on the three data points (3, 7 and 28 days) to fit the exponential model to the data in order to develop a mix calibration. This was plotted on a graph, along with the conventional mix calibration developed from 5 data points (1, 3, 7, 14 and 28 days). Both these mix calibrations are shown in Figure 4.10.

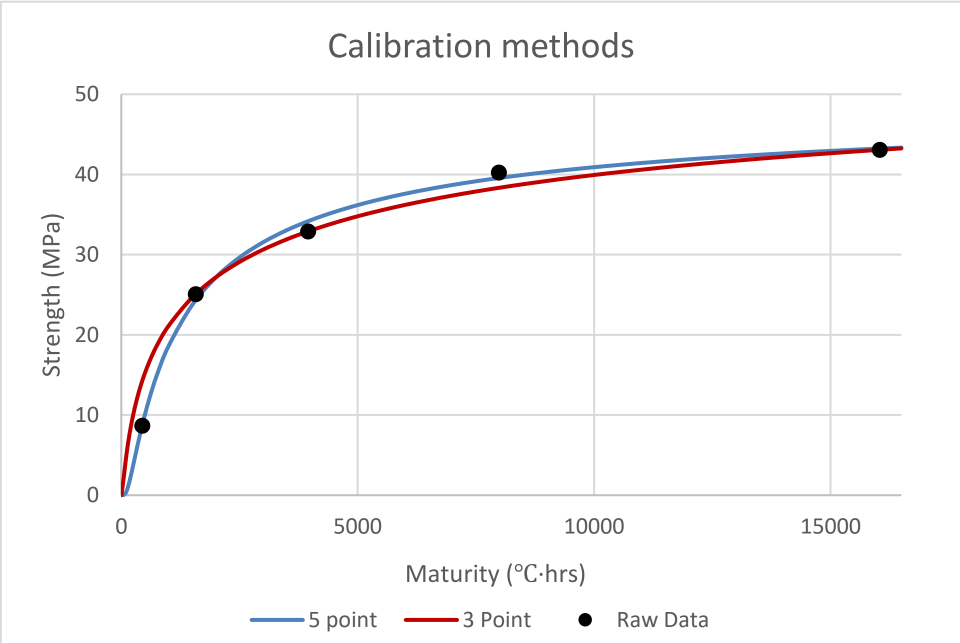

Figure 4.10: Comparison of calibration methods

The percentage difference between the two mix calibrations was also plotted and is shown in Figure 4.11.

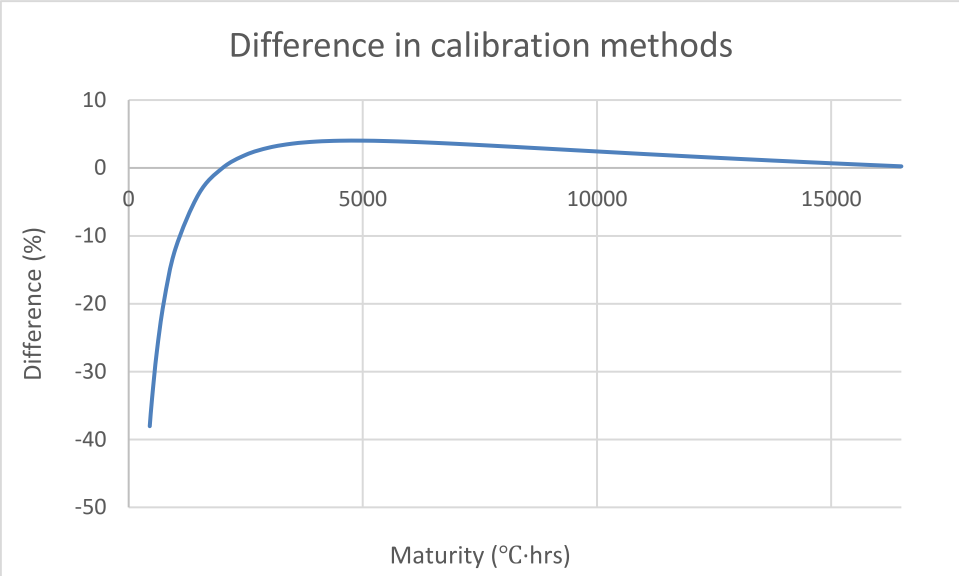

Figure 4.11: Difference in calibration methods

Figure 4.11 shows that the two mix calibrations are very similar at later ages, but for the application of the Maturity Method investigated in this study, accurate early age strength estimations are required. At early ages, these two mix calibrations differ significantly. It is therefore recommended that the mix calibration be developed from 5 data points, as described by the ASTM C 1074 (2011).

4.3.3 In-situ strength estimation accuracy

Concrete cubes were sampled on site and tested at 3, 7 and 28 days, with the in-situ maturity measured at these ages. The compressive strength of the cubes was compared to the strength estimation obtained from the SmartRock at the time of testing. This comparison is shown in Figure 4.12.

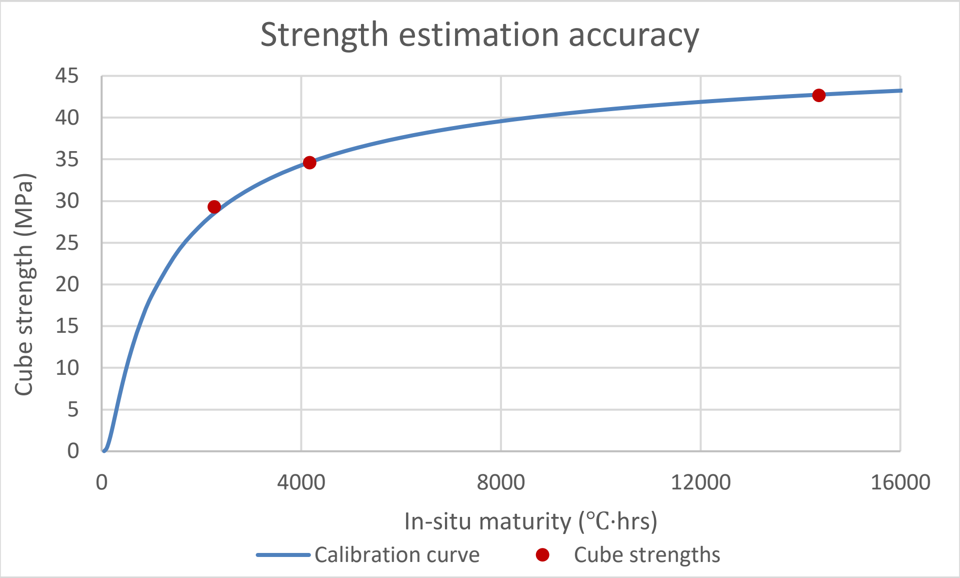

Figure 4.12: Strength estimation accuracy

Figure 4.12 shows that the strengths of the cubes that were cast from the concrete used on site, were accurately predicted by the calibration curve. It should be noted that this was because the maturity developed by the cubes, was similar to the maturity developed by the in-situ concrete. This is purely coincidental and if other weather conditions prevailed, this would not have occurred. The site tests were performed in autumn, but in summer, the in-situ concrete would have developed a higher maturity value and consequently, a higher strength. In winter, on the other hand, the in-situ concrete would have been less mature and would have had a lower strength.

As there was no way to induce the same temperature and moisture conditions on the concrete cubes as what was experienced by the in-situ concrete, the accuracy of the Maturity Method can rather be affirmed by the results obtained from the Laboratory Test Phase. Strength-Maturity relationships were developed from different curing temperatures. It can be assumed that the Strength Maturity developed from the 24 °C curing temperature represents the mix calibration curve, whilst the Strength Maturity developed from the 34 °C curing temperature represents an arbitrary higher temperature that the in-situ concrete was exposed to. These curves did not differ significantly, and it can therefore be concluded that the Maturity Method provides sufficiently accurate results. As a matter of conservatism, the mix calibration can be conducted at a higher temperature, to ensure that any possible cross-over behaviour exhibited by the in-situ concrete is taken into account during the mix calibration. It will therefore be good practice to conduct the mix calibration at the highest temperature than the in-situ concrete will be exposed to.

4.4 Relevance of SmartRocks as obtained from industry feedback

The relevance to implement the SmartRock on South African civil engineering projects was investigated by interviewing industry professionals and obtaining opinions on the associated use of the Maturity Method. A summary of each interview is given in the Appendix whilst the main conclusions of each interview are summarized in this section. Table 4.1 shows a summary of the experience of the professionals with whom interviews were conducted.

Table 4.1: Summary of interviewees experience

Professional	Experience	ECSA registered
Engineer 1	40 years	Yes
Engineer 2	21 years	No
Engineer 3	14 years	Yes
Engineer 4	21 years	Yes
Engineer 5	50 years	Yes
Engineer 6	22 years	Yes
Engineer 7	30 years	Yes
Engineer 8	31 years	Yes
Engineer 9	39 years	Yes
Contractor 1	27 years	No
Contractor 2	25 years	No
Contractor 3	35 years	Yes

It can be seen that the interviewees all had extensive experience, thereby providing important value to the feedback obtained.

Various questions were used as interview guide, and this guide is attached in the Appendix.

4.4.1 Engineer 1

Engineer 1 has 40 years' experience in the Civil Engineering industry. He currently works as a technical director at an international consulting engineering firm. He is registered as a Professional Engineer with the Engineering Council of South Africa, has a Master's degree in civil engineering and a Master's in Business Administration.

- **Lack of competence**

Unskilled labour is used in the South African construction industry. The accuracy of the strength prediction provided by the SmartRock is dependent on proper placement, consolidation and curing of the in-situ concrete and it is not always possible to control this on site. Engineer 1 has been involved in a project where the concrete that was supplied to the construction site, was not the same as the concrete that was specified. It is clear that the strength estimation provided by the SmartRock will not be accurate in this case.

Current strength estimation techniques are lacking. Firstly, the sampling and casting of concrete test cubes are not necessarily carefully controlled. Furthermore, the storing of test cubes prior to testing is also not always controlled and may not be indicative of the conditions experienced by the in-situ concrete. Secondly, the quality of the results cube crushing tests can also be debatable. It has happened before that cube samples from two different concrete mixes - 20 MPa and 30 MPa mixes - were sent to a laboratory for testing and that the results from the 20 MPa mix was as expected, whilst the results from the 30 MPa mix was too low. It was later revealed that the laboratory technician was not aware that the cube samples were from two different concrete batches. He did not test the 30 MPa mix and instead supplemented these results with the results obtained from the 20 MPa concrete.

- **Early formwork removal**

Current guidelines for formwork removal are relatively vague. The SANS 2001 – CC1: 2007 code provides ages at which formwork can be removed for various structural elements and cementitious systems at various weather conditions. These weather conditions are given as "Cold", "Cool" and "Hot or Normal". Temperature ranges are given for these weather descriptions, but these ranges are still too big. The consulting firm that Engineer 1 works for, has however developed procedures for formwork removal based on the SANS codes and their cumulative company experience.

With regards to early removal of formwork on the strength estimation provided by the SmartRock, the Engineer will carry the risk, whilst the contractor will reap the reward. Thus, there is no incentive for the Engineer to allow early removal of the formwork.

- **Merit of SmartRock**

The accuracy of the strength estimate is dependent on the successful implementation thereof and is governed by external factors. Factors include the quality of concrete provided by the ready-mix plant, accuracy of mix calibration, and if the concrete was correctly placed, consolidated and cured. In a project where these factors can be controlled, the SmartRock can prove to be very useful. An example of this, is the MyCiti Bus Rapid Transport project in Cape Town. For this project, a unique pigmented concrete was used for the exclusive bus lanes. The supply of this concrete was therefore carefully controlled and the SmartRock could have been used to open these lanes earlier, even if just for construction traffic.

4.4.2 Engineer 2

Engineer 2 is the manager of a successful precast element supplier.

- **Accelerated curing**

Accelerated curing is widely utilized in the precast concrete element manufacturing process. Steam curing is one of the methods that is used to increase the productivity and speed at which precast elements are manufactured. The methods that Engineer 2 implement are so effective that it has been possible to lift a 65-ton concrete panel 15 hours after it was cast.

As discussed earlier, the Maturity Method does not take the effects of accelerated curing into account. Accelerated curing can lead to the concrete exhibiting cross-over behaviour. Curing conditions on a precast yard is carefully controlled and therefore, the effects of cross-over behaviour can be taken into account by conducting the mix calibration at the same temperatures at which the precast element will be cured. The concrete used for the mix calibration will, hence, exhibit the same degree of cross-over behaviour and the subsequent strength prediction will take the effect of accelerated curing into account.

- **Accuracy of the maturity method**

The mixing, casting and curing of concrete on a precast yard is carefully controlled. For the precast industry to accept the strength prediction provided by the SmartRock as accurate, more tests will have to be done. A sufficient number of tests need to be done, in order for a statistical analysis to be executed. Such an analysis will quantify various statistical parameters and an exceedance probability can be determined to ensure that the SmartRocks are sufficiently accurate.

- **Cost versus benefit of SmartRock**

The current technique for strength estimation utilized by Engineer 2, is curing the cubes under the same conditions as the last precast element cast for the day. This is then taken as a conservative estimate of the strength of all the elements cast for that particular day. It has proven to be accurate, but optimization of curing times can be accomplished through the real-time strength estimation provided by the SmartRock.

Sufficient accuracy of the strength estimation provided by the SmartRock is one prerequisite for the implementation of the sensors in the precast industry. Another criterion for the SmartRock is whether it is financially beneficial for the precast element manufacturers- this needs to be investigated further. It is expected for the price of SmartRocks to decrease, but the benefits of using SmartRocks should be more than the cost thereof. Benefits can include decreased production time and also increased productivity. Another consideration is that even if the precast element is not cheaper when the SmartRock is used, the client might be willing to pay more for each element, if it can be delivered quicker.

4.4.3 Engineer 3

Engineer 3 is the Director of the Structures division for a national consulting engineering firm. The firm has branches in Gauteng and the Western Cape. Engineer 3 is registered as a professional engineer with the Engineering Council of South Africa and has 14 years' experience in the Civil Engineering industry.

- **Effective use of the maturity method**

Engineer 3 does not believe that the use of the Maturity Method needs to be included in the SANS codes. He believes that the SmartRock can be effectively applied within the scope of current standards.

Various human factors can influence the effectiveness of SmartRock. Firstly, the Maturity Method does not take insufficient compaction of the in-situ concrete into account. This, however, is also a limitation of cube crushing tests, currently used for in-situ strength estimation. Engineer 3 feels that concrete suppliers should be responsible for mix calibration, but various incidents have occurred, resulting in engineers losing confidence in the concrete suppliers. Finally, the successful implementation of SmartRocks is dependent on the foreman who supervises the construction work. In South Africa however, the skills available and the quality of supervision is often lacking.

Engineer 3 is willing to implement the SmartRocks in conjunction with cube tests, thereby building confidence in the use of the Maturity Method and doing his own accuracy verification. If the SmartRock proves to be sufficiently accurate, Engineer 3 will start to phase out cube crushing tests.

- **Cost effectiveness of SmartRock**

Engineer 3 believes that the current guideline for the number of cube samples that have to be taken per volume of concrete that is poured can be used in determining the number of SmartRocks that has be installed on site. The current guideline states that a sample, consisting of three cubes, has to be taken for each 50 m^3 that is poured. Currently, SmartRock sensors are still expensive, but at an average rate of R1400 per cubic meter of concrete, one sensor has to be installed for every R70 000 worth of concrete that is poured. The cost of the SmartRock is therefore insignificant when compared to the cost of the concrete.

With the current constrained climate in the civil engineering and construction engineering industry, there is even more pressure on project teams to complete projects quickly and cost effectively. Construction schedules are therefore developed with severe time pressure on the contractors. The effective use of the SmartRock can relieve this pressure and even result in even faster project completion.

Engineer 3 is willing to apply the SmartRock in projects for the estimation of the in-situ strength of concrete, if it can be economically justified to the client. Engineer 3 believes that the client will not authorize the use of SmartRocks if it only has more effective and accurate strength estimation as a result. There must be a cost saving transferred to the client. However, Engineer 3 strongly believes that there will be a cost saving from effective formwork use, expedited project completion, which results in reduced Preliminary and General costs, and earlier site handover.

Engineer 3 feels that it is very important to move forward, by implementing innovative tools like the SmartRock. As soon as one starts to stagnate in an industry, you are effectively falling behind. The SmartRock can act as a marketing tool for engineers, contractors and ready-mix suppliers.

4.4.4 Engineer 4

Engineer 4 is the Managing Director of a regional consulting engineering firm. Engineer 4 has 21 years' experience in the Civil Engineering industry and is registered with the Engineering Council of South Africa as a professional engineer

- **Effect of inconsistent concrete supply**

Engineer 4 has been involved in a project where the concrete that was supplied, was not performing adequality. Upon inspection, Engineer 4 could visually identify defects in the concrete which indicated that the concrete did not achieve the required strength. The concrete was tested, and it was determined that the concrete reached half of the design strength. Engineer 4 does not have a reason for why this happened, but he suspects that it as a result of a mistake in the mixing or supply of the concrete. Using SmartRocks in a scenario where the mix calibration is not applicable to the concrete that is provided on site, will lead to incorrect strength estimations.

Another project where Engineer 4 was involved in, was the casting of apron slabs of an airport. For the duration of this project, a concrete batch plant was established on site. The supply of the concrete was therefore internally controlled. For a project where an external concrete supplier is not used, an uncertain external variable is converted to a controlled constant. One could be certain that the mix calibration is accurate and applicable to the particular concrete mix. Engineer 4, further feels that when using an external concrete supplier, the supplier should be responsible for the mix calibration. The concrete supplier will not necessarily reap any direct financial rewards, but providing a mix calibration for a concrete mix, can act as a marketing tool and will imply that the concrete supplier has confidence in the product that is provided.

- **Standards and skills**

The accuracy of the current technique for in-situ strength estimation- the cube crushing test- is often lacking. Standards exist which specify the procedure for sampling, casting, curing and testing concrete cubes, but the skills are not necessarily available to implement these standards effectively. A limitation of the Maturity Method is that it does not take insufficient compaction of the in-situ concrete into account, but concrete cube samples also do not take this into account. Furthermore, because skills to sample and cast the cube samples are often lacking, these cubes do not necessarily provide an accurate representation of the in-situ concrete.

The effective use of SmartRocks to obtain accurate strength estimations on site, is dependent on stringent standards and rigorous control thereof- from the mixing of concrete to the installation of the sensor on site. Engineer 4 believes that the use of the Maturity Method should be included in the SANS codes, because the South African Civil Engineering industry requires innovation. Furthermore, he believes that until the use of the Maturity Method is ratified in the SANS codes, the use thereof can be included in the project specifications.

- **Early formwork removal**

Engineer 4 has been involved in a project where an apartment complex with a basement level and 3 stories, was developed for student accommodation. Construction commenced in February and site handover was in November. Thus, there was a lot of time pressure on the project. One of the tools that can be used to relieve this pressure, is early formwork removal. The use of SmartRocks could have facilitated the in-situ strength estimation in order to optimize the formwork removal.

4.4.5 Engineer 5

Engineer 5 is a semi-retired senior consultant for a regional consultancy firm. Engineer 5 is registered with the Engineering Council of South Africa as a professional engineer and has close to 50 years' experience in structural engineering. He has been involved in numerous projects where reinforced and post-tensioned concrete was utilized for high-rise buildings and large retail centres.

- **Confidence in the use of SmartRock**

  Engineer 5 feels that the current in-situ strength estimation technique of cube crushing is not controlled sufficiently and that there is too much variation. He feels that the use of the SmartRock can be controlled more carefully than taking cube samples. The accuracy of the subsequent strength estimation is however dependent on an accurate mix calibration. According to Engineer 5, concrete suppliers should be responsible for mix calibration, as they are the concrete specialists. They also have the resources to develop the mix calibration accurately and at a very little cost.

  Control should be exercised during the mix calibration and also during the installation of the sensor. To achieve this control, Engineer 5 believes that the use of the SmartRock should be included in the SANS standards so that it is governed to the same extent as the cube crushing test. The use of SmartRocks will not be widely adopted until it is included in the SANS standards.

  Until such time when the use of the SmartRock is ratified in the SANS standards, Engineer 5 will be willing to implement the use of SmartRocks in conjunction with cube crushing tests. This will be done to develop confidence in the use of the Maturity Method as an in-situ strength estimation technique. If this method proves to be sufficiently accurate, the use of cube crushing tests can be phased out.

4.4.6 Engineer 6

Engineer 6 is a Principal Structural Engineer for a national consultancy firm. The firm has multiple offices in South Africa. Engineer 6 is registered with the Engineering Council of South Africa as a Professional Engineer and has 22 years' experience in the civil engineering industry.

- **Optimal application of SmartRocks**

According to Engineer 6, it is common that there is pressure to remove formwork earlier during the construction of a multi-story structure. Early removal of formwork can lead to significant cost and time savings. Post-tensioned slabs are becoming more apparent in construction of residential structures, because of the quick construction time associated with early removal of formwork.

The standards which govern the removal of formwork for post-tensioned slabs are based on the concrete strength, whilst the standards which govern the removal of formwork for reinforced concrete slabs, are based on the concrete curing time. It is for post-tensioned slabs, where a certain strength has to be obtained before the formwork can be removed and the tendons can be tensioned, that an accurate early-age strength estimation can be very useful. The SmartRock is a convenient way to obtain this estimation.

The risk associated with removing the formwork of a reinforced concrete slab prematurely, is that the long-term deflections can increase beyond acceptable limits. This can be mitigated by responsibly removing formwork and installing backprops. Furthermore, as the formwork is part of the curing system, removal thereof can lead to unfavourable curing conditions and ultimately, a lower strength. Care, therefore, has to be taken to ensure the slab is cured properly when the formwork is removed earlier. Engineer 6, however believes that there is still a degree of forgiveness when removing formwork outside of the scope of the standards, but this requires the supervision of a competent person, as the standards are not quantitively based on a concrete strength.

Post-tensioned slabs, on the other hand, can be stripped and tensioned when the concrete has reached 18 MPa. One of the most apparent risks associated with early tensioning is that the anchors may damage the concrete and that the overall effectiveness of the post tensioning is reduced. Unlike with a reinforced concrete slab, this risk does not have to be mitigated on site by a judgement call from a supervisor. It can be mitigated by providing an accurate mix calibration with which accurate strength estimations can be obtained.

- **Responsibilities of the contractor and the engineer**

Engineer 6 feels that there are clear boundaries between the responsibilities of the contractor and the responsibilities of the engineer. It is the engineer’s responsibility to verify that the 28-day strength that was designed for, is achieved. The engineer is, thus, only interested in the final product. The contractor, on the other hand, is responsible for all the temporary work during construction. This includes the erecting and removal of formwork. It is not the engineer's responsibility to determine the formwork removal time, but rather the contractor's. To ensure that this is done responsibly, standards were developed to prescribe the formwork removal times.

Engineer 6 feels that there is a continuous reduction of knowledge and skills in the construction industry and that if freedom is given to a contractor regarding formwork removal, it will not be responsibly done. There are, however, competent contractors who would be able to effectively apply the SmartRock and it is these contractors that will remove formwork responsibly, and backprop and cure effectively.

Engineer 6 will, however, not prescribe the use of the SmartRock. He believes that the suggestion to use SmartRocks, should come from the contractor. This is because the contractor is responsible for formwork removal and he will have to carry the responsibility of effectively implementing the SmartRock, but he will also reap the reward of using the sensors.

4.4.7 Engineer 7

Engineer 7 has 30 years' experience in the civil engineer industry and has been involved in a wide range of structural engineering projects and also has international experience as an Engineering Manager. He is the director of a successful consultancy firm and is registered as a Professional Engineer at the Engineering Council of South Africa.

- **Drive to use SmartRock**

Engineer 7 believes that even though the SmartRock can lead to a significant cost saving through the efficient removal of formwork, the client will not be willing to carry the extra cost of the sensors. A solution to this, is for the contractor to make the decision to use the sensor. The contractor will carry the cost of using the SmartRock, but any cost saving will be directly allocated to him.

Engineer 7, further believes that he will not drive the use of the sensor from the designer's side, because of the aforementioned reluctance of the client to incur extra costs. He will, however, have no reservations to the use of SmartRocks if the contractor does decide to implement the sensors, provided that accurate strength estimations are obtained.

According to Engineer 7, the use of post-tensioned slabs is becoming more apparent and it is for post-tensioned slabs, that the use of SmartRocks will have the biggest impact. Engineer 7 has adapted current standards for post-tensioning in winter, because he has been involved in a project where tendons were tensioned prematurely. The cube samples had developed a strength of 18 MPa, but the in-situ strength had not developed the same maturity as the concrete cubes due to the lower ambient temperatures on site. The SmartRock will take these lower temperatures on site into account.

- **SmartRock as an accountability tool**

Accurate strength estimations are dependent on accurate mix calibrations and Engineer 7 believes that there has to be stringent requirements to ensure that the mix calibration is accurate and relevant to the mix that is supplied on site. This is because currently, the designer is only interested in the design strength, but using the Maturity Method, the strength development of the design strength is of concern.

Engineer 7 feels that the concrete ready-mix suppliers should be responsible for the mix calibration and that the provision of a mix calibration can act as a marketing tool for the ready-mix suppliers by giving them a competitive advantage.

According to Engineer 7, SmartRocks can serve as an additional accountability tool through the data that it provides. The temperature data can indicate whether the heat of hydration is consistent with the mix that was specified, whilst it can also indicate whether the contractor has cured the concrete sufficiently.

4.4.8 Engineer 8

Engineer 8 has 31 years' experience in the Civil Engineer industry. He has been involved in various projects, ranging from office blocks to sports stadia. He is registered as a Professional Engineer at the Engineering Council of South Africa.

- **Advantage of SmartRock**

Engineer 8 believes that the current strength estimation technique of cube tests does not provide sufficiently accurate in-situ strength estimations. The cube tests are cured under controlled conditions and does not take site conditions into account. It is, however, the only current strength estimation technique that Engineer 8 will accept, with other techniques, like the Schmidt hammer, providing strength estimations with too much variability.

Engineer 8 will accept the strength estimation provided by the SmartRock sensors. The use of SmartRocks can optimize formwork removal, but Engineer 8 believes that SmartRocks will provide the biggest advantage in the construction of post-tensioned slabs, when multiple levels are being constructed.

- **Implementation of SmartRock**

Engineer 8 does not believe that the use of SmartRocks will be widely adopted for simple projects, but he will specify the use thereof for specialized projects where accurate strength estimations are necessary. This is because of the SmartRock's capability to monitor site conditions. He further believes there is room for the use of SmartRocks to be included in the SANS standards.

The successful implementation of the SmartRock is dependent on the skills level of the contractor. The contractor needs to take responsibility for this, but the use of SmartRocks can also be advantageous to him. It can give him a competitive advantage over other contractors as it will have an overall advantage for the project.

Engineer 8 believes that the concrete supplier should be responsible for the mix calibration. As the accuracy of the strength estimations that is provided by the SmartRock, is dependent on the quality of the mix calibration, the concrete supplier should also recognize the advantage of SmartRocks for him. The construction industry has gradually lost confidence in the concrete suppliers with wrong concrete being supplied on site and the concrete suppliers reserving the right to change mix constituents without prior notice. If the concrete supplier is prepared to provide the contractor with accurate mix calibration, the contractor can also be sure of the quality of the concrete that is provided. This can restore confidence in the concrete supplier and also provide him with a competitive edge.

4.4.9 Engineer 9

Engineer 9 has 39 years' experience in the Civil Engineer industry. He is registered as a Professional Engineer at the Engineering Council of South Africa.

- **SmartRock as an additional control mechanism**

Engineer 9 believes that the SmartRock sensors can act as an additional quality control mechanism. He has been involved in a project where the concrete cubes failed, where a potential course of action, was to redo an entire slab. The concrete cubes are, however, only an indication of concrete strength and not an accurate representation of the in-situ concrete strength, with variability in curing and compaction playing a role in the in-situ concrete strength and the skills of the contractor, determining the quality of the concrete cube. The SmartRock provides an accurate alternative to other techniques that are used to verify the cube strength, such as the Schmidt hammer. SmartRocks can, furthermore, be used to identify unsatisfactory hydration behaviour, where current techniques cannot accomplish this.

The use of SmartRocks should be beneficial from a cost perspective. Engineer 9 feels that the sensor is currently too expensive to be widely adopted in the industry, but he believes that the more it is used, the cheaper it will become, up onto a point where it is cheap enough to be widely adopted. Initially, the SmartRock can be implemented in conjunction with cube tests, after which the use of concrete cubes can be phased out completely.

- **Drive to use SmartRocks**

Engineer 9 believes that concrete suppliers should be responsible for mix calibration. He further believes that concrete suppliers are in the optimal position to drive the implementation of SmartRocks in the industry. They have the capacity to develop good quality mix calibrations and also to verify the accuracy of the strength estimations. With this they can develop a database with which the use of SmartRocks can be further optimized and motivated.

The drive to use SmartRocks can act as a marketing tool for concrete suppliers and re-instill confidence that the industry has lost in the recent past. If concrete suppliers drive the use of SmartRocks, contractors will start to implement SmartRocks and develop confidence in the use thereof and successful implementation by the contractor will lead to engineers widely specifying the use of SmartRocks.

4.4.10 Contractor 1

Contractor 1 has 27 years' experience as a site agent. He currently works for a reputable multi-national construction firm as a site agent on the expansion of a retail development.

- **Cost-benefit of SmartRock**

Contractor 1 feels that engineers are often over-conservative with regards to formwork removal. Engineers commonly do not allow contractors to remove formwork for suspended slabs earlier than 7 days after casting. Thus, weather conditions, as given by current formwork removal specifications, are not taken into account. Therefore, there is room within the current guidelines, to optimize formwork removal. Earlier formwork removal can lead to significant cost savings through reduced formwork rental, and preliminary and general costs.

Currently, the SmartRock sensor is still too expensive to implement. Contractor 1, however feels that the sensor will get cheaper as it gets implemented more widely. To achieve this, there has to be a cost saving in comparison with current techniques.

- **Monitoring capability of SmartRock**

Contractor 1 feels that the SmartRock is an improvement to current strength estimation techniques. Concrete cubes do not take site conditions into account when estimating concrete strength, whereas the SmartRock does take site conditions into account. Concrete cubes often do not accurately represent the concrete strength, as the process for sampling, casting, curing and testing cannot always be carefully controlled.

Contractor 1 has been involved in projects where the sand used in concrete was contaminated and this retarded the strength development of the concrete. The temperature data provided by the SmartRock, can lead to early identification of unsatisfactory hydration behaviour.

Contractor 1 believes that the SmartRock application will streamline communication between the contractor and engineer. The SmartRock application can give access to the data of all the sensors that are installed on a site. Contractor 1 feels that current techniques are lacking and causes unnecessary delays.

4.4.11 Contractor 2

Contractor 2 has 25 years' experience as a site agent. He currently works for a reputable multi-national construction firm as a senior site agent on a high-profile commercial development.

- **Current formwork removal practice**

Contractor 2 believes that engineers are often over-conservative with regards to formwork removal, as the engineers often revert to a formwork removal time of 7 days after casting, and do not allow contractors to remove formwork earlier, regardless of the weather conditions. The process of formwork removal is the responsibility of the contractor, according to the SANS codes, but contractors often rely on guidance provided by the engineer as to when the formwork can be removed and engineers then, default to the 7 days removal time.

Engineers stringently applies this removal time due to questionable competency level of many contractors. When formwork removal is not executed correctly and the slab is not backpropped sufficiently, which is quite common, the slab can be subjected to increase deflections, that can lead to serviceability problems.

- **Potential early formwork removal**

Contractor 2 is currently a senior site agent on a project which required expedited project completion. The project is the construction of a 21000 m^2 commercial development. It is expected that the project will be completed 2 months before schedule.

The expedited project completion was partly due to earlier removal of formwork. The suspended slabs were cast in hot weather and most of the slabs' formwork were removed after 4 days. Cube crushing tests were conducted at three days to verify the concrete strength. The engineer was mindful of the advantages of earlier removal of formwork, taking weather conditions into account in the decision to remove formwork and not blindly defaulting to a 7-day formwork removal time. The contractor, however, was also experienced and skilled enough to execute this formwork removal correctly and effectively.

Contractor 2 believes that the SmartRock is currently too expensive to implement widely on a construction site. He, however, also believes that there is merit in the SmartRock, as the industry is always looking for technological advancements. The SmartRock can act as a tool for engineers to be more certain of the strength of in-situ concrete, which can lead to over-conservative engineers being more mindful of earlier removal of formwork.

4.4.12 Contractor 3

Contractor 3 is an experienced Construction Professional with close to 35 years' experience. He has worked as a Managing Director of a multi-national construction company and is currently the CEO of a national construction company. He is registered as a Professional Engineer with the Engineering Council of South Africa and has a Master's degree in construction management.

- **Increased information**

Contractor 3 believes that there is often pressure to remove formwork earlier, in the case of reinforced concrete slabs and to stress earlier, in the case of post-tensioned slabs. The decision to stress, is usually based on concrete cube results. It is important to know what the strength is at certain defined location and these strength estimations need to be accurate.

According to Contractor 3, the engineer will dictate when formwork can be removed. If the contractor can prove that the concrete has achieved sufficient strength, the engineer will accept the removal of formwork. The SmartRock can provide this strength estimation, in real time with an acceptable accuracy. Contractor 3 will experimentally implement SmartRocks.

Contractor 3 believes that the SmartRock will provide information which has not been available in the past, thereby identifying problems that may not have been identified with current methods. The contractor and engineer might be in a position where they do not know how to deal with the available information. This increased information need to be carefully managed and utilized effectively.

- **Concrete suppliers**

Based on experiences that Contractor 3 has had with concrete suppliers, he does not have confidence in concrete suppliers. Contractor 3 will delegate the mix calibration to a third party. Contractor 3 has been involved in a project where the concrete works had to be demolished due to the concrete not gaining sufficient strength. This had severe cost and time implications for the contractor.

He believes that contractors have the skill to use the SmartRock effectively on site and where the successful implementation of SmartRocks can be jeopardized, is with the mix calibration.

4.5 Conclusion

This chapter explains the methodology that was followed during the Site Test Phase, as well as the results obtained from these tests. Sensors were cast into a slab on the construction site of an 11-storey residential development. A background of the construction site is given. A number of best practices for the installation of the SmartRock sensor is given.

Sensors were cast into the slab at the same position, in plan, at the top and bottom of the slab to determine if there is a discrepancy in the maturities developed at these measurement locations. There was no significant difference between the maturities developed at the top and bottom of the slab.

SmartRocks were used by the contractor, independent of the research conducted in this project, during the construction of post-tensioned slabs. A mix calibration was developed by the contractor and another mix calibration was developed for the research, as a verification of the contractor's mix calibration. These calibration's differed significantly. It is not known under what conditions the contractor's calibration was executed, but the calibration that was done for the researched adhered to the standards specified in ASTM C 1074. This served as an illustration that special attention should be given to the mix calibration process, as it directly influences the quality of the in-situ strength estimation.

A few major conclusions can be made from the interviews with the industry professionals. Current techniques used for in-situ strength estimation are lacking, as it does not take site conditions into account. The majority of the industry professionals also feel that the concrete suppliers should be responsible for mix calibration. The required skills to implement SmartRocks are available in the South African construction industry. The contractors have to identify the advantage that the use of SmartRocks provides them and apply themselves to successfully implement SmartRocks.

Chapter 5

Conclusions and Recommendations

5.1 Introduction

This chapter outlines the various conclusions that can be drawn from the tests conducted in the Laboratory Test Phase and the Site Test Phase. During the laboratory test phase, concrete cubes from 3 mixes were tested to determine their compressive strength. These cubes were cured at three temperatures and Strength-Maturity relationships were developed for the three curing temperatures. During the site test phase, SmartRock sensors were installed in a suspended reinforced concrete slab of an 11-storey residential structure.

A summary is given of the information gathered from the interviews that were conducted with industry professionals. Conclusions are then given in terms of the Aims and Objectives identified in Chapter 1. Recommendations for further study are also given.

5.2 Effect of variable curing temperatures during mix calibration

The effect of variable curing temperatures was determined by curing sets of cubes at different temperatures and developing Strength-Maturity relationships for the different curing temperatures. The ASTM C 1074 standard which specifies the use of the Maturity Method states that the cubes used for mix calibration should be cured between 22℃ and 24℃. Thus, higher temperatures experienced on site, which may result in cross-over behaviour, is not taken into account.

Mix 1 was temperature sensitive and hence, there were discrepancies between the Strength-Maturity relationships developed from the different curing temperatures. There was, however, never a difference larger than 10% between the Strength-Maturity relationships developed from the 24 ℃ and 34 ℃ curing temperatures. The 44 ℃ curing temperature resulted in lower strengths. It should be noted that this discrepancy is conservative as it is unlikely that in-situ concrete will experience such high temperatures for an extended period of time.

Mix 2 and Mix 3 were much less temperature sensitive due to the Fly-Ash content of these mixes. The Strength-Maturity relationship developed from the different curing temperatures were more similar than the Strength-Maturity relationship developed for Mix 1.

Although there is not a significant effect of variable curing temperatures on the Strength-Maturity relationship, this process can be refined. It is recommended that, once a knowledge base is developed on in-situ concrete temperatures under various prevailing weather conditions, these temperatures be simulated in the mix calibration process. The Strength-Maturity relationship will therefore be a better representation of in-situ strength gain. As an initial measure of conservatism, the mix calibration can be conducted at the highest temperature that the in-situ concrete will be exposed to. This will ensure that any potential cross-over behaviour exhibited by the in-situ concrete is taken into account

5.3 Relative accuracy of Maturity Functions

To develop the Strength-Maturity relationships, the maturities were calculated from the concrete's temperature histories using two maturity functions, the Nurse-Saul and Arrhenius maturity functions. The Nurse-Saul maturity function requires a Datum Temperature as an input constant, whilst the Arrhenius maturity function requires an Activation Energy as an input constant. Various recommendations are given in literature for these values and these recommendations were evaluated in this study.

The Nurse-Saul maturity function calculates the maturity value as a temperature-time product (°C·hrs) whilst the Arrhenius maturity function calculates the maturity value as equivalent age (hrs). To compare these two maturity values, the Nurse-Saul maturity value was converted to equivalent age using an Age Conversion Factor. The maturity values calculated from the two maturity functions were similar for the three mixes that were investigated, whilst there was also no significant difference between the Strength-Maturity relationships that were developed. From this it can be recommended that the Nurse-Saul maturity function rather be used for the practical application of the Maturity Method. The Nurse-Saul maturity function is deemed simpler to apply and it is easier to visualize the concept of a Datum Temperature than it is to visualize an Activation energy.

The Nurse-Saul maturity function was not sensitive to changes in Datum Temperature. Selecting a smaller Datum Temperature value, resulted in a constantly larger maturity value being calculated. It should be noted that the choice of Datum Temperature only impacts the maturity calculation when the concrete temperature falls below this temperature. Therefore, during mix calibration, the choice of Datum Temperature will not influence the mix calibration accuracy. The same Datum Temperature as was used for the mix calibration, however, needs to be used for the in-situ maturity calculation. It is with the in-situ maturity calculation, that the choice of Datum Temperature is important. It should be noted that it is non-conservative to choose a smaller Datum Temperature as strength gain may be erroneously assumed under low temperatures.

It should further be noted that the low temperatures that will cause concrete to cease strength development are not as common in South Africa, as in the Northern Hemisphere where the Maturity Method was developed. It is recommended that the Datum Temperatures are estimated from Table 2.1. If the mix design is not within the scope of the values provided in Table 2.1 so that the Datum Temperature can be interpolated, a conservative value of 10 °C can be used for OPC/CS blends and 5 °C for OPC/FA blends. For regions where temperatures below the estimated Datum Temperature can be expected for extended periods, an accurate Datum Temperature can be experimentally determined with the process outlined in ASTM C 1074:2011.

5.4 Most applicable strength prediction model

Three strength prediction models were investigated in this study. The models were logarithmic, hyperbolic and exponential models respectively. The logarithmic model is incorporated into the SmartRock application where the strength-maturity datapoints can be used in the application, which will in turn, execute the regression analysis and calculate a Strength-Maturity relationship. The in-situ maturity is calculated by the application with the strength estimation being provided in real time, based on the calculated Strength-Maturity relationship. It is, therefore, very convenient to use the logarithmic model. In this study, it was found that the logarithmic model does not accurately predict the concrete strength development. The logarithmic model underestimates early-age strength and overestimates later-age strength.

The hyperbolic model was more sensitive to changes in the strength gain rate at early and later ages and predicted the strength development more accurately. The exponential model was the most accurate and predicted early-age and later-age strength development accurately.

It is recommended that the exponential model be used to predict the Strength-Maturity relationship. With the spreadsheet developed in this study, the regression can be easily executed to develop the Strength-Maturity relationship. The in-situ maturity calculated by the SmartRock application can be used in this relationship to obtain an in-situ strength.

If it is decided to use the logarithmic model, based on its ease of use, care has to be taken and the user should be knowledgeable in order to identify the point where the model starts to overestimate the in-situ concrete strength.

5.5 Guidance for use of SmartRocks on site

A Project Specification for the use of SmartRocks on site was developed and is given in the Appendix.

5.5.1 Good practice for installation

A number of good practices were identified to ensure that the sensor effectively measures temperature:

- Twist activation wires together on both sides of the reinforcement.
- Fix the sensor body onto the second level of reinforcing steel to minimize the risk of the sensor being stepped on and damaged.
- Twist the temperature sensor around reinforcing steel to control the measuring location.
- Install the sensor close to a column so that compaction close to the sensor can be easily controlled and an approximate location of the sensor is known, after the concrete has been cast.

5.5.2 Measurement depths

SmartRock sensors were installed at the same location in plan, at the top and bottom of the slab. The calculated maturity value did not differ by more than 1% at 28 days. This could be attributed to a combination of the top of the slab being exposed to direct sunlight in the day, but also cooling down faster at night and the slab being insulated at the bottom by the formwork.

5.6 Accuracy of the in-situ strength estimations

The accuracy of the strength estimations provided by the SmartRock is dependent on two factors. The first is the accuracy of the Maturity Method, whilst the second is the accuracy of the mix calibration to predict the in-situ concrete strength

5.6.1 Accuracy of the Maturity Method

The accuracy of the Maturity Method was verified in the Laboratory Test Phase by curing concrete cubes at different temperatures. These cubes were tested at 1, 3, 7, 14 and 28 days with the maturity being calculated at these ages. The exponential model was fitted to this data and Strength-Maturity relationships were, hence, developed for three different curing temperatures.

The different curing temperatures simulated an arbitrary different temperature that in-situ concrete may be exposed to in comparison with the temperature at which the concrete mix is calibrated. This determined the extent of cross-over behaviour exhibited at different temperatures.

As discussed earlier, there were discrepancies in the Strength-Maturity relationships developed from the different curing temperatures. Despite these discrepancies in the Strength-Maturity relationships, it can be concluded that the Maturity Method is still sufficiently accurate to obtain in-situ concrete strength estimations, whilst the strength prediction can be refined by simulating in-situ temperatures during the mix calibration, as discussed in Section 5.2.

Independent cube tests were done during the Site Test Phase and compared to the strength estimation provided by the SmartRock. There was a good correlation between the strength estimation provided by the SmartRock and the cube tests. This was, however, coincidental, since the maturity developed by the cubes that were cured under controlled conditions was similar to the maturity developed by the in-situ concrete due to the prevailing weather conditions.

5.6.2 Mix calibration accuracy

The accuracy of the in-situ strength estimation is heavily dependent on the quality of the mix calibration. ASTM C 1074: 2011 states that the concrete used for mix calibration should contain similar constituents to the in-situ concrete. Mix 2 and Mix 3 had the same proportion of fly ash to cement but a 5% difference in w/c ratios and different design strengths. The Strength-Maturity relationship of Mix 3 was scaled to have the same design strength as Mix 2 and there was no significant difference between the two Strength-Maturity relationships. It can be concluded that the mix calibrations, in this case, was not sensitive to small changes in the mix design.

The mix calibration developed by the contractor differed significantly from the mix calibration that was developed as a verification for this study. It is important that the mix calibration is executed by attentive individuals, under controlled conditions of casting and curing to ensure that an accurate mix calibration can be developed. The ASTM C 1074: 2011 which specifies the process for mix calibration should be stringently adhered to. However, as discussed earlier, the mix calibration can be conducted at a higher temperature, as a measure of conservatism, to ensure that any potential cross-over behaviour exhibited by the in-situ concrete, is taken into account.

5.7 Applicability of SmartRocks in South Africa

Interviews were conducted with numerous industry professionals to determine the applicability of SmartRocks in the South African construction industry. The main conclusions are summarized in this section.

5.7.1 Current techniques are lacking

Various engineers feel that the process using concrete cube tests, currently used to estimate in-situ concrete strength, is lacking. The cubes do not take in-situ curing conditions into account and is therefore not an accurate representation of in-situ strength. Furthermore, there is not always control over the sampling, casting, curing and testing of the cubes.

Some contractors feel that the use of SmartRocks can identify unsatisfactory hydration behaviour. The SmartRock application can act as an additional accountability tool with the information that it provides and also promote effective information transfer.

Engineers are willing to implement SmartRocks in conjunction with current techniques. If the industry gets more acquainted with the use of SmartRocks, the current techniques can be phased out.

5.7.2 Mix calibration

Engineers and contractors have lost confidence in concrete suppliers. It has happened that wrong concrete was delivered on site, without the contractor's knowledge. The majority of the industry professionals do, however, feel that the concrete supplier should be responsible for mix calibration. They have the necessary skills and equipment to develop a mix calibration.

SmartRocks, and the ability to provide a mix calibration, can act as a marketing tool for concrete suppliers and can be a way to regain the confidence of the industry in their product. In this way, concrete suppliers can assure contractors that the concrete that arrives on site, is what was specified and is accurately described by the mix calibration that they provide.

5.7.3 Required skills

Engineers have lost confidence, to some extent, in the skills level of contractors in South Africa. In particular with regards to formwork removal, engineers do not allow contractors to remove suspended slab formwork earlier than seven days. Even though the SANS codes allow formwork to be removed earlier in hot weather, engineers are weary of early formwork removal, due to insufficient backpropping from the contractor which can lead to increased deflections.

However, there are contractors that will be able to effectively apply the SmartRock sensors on site and optimize formwork removal, even if it's just within the scope of current standards. If SmartRocks are more widely adopted, formwork removal can be optimized further.

SmartRocks can be effectively applied during the construction of post-tensioned slabs. Unlike reinforced concrete slabs, where the formwork removal is governed by curing time, the formwork removal and tensioning time is governed by a required strength. Tensioning can commence when concrete reaches 18 MPa or after three days, whichever occurs first. SmartRocks provide an effective way to estimate the in-situ strength, to determine when tensioning can commence. Because SmartRocks take site conditions into account, it can lead to optimization in hot weather and enhanced assurance in cold weather.

5.7.4 Cost-benefit of SmartRocks

There should be an overall benefit to the project by using the SmartRocks. Contractors need to identify the advantages of using SmartRocks and drive the use thereof, from their side. They will be able to reap the reward thereof, by tendering lower and completing projects within budget.

If contractors can implement SmartRocks effectively, it will be adopted more widely, after which engineers will start specifying the use of SmartRocks on projects. This will result in an overall benefit for the project, including a financial benefit to the client. The extent of the financial benefit should be further investigated.

Overall, the use of SmartRocks can provide a competitive advantage for any role player who is willing to implement it, whether it be financial or the image of enhanced skills utilization which goes with the implementation SmartRocks.

5.8 Recommendations for further studies

5.8.1 Extent of changes in mix design after mix calibration

The ASTM C 1074 standard that specifies the use of the Maturity Method states that the concrete with which the mix calibration is done, should contain 'similar constituents' to the in-situ concrete of which the strength will be estimated. This standard, however, does not define the extent to which the mix design can be changed after the calibration process.

This study, briefly, discussed the sensitivity of the mix calibration to changes in the mix design. However, it is recommended that this be further investigated with regards to various mix design parameters such as w/c ratio and aggregate content. The extent to which these parameters can be altered without influencing the mix calibration significantly, should be quantified.

5.8.2 Cost-benefit of SmartRock

Varying opinions were obtained from industry professionals regarding the cost of SmartRocks. Some said within the broader scope of a construction project, the cost of the sensor is negligible, and with the possible savings that could arise from implementing the sensor, it is worth the cost. Other individuals, including most of the contractors, were of the opinion that the sensor is too expensive.

A study should be conducted which thoroughly compares the cost of the current strength estimation techniques, along with the current formwork removal regimes, to the alternative of using SmartRocks, with the associated possible formwork removal optimization and expedited project completion.

5.8.3 Absolute accuracy of strength estimations

The absolute accuracy of the in-situ strength estimations could not be verified in this study, as it was not possible to impose the exact temperature and moisture conditions, that the in-situ concrete was exposed to, on the concrete cubes that were tested as verification. It is also not possible to drill concrete core samples as a verification. To obtain accurate results from core samples, the samples cannot be drilled before 14 days. The accuracy of the Maturity Method, was rather affirmed by laboratory tests

To verify the absolute accuracy of the in-situ strength estimations, the estimations provided by the SmartRocks should rather be compared to cube samples that are exposed to the same conditions as the in-situ concrete. It is recommended that steel moulds be cast into the slab, in which the samples can be cast and cured and then tested. These samples will give the best representation of the compressive strength developed by the in-situ concrete.

5.8.4 Refinement of mix calibration procedure

One of the main limitations of the Maturity Method, is that it does not take cross-over behaviour into account. However, if the in-situ temperature conditions can be simulated during the mix calibration procedure, the cross-over behaviour can be modelled. Taking cross-over behaviour into account, will result in better quality in-situ strength estimations.

This can be done by building up a knowledge base on the in-situ temperature of various concrete mixes under a range of prevailing weather conditions.

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Appendix

Project Specification

Determination	Recommendation	Comment
Maturity Function	Nurse-Saul maturity function	
Datum temperature	Obtain from literature (Nurse-Saul maturity function)	Can be experimentally determined
Strength prediction model	Exponential model	https://drive.google.com/open?id=18KH1fH0UXRxuwHfYI2Ym5UOd9xIzuQVH
Mix calibration	Conducted by concrete suppliers for each different mix	Strictly in accordance with ASTM C 1074. Curing temperature can be increased to take cross-over into account
Good practice for installation	No significant difference between different installation depths	Up to a slab thickness of 300 mm
	Twist activation wires together on both sides of reinforcement	
	Fix sensor onto second level of reinforcement	
	Twist temperature sensor around reinforcing steel	
	Install sensor close to column	

*more information on above mentioned determinations on next page

Maturity calculation

The maturities should be calculated with the Nurse-Saul maturity function. This function is given by:

$$M(t) = \sum_{t=0}^{t^*} (T_a - T_0) \cdot \Delta t \qquad \text{[Eq. 1]}$$

where:

$M(t)$ = Maturity as the time-temperature product at age t^* (°C·hrs)

Δt = Time interval (hrs)

t^* = Concrete age at time of strength estimation (hrs)

T_a = Average concrete temperature during Δt (°C)

T_0 = Datum temperature (°C)

This function incorporates a datum temperature. The datum temperature is defined as the minimum temperature at which the concrete will still gain strength. The datum temperature is unique for each cementitious system. Limited cementitious systems have been investigated in South-Africa. The datum temperatures for these systems are given in Table 1

Table 1: Known datum temperatures

Cement Type	w/c = 0.45	w/c = 0.60
CEM I	11	9
CEM I + 20% Fly Ash	-5	0

For different w/c ratios, the datum temperature can be interpolated. It should be noted that it is more conservative to choose a higher datum temperature, as strength gain at low temperatures will not be erroneously assumed. If a unique cementitious system is used, the datum temperature can be experimentally determined with the process outlined in ASTM C 1074.

It should be noted that the SmartRock Application automatically calculates the maturity once the maturity function is selected and the datum temperature is inputted.

Mix calibration procedure

The quality of the in-situ strength estimation is directly dependent on the quality of the mix calibration. The mix calibration procedure should be done in accordance with ASTM C 1074 for each unique concrete mix. Minute changes in the mix design will not impact the mix calibration's efficacy, but it is recommended that if there is changes in the mix design, that the mix be recalibrated.

As a matter of conservatism, the mix calibration can be conducted at a higher temperature to ensure that any possible cross-over behaviour exhibited by the in-situ concrete is taken into account. It will therefore be good practice to conduct the mix calibration at the highest temperature than the in-situ concrete will be exposed to.

It is further recommended that the exponential model be fitted to the Strength-Maturity data to develop the Strength-Maturity relationship for the particular mix (this is the mix calibration). A spreadsheet to fit the exponential model to the Strength-Maturity data can be found at https://drive.google.com/open?id=18KH1fH0UXRxuwHfYI2Ym5UOd9xIzuQVH

Good practice for installation

A number of good practices were identified to ensure that the sensor effectively measures temperature:

- Twist activation wires together on two sides of the reinforcement.
- Fix the sensor body onto the second level of reinforcing steel to minimize the risk of the sensor being stepped on.
- Twist the temperature sensor around reinforcing steel to control the measuring location.
- Install the sensor close to a column so that the location is known and compaction close to the sensor can be easily controlled.
- There is not a significant difference between measurement depths in the slab. However, to ensure that conservative maturities is measured, the sensor should be installed in the bottom of the slab in summer months, and at the top of the slab in winter months.

Interviews

Interview Guide:

1. Are you aware of the Maturity Method as an in-situ concrete strength estimation technique?
2. Have you been involved in a project where concrete had to be redone due to insufficient strength gain?
3. Have you been involved in a project where there was pressure to remove formwork earlier than what SANS specifies?
4. Have you heard about SmartRocks as a wireless concrete temperature measuring device?
5. Would you accept the limitations of the Maturity Method and trust the accuracy of the strength estimation provided by the SmartRocks?
6. Would you implement the use of SmartRocks on site?
7. Who, in your opinion, should be responsible for mix calibration?
8. Do you think the use of the Maturity Method should be included in the SANS codes?
9. Do you think contractors (and their labour) will be able to place SmartRocks effectively?
10. For which structural elements would you find the most value of using SmartRocks?
11. Would it make a difference to you if SmartRocks results are given for top or bottom of suspended concrete slab sections?
12. How many SmartRocks results (measuring locations) would you be satisfied with for a suspended slab (number per 100m2)?
13. What would you like to know before specifying SmartRocks for a project?
14. Would you rely on SmartRocks:
    a. to replace cube testing and to what extent?
    b. to provide information on early strength only, or both early and 28 day strengths?

Engineer 1

Engineer 1 has experienced many difficulties with the engineering and construction industry during his career. He was involved in projects where the ready-mix concrete that was specified, differed from the concrete that was supplied on site. It is clear to see that the strength estimation provided by the SmartRock will be inaccurate if the wrong concrete mix is cast on site. Furthermore, it is very difficult to control the unskilled labour on construction sites in South Africa and the limitation of the Maturity Method of not taking curing and compaction into account can have a significant influence on the accuracy of the strength prediction provided by the SmartRock.

The current strength estimation technique of concrete cube crushing also does not take poor compaction and curing into account. Engineer 1, however, is not content with the current techniques and feels that it is not accurate enough. The fairly rigorous process of sampling and casting cubes specified by SANS is not always adhered to and the cubes are not properly cured. He feels that to get an accurate strength estimation from cube crushing tests, the cubes need to be cured on the slab that was cast to ensure that the cubes experience the same conditions as the in-situ concrete, but this is not always possible. He is also not satisfied with the quality of the results obtained from the testing laboratories. It has happened before that cubes from two different concrete mixes were sent to a laboratory. The lab provided expected tests results for the 20 MPa mix, but provided strengths that were too low for the 30 MPa mix. It came out later, that the laboratory technician did not deem it necessary to test the cubes from the 30 MPa mix as he thought that all the cubes were from the same batch. He provided fake test results for the 30 MPa mix.

Regarding the earlier removal of formwork, he is not willing to take the risk of removing formwork earlier, whilst the contractor reaps the reward thereof. He admits that current standards of formwork removal are very vague as it is given for several structural elements for “Cold”, “Cool” and “Hot or Normal” weather. Ranges are given for these temperatures, but he feels that the ranges are too big and is still too open for own interpretation. The consulting firm he works for, has however built up experience regarding formwork removal, and has developed their own guidelines based on the SANS specifications. This has proven to be successful.

He feels that there is merit in using the SmartRock as an in-situ strength estimation device. He believes that the accuracy of the SmartRock can be verified by research, but that the successful implementation thereof is governed by other external factors. Such factors include the quality of the concrete provided by the ready-mix plant, the accuracy of the mix calibration, and if the concrete was correctly placed, consolidated and cured. The use of SmartRocks will be valuable in a project such as the MyCiti Bus Rapid Transport project. For this project, a unique pigmented concrete was used for the bus lanes, and therefore it could be certain that the supplied concrete mix, had been carefully controlled. Furthermore, the bus lanes could have been opened earlier- even just for construction traffic - if the compressive strength of the concrete could have been monitored.

Engineer 2

Engineer 2 is aware of maturity sensors and has familiarized himself with published research on the topic of strength estimation with maturity sensors but has never used the sensors.

To speed up the production of the precast elements, accelerated curing is used widely. Engineer 2 has supplied 65-ton panels for wind tower construction. By using accelerated curing methods, these panels were already lifted at 15 hours. It is clear that an accurate strength estimation needs to be obtained to ensure that these elements are not prematurely lifted, which can result in the elements being damaged. Engineer 2 currently employs a method where cubes are cured at the same location where the last element of the day is poured. The last element will be the worst case, as it will be the weakest of the elements that were cast in a day. Curing the cubes at the same location will subject it to the same curing conditions than what the precast element is subjected to. The strength of the precast element is then directly estimated from the cube results. This method has proven to be effective.

Accurate, real-time strength estimations provided by the SmartRock, will result in reduced manufacturing time and an overall improvement in effectivity on the precast yard. However, the cost of the sensors will determine whether it is viable to use the sensors. If the benefits of the sensors outweigh the cost thereof, it will be useful for the precast industry to implement the sensors. Furthermore, to verify the accuracy of the SmartRock, for use in the precast industry, more tests have to be done. This will enable the precast supplier to base his determination on whether to use the SmartRock, on statistical evidence of its accuracy.

Precast element suppliers often work with high-strength concrete. According to Engineer 2, the higher the strength of concrete, the less accurate cube tests will be. This is another advantage of the SmartRock, as it can provide a verification of the cube test results. Furthermore, faster precast element production time has the potential to speed up project delivery for the client.

Engineer 3

Currently, the sensor is still expensive, as the SmartRock technology is relatively new in South Africa. As is the case for the precast industry, the use of the SmartRock should yield an economic benefit to the client. Following the guideline for the number of concrete cube samples that need to be taken for a concrete pour, which states that a sample has to be taken for each 50 m^3 of concrete that is poured, one sensor can also be installed for each 50 m^3 of concrete that is poured. Working at an average rate of R1400 per cubic meter of concrete, a sensor has to placed for each R70000 worth of concrete that is poured. Even at the current price, the cost of the SmartRock is insignificant.

Contractors are pressured to complete projects as fast as possible- the faster they can complete a project, the more profit there is for everyone. Construction schedules are therefore very tightly constrained. The SmartRock can provide a degree of relief from these tight schedules. By providing accurate strength estimations, formwork can be removed earlier, and subsequent pours can be executed quicker.

Engineer 3 does not believe that the implementation of the SmartRock does necessarily have to be included in the SANS codes. There is enough other guidelines to verify the effective use of SmartRocks. An example of this is the current guidelines on formwork removal. These guidelines, however, still contain grey areas. Engineer 3 has adapted this code for summer and winter months, in stead of using the “Hot or Normal”, “Cool”, and “Cold” terminology used by the codes.

Human factors do, nevertheless play a role in the implementation of the SmartRock. This is, however, also the case with current in-situ strength estimation techniques. The concrete cubes that are tested to verify the in-situ strength, are not always sampled and cured correctly. The industry has, nevertheless accepted this method as an in-situ strength estimation technique and it is widely used, despite the limitations thereof.

Engineer 3 is willing to apply the SmartRock for estimating the in-situ strength of concrete, if it could be justified to the client that it is beneficial to use the SmartRock from an economical point of view. As the SmartRock has the potential to expedite project completion, various savings can be achieved. A simple example of these savings is the Preliminary and General costs. Secondary to the direct savings, site handover can be achieved quicker. Accuracy of the strength estimation is, therefore, not the only criteria in the decision to apply the SmartRock. It should also be economically beneficial to the client.

Concrete specialists should be responsible to perform the mix calibration, and Engineer 3 believes that the ready-mix suppliers has enough expertise to provide an accurate mix calibration. However, there has been incidents in the industry of concrete failing and wrong concrete that has been provided which resulted in consulting engineers losing trust in the products provided by ready-mix plants.

The successful implementation of SmartRocks on site is heavily dependent the foreman which supervises the work. Unfortunately, the quality of supervision provided by foreman is often lacking.

Engineer 3 feels that it is very important to move forward, by implementing innovative tools like the SmartRock. As soon as one starts to stagnate in an industry, you are effectively falling behind. The SmartRock can also act as a marketing tool for engineers, contractors and ready mix suppliers.

The SmartRock needs to prove itself to engineers in the industry. Engineer 3 is willing to start to implement the SmartRocks in conjunction with current techniques. Thereby building trust in the use of SmartRocks- if the sensors prove to be accurate. After which current techniques can be phased out.

Engineer 4

Engineer 4 has been involved in a project where there was a need to rework the concrete. He could see that the in-situ concrete was not developing sufficient strength and had it tested at 28 days. The 28 day strength of the concrete was only 15 MPa and Engineer 4 still does not have information from the concrete supplier on what caused this underperformance. The SmartRock will not give accurate results in this scenario. It is up to the engineer on site to use his discretion on whether the concrete is performing sufficiently. Other limitations, such as insufficient compaction and curing will also not be identified by the sensor, but cube crushing tests also does not take this into account. Furthermore, cubes cast on site are often of a lower quality than the in-situ concrete. This can be attributed to construction workers deviating from the standards which govern sampling and casting of cubes for testing. The worker casting the cube, should be skilled enough to execute this process effectively.

Obtaining accurate results from the SmartRock requires a standard from the manufacturing of the concrete through to the installation of the sensors and also skilled individuals to apply these standards. Engineer 4 feels that the South African construction industry requires innovation.

Engineer 4 has been involved in a project where apron slabs had to cast for an airport. A ready-mix plant was established on site and therefore the supply of concrete could be controlled internally. This would have been an ideal application for the SmartRock, as a lot of uncertainty is eliminated by not using an external concrete supplier.

Another project where Engineer 4 has been involved in, was an apartment complex with a basement level and 3 stories, developed for student accommodation. Construction commenced in February and site handover was in November. Thus, there was a lot of time pressure associated with the project and therefore the contractor wanted to remove the formwork earlier. Accurate early-age strength estimations was therefore critical. For such a project the use of SmartRocks can be written into the project specifications.

Engineer 4 feels that the use of the Maturity Method should be included in the SANS standards.

Engineer 5

Engineer 5 feels that there is always time pressure to remove formwork earlier. Care has to be taken for slabs to ensure that deflection limits are not exceeded when formwork is removed earlier. Especially for Post-Tensioned slabs where the dead load of the structure is large when compared to the live load, as is the case with parking structures. For such a scenario Engineer 5 does not remove formwork earlier than 7 days after casting.

Engineer 5 is willing to apply the use of SmartRocks on site, if he has confidence in the accuracy thereof. The engineer has very little control of test cubes, which are currently used for in-situ strength estimation, and Engineer 5 feels that more control can be exercised by using the sensor. However, accurate mix calibration is a prerequisite. This mix calibration should be provided by the concrete supplier.

Engineer 5 feels that the use of SmartRocks should be included in the SANS codes. This will provide engineers in the industry with peach of mind to widely apply the SmartRock, as is the case with cube tests.

To apply the sensors in South Africa, there must be proper supervision. Furthermore, current in-situ strength estimation techniques can be phased out, if the SmartRocks provide accurate results and engineers are confident with the results it provides.

Engineer 6

Engineer 6 feels that it is common that there is pressure to remove the formwork earlier on construction projects. This is very apparent during the construction of Post-Tensioned slabs. The faster that the formwork can be removed, the faster you can cast subsequent slabs. Engineer 6, however feels that for normal reinforced concrete slabs, that early removal of formwork can lead to increased long-term deflection, where for post-tensioned slabs, this effect will not be pronounced. Engineer 6 feels that for multi-story construction, optimization of formwork removal can lead to significant construction time reductions and that it is for this reason, that post-tensioned slabs are becoming more popular. The current formwork removal codes does not have a strength requirement, but rather a curing time requirement and this is why Engineer 6 feels that a good application of the SmartRock, is for Post-Tensioned slabs.

Engineer 6 feels that there is a clear boundary between the responsibilities of the contractor and the responsibilities of the designer. All temporary works are the responsibility of the contractor. There are standards that govern the removal of formwork and the permission to remove the formwork outside the scope of these standards is not the designer's to give. It is the contractor's responsibility to remove the formwork at an acceptable time. The designer is only interested in the final product, and that is where the 28-day cube strength is critical. Engineer 6 believes that there is still a degree of forgiveness when stripping outside the scope of the standards, but one has to be sure that if there is a strength requirement, that this strength is reached. Engineer feels that that knowledge is being lost in the industry with contractors being more irresponsible with their construction methods. Competent contractors can be given flexibility within the scope of the standards, but no room for interpretation can be given to incompetent contractors.

There is, however, a significant risk when removing formwork earlier and tensioning earlier during the construction of post-tensioned slabs. The earlier removal of formwork has a much lower risk, provided that formwork is removed and backprops are installed responsibly and the slab is also cured sufficiently.

The accuracy of the strength estimation is dependent on the accuracy of the mix calibration, whilst the accuracy of the mix calibration is dependent on the competence of the individual responsible for the calibration. According to Engineer 6, the contractor should be responsible that the mix calibration is accurate, but he can nominate a competent person to perform the mix calibration. For the projects where the SmartRock will be used, a competent person will be on site to supervise the work and will, hence be competent to effectively apply the SmartRock on site. Engineer 6 will not prescribe the use of the SmartRock for use on a project. It will have to come from the contractor's side and be reasoned with a cost saving that can be transferred to the client. The contractor will reap the reward of effective use of the SmartRock, but he will have to carry the responsibility thereof.

Engineer 7

Engineer 7 feels that there can be a significant reduction in project costs, if the SmartRock is applied effectively. He was recently involved in a project where there was a reduced backpropping requirement, due to construction load being significantly less than the design load. This had resulted in a cost saving for the client. However, the contractor needs to drive it from his side, as the engineer has not control over how effective and accurately the sensors are applied. There has to be evidence that the strength estimation provided by the SmartRock, and it is then, that Engineer 7 feels that he will not have a problem with removing formwork earlier. Another application of the SmartRock can be to monitor the hydration heat of the concrete.

The main limitation of the using the SmartRock, is that the mix should not change after the mix calibration is done. All project participants should be aware of the fact that the SmartRock is used, and that care has to be taken to ensure that the mix calibration is accurate and relevant to the concrete that is cast on site. Engineer 7 feels that the ready-mix supplier should be responsible for the mix calibration and that this would give him a competitive advantage. A potential disadvantage to ready-mix suppliers, is that the SmartRock can provide information on the hydration behaviour of the in-situ concrete and that discrepancies in the concrete mix can be identified by the contractor. It is, however, good for the project, but this may be a reason for opposing the use of SmartRocks from the ready-mix supplier's point of view. The SmartRock therefore provides tool with which accountability can be assigned.

Engineer 7 feels that a client will not be willing to carry the extra cost of the sensors, even though it will result in a net cost saving. In the event that the client is not willing to finance the use of the sensor, the contractor can drive the use of the sensor from his side. He can reap the reward thereof by removing formwork earlier, with the cost savings directly being translated to him.

Engineer 8

Engineer 8 feels that the main advantage of SmartRocks is that it takes the in-situ temperature of the concrete into account, where the current practice of cube tests, does not take site conditions into account at all. It is, however, the only strength estimation technique that Engineer 8 will accept as a reasonably accurate strength estimation. He will accept strength estimations given by the SmartRock.

Engineer 8 feels that by using the SmartRock, there has to be an advantage to the project. This can be achieved by formwork optimization and Engineer 8 believes that the SmartRock will be most effective for post-tensioned slabs and when there is multiple levels of slabs. He further believes that the SmartRock will not be widely adopted, but rather be specified by engineers on specific projects where accurate strength estimations are required.

Engineer 8 has experienced that formwork is often removed to early, even for post-tensioned slabs, and as a result of this, the slabs have cracked.

The successful implementation of the SmartRock is dependent on the skills level of the contractor. The contractor needs to take responsibility to implement the SmartRock successfully and because the SmartRock can give you an indication of the site conditions, Engineer 8 will be willing to specify the use of SmartRocks on relevant projects. He feels that there is merit in including the use of SmartRocks in the SANS codes.

The use of SmartRocks can give contractors and ready-mix suppliers a competitive edge.

The mix calibration needs to be carefully monitored as concrete suppliers reserve the right to change mix designs without prior notice. It can therefore act as a marketing tool for concrete suppliers and also give them a competitive edge.

Engineer 9

Engineer 9 feels that the price of the SmartRock sensor will be the main factor in the determination of whether to use the SmartRock on site, and at the current price, he feels that engineers will not be willing to implement the sensors. However, if the sensors are implemented more, he believes that the price of the sensors will come done, to an extent where engineers can specify the use of SmartRocks on projects. Engineer 9 feels that the SmartRock can be used in conjunction with concrete cubes, with cubes being phased out as the industry's confidence in the use of SmartRocks increases, provided that there is a cost benefit of using SmartRocks. If SmartRocks are adopted in the industry, a database can be developed to further optimize and motivate the use of SmartRocks.

Engineer 9 believes that the SmartRock can act as another control mechanism. He has been involved in a project where the concrete cubes failed. This was not necessarily an indication that the in-situ concrete was not up to standard. The SmartRock can identify unsatisfactory hydration behaviour and provide an alternative and accurate strength estimation, where current alternative strength estimation techniques, like the Schmidt hammer, does not give accurate results.

Engineer 9 believes that the use of cube tests can be minimized through the use of SmartRocks.

The concrete supplier needs to be responsible for the mix calibration and they are also in the optimal position to drive the use of the SmartRocks. Concrete suppliers have the capacity to develop accurate mix calibrations and also conduct tests to verify the accuracy of in-situ strength estimations. This can act as a marketing tool for the concrete suppliers. After this, the contractor can start to implement the use of SmartRocks in conjunction with the concrete supplier, after which the engineer can start specifying the use thereof.

Contractor 1

Contractor 1 believes that the construction industry, and especially his company, is always looking for technological advancements to improve their project delivery. However, at the current price, the SmartRock seems to be too expensive for them to implement.

Contractor feels that engineers are often over-conservative with regards to formwork removal. Engineers often rigidly stick to a 7-days stripping time for suspended slabs, rather than taking weather conditions into consideration. Thus, there is room for optimization within the scope of current standards.

Contractor 1 has had it happening that concrete that was supplied on site, did not adhere to the specifications that was provided to the supplier. Contractor 1 experienced various factors which caused this. These factors ranged from contaminated sand and aggregate to retarder that was erroneously added to the concrete in the truck, due to concrete that was previously transported in the same concrete truck that was not cleaned properly. Inconsistent hydration behaviour can be identified with the temperature data that is provided by the SmartRock.

Contractor 1 believes that the SmartRock application will streamline communication between the contractor and engineer. The SmartRock application can give access to the data of all the sensors that are installed on a site. Contractor 1 believes that current techniques are lacking and causes unnecessary delays.

Contractor 1 believes that the current technique of cube tests has a significant number of limitations. These limitations include the fact that the cubes do not take site conditions into account. Furthermore, the production, curing and testing of the cubes are not always carefully controlled and therefore does not give an accurate representation of concrete strength.

Contractor 2

The construction site where Contractor 2 is currently a site agent, will provide 21000 m^2 of commercial space and it had to be completed within 14 months. The contractor injected significant resources into this project, to ensure that it is completed on time. It is projected that the project will be completed within 12 months.

The expedited project completion was partly due to earlier removal of formwork. The suspended slabs were cast in hot weather and most of the slabs' formwork were removed after 4 days. Cube crushing tests were conducted at three days to verify the concrete strength.

Contractor 2 believes that engineers are often over-conservative with regards to formwork removal, as the engineers often default to a formwork removal time of 7 days after casting, and do not allow contractors to remove formwork earlier. The process of formwork removal is the responsibility of the contractor, but contractors regularly rely on the engineer to provide guidance as to when the formwork can be removed and engineers then, default to the 7 days removal time.

The over-conservatism is due to the questionable skills level of some contractors to properly remove formwork and backprop effectively. This poor formwork removal process can result in increased deflections which can lead to serviceability issues. The engineer also is not always aware of the rate at which in-situ concrete can gain strength.

It should be noted that Contractor 2 worked with an engineer that was mindful to the advantages of early formwork removal, but also that Contractor 2 is an experienced contractor which could effectively remove the formwork without the risk of increased deflections.

Contractor 2 believes that the SmartRock is currently too expensive to implement widely on a construction site. He, however, also believes that there is merit in the SmartRock, as the industry is always looking for technological advancements. The SmartRock can act as a tool for engineers to be more certain of the strength of in-situ concrete, which can lead to over-conservative engineers being more mindful of earlier removal of formwork.

Contractor 3

Contactor 3 has been involved in a project where the concrete works had to be demolished due to the concrete no gaining sufficient strength. This had severe cost and time implications for the contractor. There is also pressure to remove formwork earlier for reinforced concrete slabs, and also to tension earlier for post-tensioned slabs. The decision to tension, is usually based on concrete cube results. It is important to know what the strength is at certain defined location and these strength estimations need to be accurate.

According to Contractor 3, the engineer will dictate when formwork can be removed. If the contractor can prove that the concrete has achieved sufficient strength, the engineer will accept the removal of formwork. The SmartRock can provide this strength estimation, in real time with an acceptable accuracy. Contractor 3 will experimentally implement SmartRocks.

Engineers are weary of deflection behaviour, regardless of the strength that the concrete has achieved. Contractor 3 believes that there is room for the Maturity Method to be included in the SANS codes.

Based on experiences that Contractor 3 has had with concrete suppliers, he does not have confidence in concrete suppliers. Contractor 3 will delegate the mix calibration to a third party. He believes that contractors have the skill to use the SmartRock effectively on site.

Contractor 3 believes that the SmartRock will provide information which has not been available in the past, thereby identifying problems that may not have been identified with current methods. The contractor and engineer might be in a position where they do not know how to deal with the available information.