Self-compacting concrete versus normal compacting concrete: A techno-economic analysis.

by

Jan Stephanus Malherbe

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Supervisor: Professor J.A. Wium

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DECLARATION

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SYNOPSIS

Self-compacting concrete (SCC) also referred to, as self-consolidating concrete, is a relatively new concrete technology used in the construction industry. It is able to flow under its own weight and compact into every corner of the formwork, purely by means of its own weight.

According to the University of Johannesburg, engineers can expect a strong demand for their services over the next four years and construction projects might start experiencing even higher pressure on their schedules. This will force the industry to look at possible time saving technologies.

It is therefore useful to investigate possible construction methods that might accelerate project schedules and to understand their financial impact. It is also important to see if it will be worthwhile for the South African construction industry to follow the international trend for SCC application.

The primary objective of this study was to construct an accurate cost implication model to quantify the impact of the decision to implement self-compacting concrete on a South African construction project. This was done by constructing a static costing model and by performing a sensitivity analysis and a Monte Carlo analysis on the static results of the relevant Key Performance Indicators (KPI's). As a secondary aim, the study examined the labour requirements at a typical South African construction project. This was done to enable a project leader to easily implement self-compacting concrete technology without facing the perceived challenges concerning job creation policies in South Africa.

The technical information regarding the material properties of SCC is well researched and guidelines for implementing the material in a project already exist. The knowledge gap about the detailed cost impact of using SCC on a South African construction project still exists.

Interviews with industry representatives showed a good, but fragmented, knowledge of SCC in the South African industry. The factors that influence the cost of using SCC and how these factors influence the construction cost are known, but the size of the influence on the different cost constituents are still uncertain. The labour requirements set out by the National Development Plan (NDP) and the Expanded Public Works Programme (EPWP) for labour-intensive construction was also identified as a perceived obstacle for SCC implementation.

A modelling and calculation methodology was proposed in this research to quantify the financial impact of using SCC on a South African construction project. This methodology was tested and found to be useful when applied to a case study. The case study was a six span bridge constructed near George in the Western Cape. The results obtained are of particular value to the client and contractor in a project team.

The cost quantification results are presented in terms of cost KPI's that can be used for interpreting the influence of SCC on the construction cost. For this case study it was found that the construction cost would increase by 17.4% if SCC had been used. This is mainly due to the increased material and formwork cost. The higher cement content of SCC raises the material unit price and the increased formwork strength requirements, needed to accommodate hydrostatic pressures, manifests as an increased expense. A Monte Carlo analysis yielded a 90% confidence that the total cost difference would be between 14.0% and 20.9% (R294 800 and R438 200) on a total amount of R2 098 700.

The labour requirements set by the EPWP and the NDP for labour-intensive infrastructure projects was shown to have a limited influence on the decision to implement SCC. The labour reduction resulting from the use of SCC implementation is small. The labour reduction should not prevent the implementation of a new technology.

The main risks applicable to this case study are the lack of SCC expertise and the possibility of formwork failure or leakage that can result in total concrete material loss during concrete placement.

The cost comparison should be done prior to the construction phase in order to manage and lower the cost difference by identifying the most efficient way to focus cost reduction strategies.

A project dashboard with all the graphical results and the KPI summary, can be used to summarise the effect of implementing SCC at a South African construction project if the proposed calculation method is used. The information contained on the dashboard can then be altered to suit the needs of a specific decision maker. The heuristic modelling, especially the Monte Carlo analysis, should be tailored to cover only the information that has inherent uncertainty for a specific project.

To minimise the cost increase, the incorporation of cement extenders should be considered. SCC expertise and a formwork specialist should be included in the project team during the project inception phase.

Further research should be done to enhance the knowledge about the SCC cost implication, opportunities of SCC in the South African market as well as the implementation intensity and success of SCC in South Africa.

OPSOMMING

Self-kompakterende beton (SKB), ook bekend as self-konsoliderende beton, is ‘n relatief nuwe betontegnologie wat in die konstruksie industrie gebruik word. Dit het die vermoë om onder die las van eie gewig te vloei en te kompakteer tot in elke hoek van die bekisting.

Volgens die Universiteit van Johannesburg kan ingenieurs ‘n sterk aanvraag na hul dienste verwag in die volgende vier jaar en konstruksie projekte kan hoër druk ervaar op skedules. Dit sal die industrie dwing om tydsbeparende tegnologieë te oorweeg.

Dit is dus van waarde om konstruksiemetodes te ondersoek wat projekskedules kan versnel en om die finansiële impak van die metodes te verstaan. Dit is ook belangrik om te ondersoek of dit die moeite werd is om die internasionale tendens van SKB toepassing te volg vir die Suid-Afrikaanse konstruksie industrie.

Die primêre doelwit van hierdie studie was om ‘n akkurate koste-implikasiemodel op te stel wat die impak kwantifiseer van die besluit om SKB tegnologie te implementer op ‘n Suid-Afrikaanse konstruksieprojek. Dit is gedoen deur ‘n statiese kostemodel op te stel en ‘n sensitiwiteits analise, sowel as ‘n Monte Carlo analise, op die statiese model se relevante Sleutel Prestasie Aanwysers(SPA) uit te voer. As ‘n sekondêre doelwit het die studie die arbeidsvereistes bestudeer by ‘n tipiese Suid-Afrikaanse konstruksieprojek. Dit was gedoen om ‘n projekleier te bemagtig om SKB tegnologie maklik te implementeer, sonder om gekniehalter te word deur die verwagte uitdagings aangaande werkskeppingsbeleid in Suid-Afrika.

Die tegniese inligting aangaande die materiaaleienskappe van SKB is reeds deeglik nagevors en riglyne is reeds daargestel oor die implementering van die materiaal op ‘n projek. Daar is egter steeds ‘n gebrek aan kennis aangaande die werklike koste-invloed van SKB implementering.

Onderhoude is gevoer met verteenwoordigers van die industrie en goeie, maar gefragmenteerde, kennis is waargeneem oor SKB in die Suid-Afrikaanse industrie. Die faktore wat die koste van SKB beïnvloed, sowel as hoe die faktore die koste beïnvloed is bekend. Die relatiewe bydraes van die onderliggende koste komponente is egter steeds onbekend. Die arbeidsvereistes wat daargestel is deur die Nationale Ontwikkelingsplan en die ‘*Expanded Public Works* Programme’ (EPWP) vir arbeidsintensiewe konstruksie was ook geïdentifiseer as ‘n verwagte uitdaging vir die implementering van SKB.

‘n Modelering en berekeningsmetodologie is voorgestel in die navorsing om die finansiële impak van SKB implementering op ‘n Suid-Afrikaanse projek te kwantifiseer. Die metodologie is getoets op ‘n gevallestudie en het tot insiggewende gevolgtrekkings gelei. Die gevallestudie was ‘n ses-span brug wat naby George, in die Wes-Kaap, gebou is. Die resultate is die nuttigste vir die besluitnemende partye van kliënte en kontrakteurs in die projekspan.

Die resultate wat afkomstig is van die koste kwantifisering word voorgestel deur middel van die onderskeie SPA’s wat gebruik kan word om die koste-invloed te interpreteer. Vir hierdie spesifieke gevallestudie is ‘n kosteverhoging van 17.4% op die konstruksiekoste bereken indien SKB benut sou word. Die verhoging is hoofsaaklik as gevolg van die verhoogde materiaal en bekistingkoste. Die verhoogde sementinhoud van SKB verhoog die eenheidsprys van die beton en die hoër sterktevereistes vir bekisting, om hidrostatiese drukke te weerstaan, manifesteer as ‘n

prysverhoging. ‘n Monte Carlo analise het ‘n 90% vlak van betroubaarheid opgelewer dat die totale kosteverskil as gevolg van SKB tussen 14.0% en 20.9% (R294 800 en R438 200) sal wees, op die basiskoste van R2 098 700.

Die vereistes vir arbeidsintesiewe infrastruktuurprojekte, wat daargestel is deur die EPWP en die NDP, het beperkte invloed getoon op die besluit om SKB te implementeer. Die arbeidsmag vermindering as gevolg van die gebruik van SKB is ook klein en behoort nie ‘n hindernis te wees vir die implementering van die nuwe tegnologie nie.

Die grootste risiko’s vir die gevallestudie is die tekort aan SKB kundigheid (kennis en vaardigheid) en die moontlikheid van bekistingfaling of –lekkasies wat tot totale materiaalverlies kan lei tydens die plasing van die vars beton.

Die kostevergelyking moet uitgevoer word voor die konstruksiefase geskied. Dit sal ‘n beter begrip tot gevolg hê oor hoe om die kosteverskil te bestuur en te verminder deur kosteverlagingsstrategieë meer doeltreffend aan te wend.

Indien die voorgestelde berekeningsmetodiek gebruik word, kan ‘n projek paneelbord opgestel word wat al die grafiese resultate en die Sleutel Prestasie Aanwyser (SPA) opsomming bevat. Hierdie paneelbord kan dien as ‘n opsomming van die effek van SKB implementering by ‘n Suid-Afrikaanse konstruksieprojek. Die inligting wat hierdie paneelbord bevat kan aangepas word om te voldoen aan die behoeftes van ‘n spesifieke besluitnemer. Die heuristiese modelering, veral die Monte Carlo analise, moet aangepas word om slegs die inligting te dek wat inherent onseker is vir ‘n spesifieke projek.

Om die kosteverhoging te minimaliseer kan die insluiting van sementvervangers oorweeg word. Die SKB kundigheid en die bekisting spesialis moet ook vanaf die beginfase van die projek ingesluit word in die projekspan om SKB verwante risikos te minimaliseer.

Verdere studie kan gedoen word om die kennis te verbeter oor die koste implikasie, die geleenthede van SKB in die Suid-Afrikaanse mark en die implementeringsintensiteit sowel as die sukses van SKB in Suid-Afrika.

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LIST OF ABBREVIATIONS AND TERMS

CPA	Critical Performance Area
DPW	Department of Public Works
EPWP	Expanded Public Works Programme
HCC	Hybrid Concrete Construction
KPI	Key Performance Indicator
NCC	Normal compacting concrete (conventional mix design)
NDP	National Development Plan
SAFCEC	South African Forum of Civil Engineering Contractors
SCC	Self-compacting concrete

"Cost constituent"	This term is used to describe an item that has a cost of its own, and this cost contributes towards another, higher level cost. Per example: "*The formwork cost for NCC in slab elements is a cost constituent of the total construction cost of slab elements"*

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1 INTRODUCTION

1.1 Topic

This dissertation describes a techno-economic analysis to compare the use of self-compacting concrete with the use of normal compacting concrete (conventional concrete) in the South African construction industry.

1.2 Background

Self-compacting concrete (SCC), also referred to as self-consolidating concrete, is a relatively new concrete technology that is used in the construction industry. It differs from normal compacting concrete (conventional mix design) in one key material property, it is able to flow under its own weight. Because of this material property, it is able to compact into every corner of the formwork, purely by means of its own weight and without the need for vibrating equipment (Ouchi, 2000:29).

SCC was first developed in 1988, in Japan. The main reason for the development of this material was the lack of skilled workers that could provide adequate compaction for the creation of durable concrete structures (Okamura & Ouchi, 2003). The material has since been applied for a multitude of reasons, as is the normal course of a new technology, but the high flowability is still the main advantage.

The material has been described as one of the most important developments in the building industry (Brouwers & Radix, 2005:2116). It has also been noted that it (SCC) has the potential to dramatically alter and improve the future of concrete placement and construction processes (The Concrete Society of Southern Africa, 2013:12).

The implementation of SCC in South Africa is still limited despite the wide usage of the technology in developed countries. By 2007 it was only used for a relatively small number of applications and the acceptance of SCC by the South African industry was described as limited (Geel, Beushausen & Alexander, 2007:11). Not much has changed, SCC has remained a specialized concrete material and the implementation thereof in South Africa is lagging behind that of the developed world.

The first time SCC was used on a large scale in South Africa was in 2002, during the construction of the Nelson Mandela Bridge in Johannesburg. It took fourteen years for South Africa to harness the potential of this product, a fact that indicates that there is extensive knowledge that still needs to be acquired by our industry. (Jooste, 2009:18)

The industry has however been shifting gradually towards accepting SCC, mainly due to researchers and producers of self-compacting concrete and/or superplasticisers that fuel the knowledge transfer. The implementation of the technology is however, still minimal, as will be discussed during the interview analysis in this study.

According to the University of Johannesburg, engineers can expect a strong demand for their services over the next four years. The shift towards the use of high technology and labour-saving capital equipment in the manufacturing sector is expected to be a major contributor to the high growth in demand for engineers (Van den Berg, 2014). This view includes civil engineers with degrees as well as diplomas. If this information is taken into consideration, together with the expected increased industry investments, because of the envisaged National Development Plan (The

Presidency, 2012/2013), it is possible that construction projects will start to experience even higher pressure on their schedules. This will force the industry to look at possible time saving technologies.

This increased demand and schedule pressures render it useful to investigate possible construction methods that could accelerate project schedules, but also to understand their financial impact. It is furthermore important to see if it will be worthwhile for a South African construction project to follow the international trend of SCC application.

The fact that South Africa is not implementing SCC in the same order of magnitude as developed countries, despite the published perceived advantages, was one of the aspects that inspired this research. With the growing demand for engineering skills and decreasing resource availability, the question of why SCC is not implemented regularly, became even more apparent. It was therefore decided to investigate the technological and economic effects of implementing SCC.

This thesis presents a study into the technical and financial impact of implementing SCC, in comparison to normal compacting concrete (NCC), for a specific application in the South African construction industry. The technical material properties are discussed and the main SCC cost parameters, as well as their sensitivities, are analysed and reported on. Structural challenges due to legislation and other labour requirements were identified as well as the construction risks involved with the use of SCC.

The identification of the parameters that influence the financial decision of implementing SCC is included as part of the study. Certain perceived labour requirements, as identified through the interviews and that exist in the construction environment was also investigated and discussed.

The labour requirement investigation was included because the South African economy focuses on job creation while SCC is a labour-saving technology. The perceived labour requirements might prevent the implementation of SCC at present and therefore this aspect was investigated.

1.3 Objectives of the study

The perceived published advantages of using self-compacting concrete (SCC) include overall project savings on cost and time, whilst improving the quality of the hardened concrete. This study tested the first two claims on a quantitative basis and it investigated the mechanical properties of SCC through a literature study.

The primary objective of this study was to construct an accurate cost implication model to quantify the impact of the decision to implement self-compacting concrete technology on a South African construction project.

As a secondary aim, the study examined the influence of labour requirements on the decision to use SCC at a typical South African construction project. This was done to investigate if these job creation policies should discourage the use of the product at present.

Additionally, the study pursued to identify the major reasons for the lack of implementation of self-compacting concrete in the South African construction industry. The identification was done by conducting interviews with key people in the industry. The results are included in the report and in the model.

The construction risks related to the use of SCC were extracted from the interview information and literature and included in the report. This was done to ensure that the model results can be analysed in perspective of the change in construction related risk when SCC is implemented.

The model was constructed to provide a better understanding of the identified problems and where possible, to quantify the effects of these problems through different outputs connected to financial incentive.

The aim of the study was to create a milieu in which the decision to implement SCC can be quantified and be made as beneficial to all the stakeholders as possible.

1.4 Problem statement

The study investigated the financial viability and the cost implication of implementing SCC at a South African construction project. It is necessary to know what the financial implications are and how to calculate them when SCC is implemented at a South African construction project. In addition, the implication of the labour requirements in an economy focussed on employment creation must be understood.

The two problems are of a different type and each must be addressed in its own manner. The financial implication is empirical in nature and can be addressed through modelling and computer analysis. The labour aspect necessitates qualitative research. The complex relationships, policies and regulation regarding labour might obstruct SCC from gaining ground in the construction industry. These obstructions have to be investigated, and if they truly exist, a possible strategy must be developed to overcome them if the decision is made to implement SCC.

The research can thus be subdivided into a primary and secondary research area. The primary area addresses the development of a descriptive quantitative model to calculate the cost implication of implementing SCC. The secondary area addresses the problem of identifying and investigating the labour requirements in the South-African construction industry with respect to the implementation of SCC, a labour reducing technology.

1.5 Scope and limitations

This research was conducted from the standpoint of the South African construction industry. Global considerations were only included if it had a direct influence on the local industry. Some constraints, limits and boundaries were applied to the study. The study investigated a South African construction project and was thus limited to the labour requirements set by the South African legal systems. The following limits and boundaries were applied to the research and to the mathematical model:

- SCC and NCC are evaluated for the same 28-day characteristic compression strength (or SCC must outperform NCC).
- Only standard strength concrete is evaluated, and the upper limit for strengths is 60 MPa.
- Financing of the project can be done with existing capital, or with borrowed capital, (this can influence the quantification of time savings if a nett present value is of interest).
- Only regular concrete applications are considered. Frost resistant concrete, fibre reinforced concrete, submersible concrete etc. are not considered explicitly, the model can however accommodate such applications.

- The model input requires, amongst others, material used, cost of materials, and a concrete placement schedule.
- Concrete placement that is on the critical path of the project is considered separately since the cost implication differ for these placements, due to potential of additional overhead savings when the schedule is accelerated.
- Only South African labour requirements are considered for the secondary objective.
- Risk factors such as strikes, safety requirements and low productivity at the start of SCC implementation is not included in the quantitative model.
- All materials are assumed readily available without shortages or delays, possible price fluctuations in materials are not included.
- Training cost before implementation is considered negligible and is not included in the model.

1.6 Research methodology

This dissertation is based on the information and results obtained from the four main components of the study. These components are:

1. A comprehensive literature study and review
2. An interview phase in which industry representatives were consulted
3. The modelling of a South African case study
4. The statistical investigation into the sensitivity of the parameters of the case study

The information in the literature study is extracted from international literature and electronic databases. Self-compacting concrete was investigated first, followed by the investigation into the methods and elements involved in a techno-economic analysis. The quality of the material and other relevant material properties were also investigated through literature.

The interview phase served as an extension and validation of the literature study, as well as a method for identifying the parameters involved in the cost comparison. The majority of the identified risks are also sourced from the interviews. Eleven representatives participated in the interviews and they will be mentioned in Chapter 3.

The modelling of the case study was performed after a visit to a bridge construction site in George. The choice of including a case study in the research methodology is further motivated in Chapter 5. The information used in the modelling is a combination of the information gathered from the interviews, the literature review and the site visit itself. The suitability of the project is discussed in Section 5.3.

The statistical investigation into the sensitivity of the cost parameters of the case study was done by performing a Monte Carlo analysis on the computer based model. The details and reasoning behind the choice of the statistical approach and the Monte Carlo analysis is provided in Section 4.2.2.

1.7 Plan of development

This study was divided into five phases, which are shown in Figure 1.

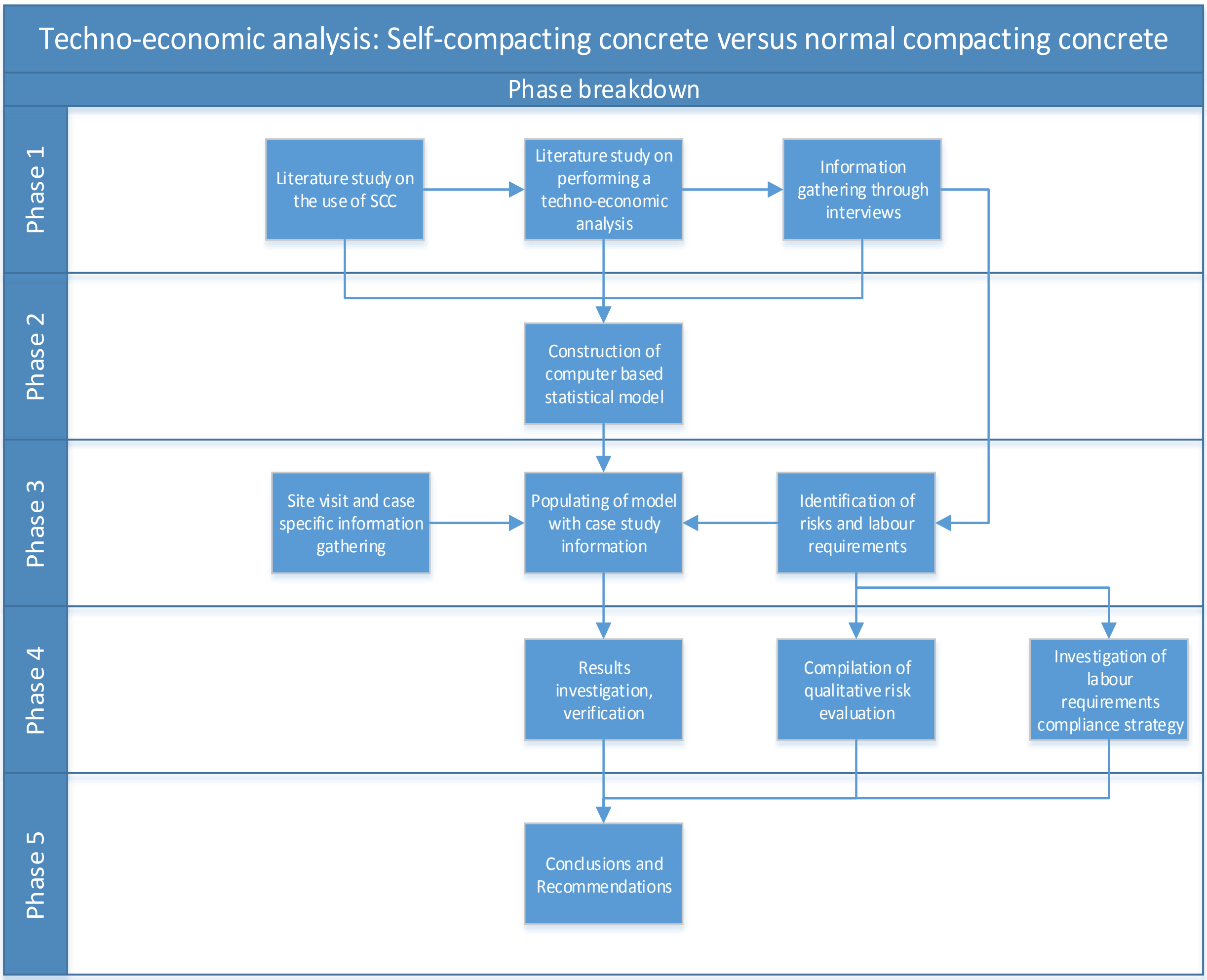


Figure 1: Phase breakdown of research

The report is broken down into nine chapters. The structure of the report can be seen in Figure 2, a more detailed description of every chapter is included in the respective chapter introductions.

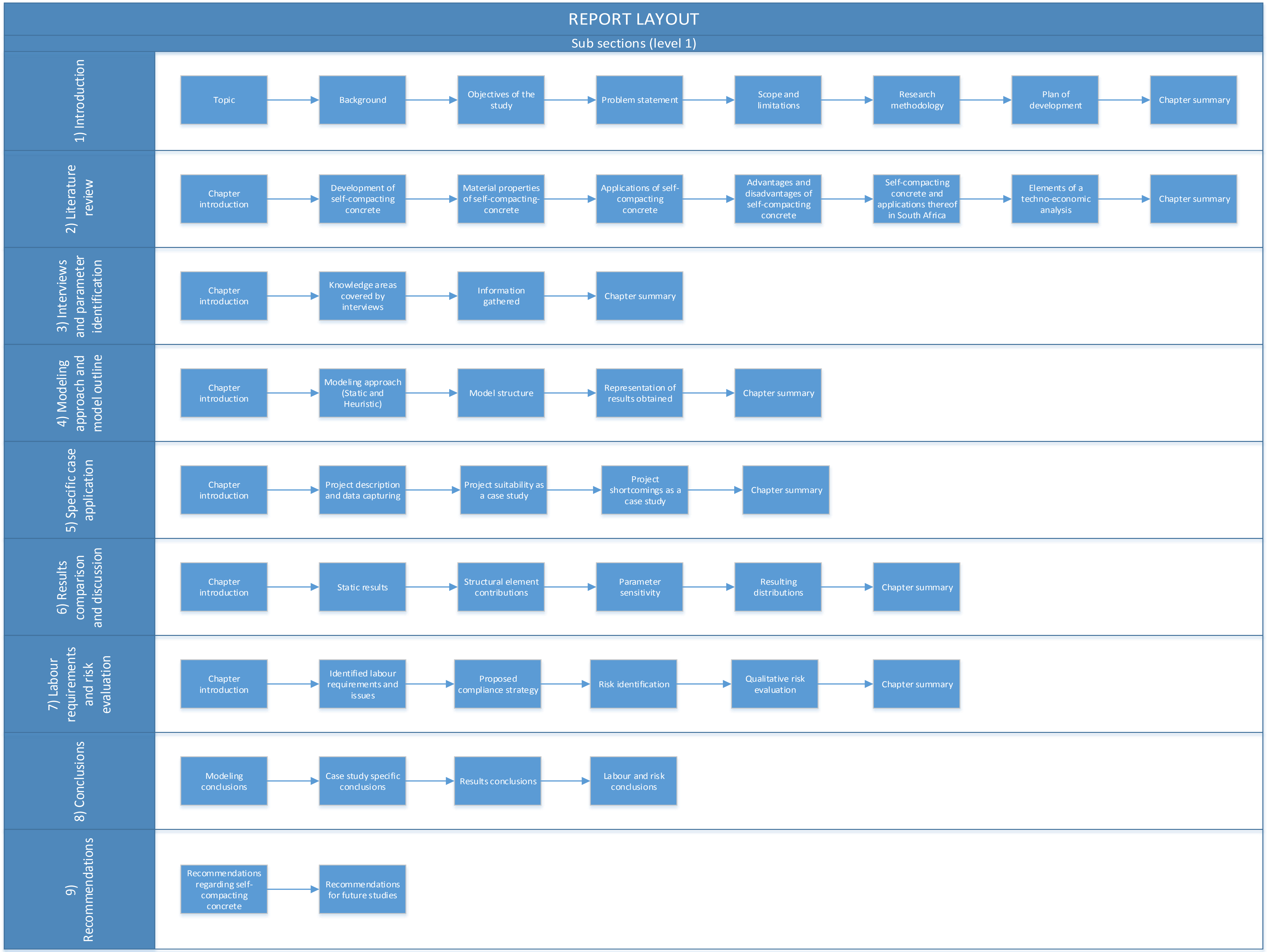


Figure 2: Report layout

1.8 Chapter summary

This chapter served as the introduction to the research and to familiarise the reader with the problem and the material under consideration, namely self-compacting concrete (SCC).

The topic was introduced as a techno-economic analysis, which was done to compare the use of self-compacting concrete with the use of normal compacting concrete (conventional concrete), in the South African construction industry.

A brief background on SCC and its use in a global and local context were given. SCC was introduced as a concrete material that is able to flow under its own weight. The background of the research problem was given to show the necessity of this research.

The primary objective of this study was to construct a cost implication model to quantify the impact of the decision to implement self-compacting concrete technology at a South African construction project. As a secondary objective, the study examined the labour requirements at a typical South African construction project to investigate if it discourages the use of SCC. Additionally, the study pursued to identify the major reasons for the lack of implementation of self-compacting concrete in the South African construction industry. The risks involved with the implementation of SCC were also identified since it is an important consideration when using SCC.

The problem statement was given as well as the scope and limitations of the research project. This was followed by an explanation of the methodology employed in conducting the research, with a breakdown of the work into its five phases.

The report layout was presented graphically to show the flow of information that is discussed in this report.

2 LITERATURE REVIEW

2.1 Introduction

The literature review was performed by investigating local and international literature sources. This was done to enhance knowledge areas, clarify uncertainties and to ensure that the study will not be a duplicate of previous research. This literature review aims to answer the most obvious and frequent questions concerning SCC. The objectives of the literature review include the following:

- To familiarise the reader with self-compacting concrete
- To establish the technical characteristics of the material
- To identify the existing applications of the material
- To identify the advantages and disadvantages of using SCC
- To familiarise the reader with the material's successful applications in South Africa
- To provide a general overview of a techno-economic analysis and why it needs to be performed on SCC in the South African context

2.2 Development of self-compacting concrete

Self-compacting concrete is also known by the following terms: self-consolidating concrete, self-levelling concrete and flowing concrete (Mehta & Monteiro, 2006; Rols, Ambroise & Péra, 1999:261). Certain companies have also named it as a product such as "Agilia", which is the product name for Lafarge's SCC.

The development of SCC was a reaction to poor workmanship and low quality end-products in the Japanese construction industry (Ouchi, 2000:29). It was developed in 1988 by professor Okamura at the University of Tokyo (Okamura & Ouchi, 2003). The idea was formed in 1986, by Okamura, and the research impetus was provided by the successful development of superplasticised, anti-washout, underwater concrete in West Germany during the 1970's (Mehta, 1999:69).

From the creation in Japan, it spread through Asia and found its way to Europe in 1993. Probably through civil works for transportation networks in Sweden in the mid 1990's (Self-Compacting Concrete European Project Group, 2005). In North America, the use of SCC expanded from virtually nothing in the year 2000 to over 1 million cubic metres in 2002. The material was first used in South Africa in 2002. Britain also had almost no SCC usage in 2000 and more than 400 000m^3 of SCC was used in Britain during 2008 (Jooste, 2009:18).

SCC has been accepted with enthusiasm across Europe. It is used for in-situ as well as precast concrete work. Practical applications has been aided and investigated by the academic society who researches the physical and mechanical characteristics for SCC on a continual basis (EFNARC, 2002:32).

The major developments and global spread of SCC, as described above, can be illustrated on a timeline as seen in Figure 3.

1970's	1986	1988	Mid 1990's	2000	2002	2005
• Successful development of superplasticised, anti-washout, underwater concrete in West Germany	• Lack of skilled construction workers lead to structure durability problems in Japan • Development of SCC is started in Tokyo	• The first acceptable prototype of the SCC material is published	• Arrival of SCC in Europe	• North America and Britain still have insignificant usage of SCC, but it is available in the market	• North America uses more than 1 million cubic metres of SCC • Britain uses more than 400 000m³ • The first major usage of SCC in South Africa takes place during the construction of the Nelson Mandela Bridge • EFNARC publishes specifications and guidelines for SCC	• Publishing of the European guidelines for SCC

Figure 3: Basic timeline of SCC development

The questions now are how the South African industry will implement SCC in the future, what the current position is and what the reasons are for this current position.

The use of SCC has been defined and encapsulated by regulating boards and standard bureaus around the world. Documentation and codes have been set up to guide the industry on the use of SCC. In South Africa however, the implementation of SCC is very limited, as will be discussed in Section 2.6. The major international codes and guidelines are summarized in Table 1. It should be noted that SCC is also designed according to the relevant concrete standards (EN, 2006:1; SANS 10100-2, 2014:1).

Table 1: Codes and Guidance documents regarding SCC

Property/Interest field	Codes / Guidance documents		
	The European Guidelines for Self-Compacting Concrete*	EFNARC Specification and Guidelines for Self - Compacting Concrete**	Best Practices Guidelines for Self-Consolidating Concrete***
Description of engineering properties	☑	☐	☑
Specifying SCC for ready-mixed and site-mixed SCC	☑	☐	☐
Constituent materials guide	☑	☑	☐
Mix composition	☑	☑	☐
Production of ready-mixed and site mixed SCC	☑	☑	☑
Site requirements and specification	☑	☐	☑
Placing and finishing on site	☑	☑	☑
Precast concrete products	☑	☑	☐
Appearance and surface finish	☑	☐	☑
Trouble shooting guide	☐	☑	☐
Test methods for SCC quality control	☑	☑	☑

*(Self-Compacting Concrete European Project Group, 2005)

**(EFNARC, 2002:32)

***(Ready Mixed Concrete Association of Ontario, 2009)

2.3 Material properties of self-compacting concrete

When SCC is the topic of discussion, a common question is how it can gain sufficient strength if it is so flowable? This question indicates a necessity to discuss SCC material properties. Misconceptions regarding this material and its fresh state properties are common and it frequently leads to the hardened properties being misunderstood. These misconceptions justify a material properties review and that is the purpose of this section of the literature review.

The investigation of the material properties is a part of the technical side of the techno-economic analysis. It demonstrates to the reader that the material is technically sound, prior to investigating the economic impact of SCC technology.

The mix composition of SCC is discussed and how it differs from normal compacting concrete. This is followed by an explanation of how the superplasticiser admixture works, what the fresh state properties are, and which tests can be used to verify them. Lastly, the long-term properties and durability are evaluated.

2.3.1 Mix composition

One of the major advantages of SCC is that it can be produced with readily available materials, with only the addition of a superplasticiser that differs from normal compacted concrete (NCC). The only other difference in the mix design is the proportions between the constituent materials. This is shown in Figure 4:

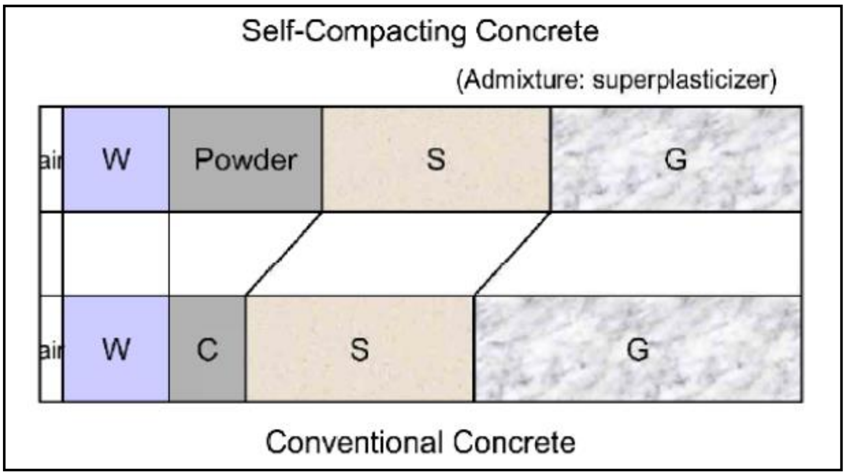


Figure 4: SCC vs NCC constituents (Okamura & Ouchi, 2003)

W = Water
S = Sand
G = Gravel
C = Cement
Powder = Cement and cement replacers, such as fly ash.

It can be seen that the aggregate component is effectively reduced in order to increase the binder fraction of the mix. The result is a mix with a much higher fines content. One might expect a higher moisture demand due to the increased fines, but this is not the case because of the addition of the superplasticiser, as will be explained in Section 2.3.2.

The EFNARC Specifications and Guidelines also support these prescriptions for SCC (EFNARC, 2002:32). A typical range of mix composition, as given by these specifications can be seen in Table 2.

Table 2: Typical range of SCC mix compositions (EFNARC, 2002:32; Jooste, 2009:18)

Constituent	Typical range by mass (kg/m³)	Typical range by volume (litres/m³)
Powder	380-600	
Paste		300-380
Water	150-210	150-210
Coarse aggregate	750-1000	270-360
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48 - 55% of total aggregate weight.	
Water/Powder ratio by Vol		0.85 - 1.10

It is important to note that the water content is not increased, thus with a constant amount of water and an increased amount of binder, the water/binder ratio will decrease. This will translate into a higher strength concrete. This mixture proportioning was also investigated by Domone, the study investigated the range of mixture proportions (in volumetric terms) which can be used to create SCC and found the following (Domone, 2006:197):

- 30-34% of the total concrete volume should be coarse aggregate
- 0.25-0.5 should be used as the water to powder ratio (ratio by mass). If the mixture is at the upper range, it will require viscosity modifiers
  (similar to the ratio expressed in terms of volume in Table 2)
- 34-40% of the total concrete volume should be paste
- 40-50% of the mortar volume should be fine aggregate

Jooste translated this into approximate mass and found the following (Jooste, 2009:18):

- Coarse aggregate 750 - 920 kg/m^3
- Fine aggregate 710 - 900 kg/m^3
- Powder 450 - 600 kg/m^3
- Water 150 - 200 kg/m^3

These masses are in close comparison to that described by the EFNARC guidelines in Table 2. The seemingly different values of the water-binder ratio is due to the difference in the way it is expressed, EFNARC expresses it in terms of volume and Jooste expressed it in terms of mass.

2.3.2 Superplasticisers and their role in SCC

Superplasticisers are admixtures that are added to concrete to enhance workability and/or to reduce water demand. They are more powerful than plasticisers are and they are used to achieve greater fluidity and workability in concrete.

Figure 5 illustrates how the superplasticiser adsorbs (when a liquid is held on the outside surface or on the internal surfaces of a material, as a thin film) onto the cement particle by means of electron charge. In Figure 6, the electron on the outside, with the nett negative charge, is shown. This leads to greater fluidity by giving all the particles a nett negative charge. The negatively charged particles repel one another slightly, making it possible for SCC to flow under its own weight.

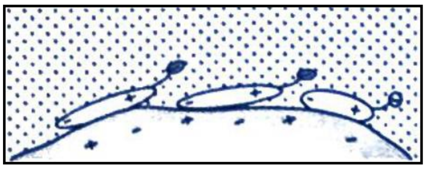


Figure 5: Adsorption onto cement particle surface (Domone & Illston, 2010)

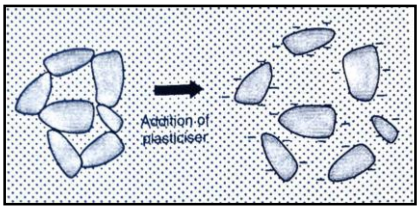


Figure 6: Dispersion of particle flocks and release of entrapped water to give greater fluidity (Domone & Illston, 2010)

This concept shows that the fluidity is not based on extra moisture in the mixture, but rather on a chemical principle at the micro level of the mixture (the idea that the flowability of SCC is due to additional moisture is a common misconception). The flowability is thus due to net negative charge of the particles, rather than an increased moisture content.

The Bingham model approach is a two-parameter approach used to measure the flow properties of concrete. This model is based on rheological principles and proposed by Tattersall with the advent of more fluid concretes, it provide a better measure of workability than the conventional one parameter slump test (Tattersall, 2003). Rheology measurements on fresh concrete show that it is reasonable to approximate the flow behaviour using the Bingham model (Ferraris & Gaidis, 1992; Nielsson & Wallevik, 2003:59). Note that the shear yield stress indirectly measures inter-particle friction and the plastic viscosity depends on the rheology of the paste and the volume fraction of the aggregates. For SCC the shear yield stress is 0-60 Pa, this is very low compared to the couple of hundred Pascal for NCC. The plastic viscosity for SCC is highly variable and can range between 20 and 100 Pa.s (Wallevik, 2003:23).

The effect of superplasticiser on a fresh concrete mix can be illustrated with the Bingham model as shown in Figure 7. This model is used to explain the effect of changing different mix components on the rheological parameters of fresh concrete.

Since the addition of superplasticiser leads to a lower yield stress without affecting plastic viscosity at low volumes, the fresh concrete will be flowable without segregation. The addition of too much superplasticiser leads to higher plastic viscosity and further lowering the yield stress in fresh concrete, this will lead to very flowable concrete but it can cause material segregation.

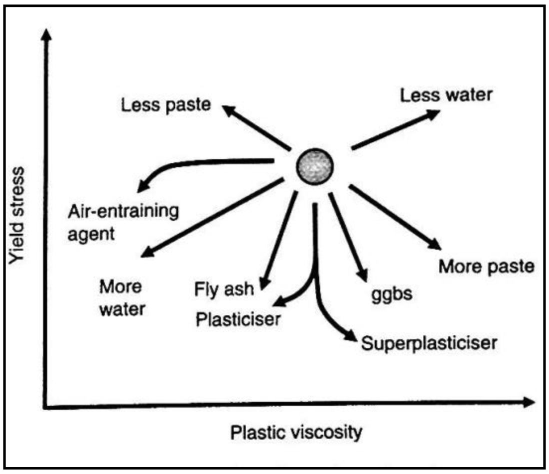


Figure 7: Influence of varying concrete constituents on the Bingham constants (Domone & Illston, 2010)

According to Domone and Newman (Domone & Illston, 2010; Newman & Choo, 2003), the ranges of rheological properties of SCC can be as shown in Figure 8. This change in the two rheological parameters is brought about by the nett negative charge caused by the superplasticiser. The reduction in the shear yield strength is the manifestation of the nett negative charge, leading to increased flowability.

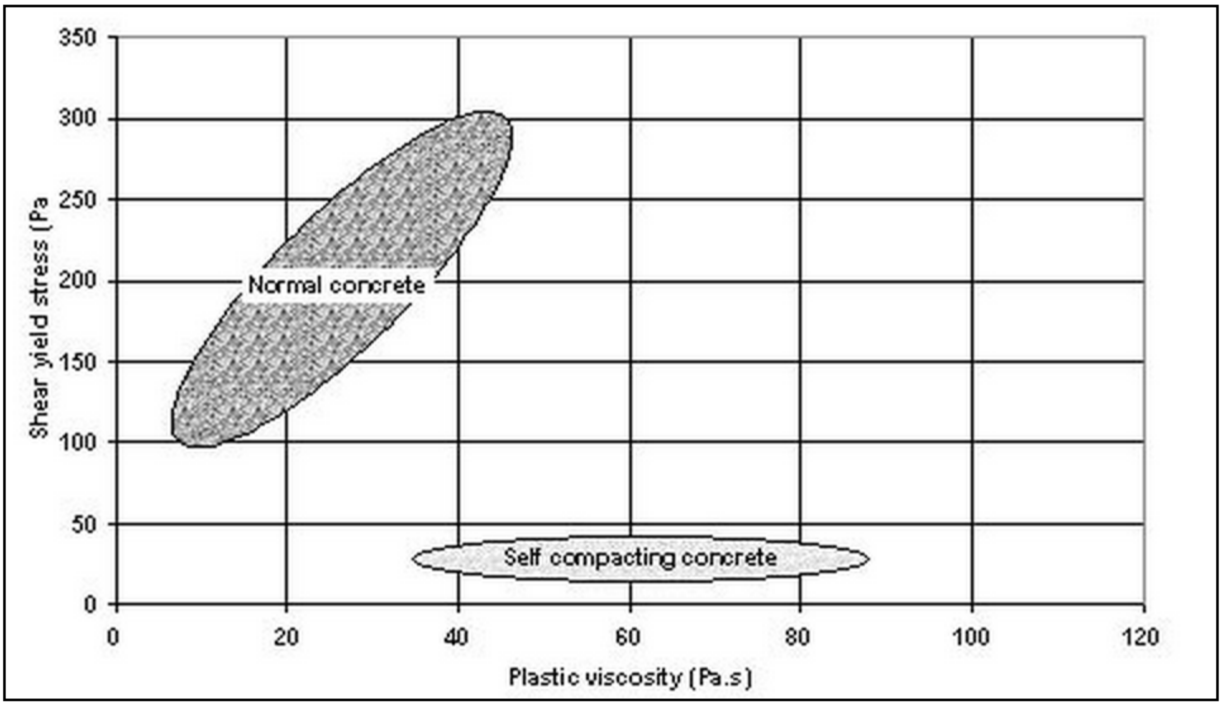


Figure 8: Rheological properties of SCC vs NCC (Newman & Choo, 2003; Wallevik, 2003:23)

2.3.3 Fresh state properties

2.3.3.1 Rheology

Since SCC is defined as a concrete with high workability and no need for vibration, it is obvious how this property differs from NCC. The rheological differences are properly covered in the previous section and are shown in Figure 8.

For concrete to be considered as SCC it needs a slump-flow of more than 550mm without significant segregation. It also needs to reach a diameter of 500mm within two seconds (Domone, 1998:177). The volume used for this test is the same as for the regular slump test. The Tattersall Two Point Test is used by the South African industry, in addition to the slump flow test, to measure concrete rheology (Jooste, 2009:18).

As explained by the Bingham model in Figure 7, SCC can be less viscose than NCC, but it must have cohesion to stay uniform (Domone & Illston, 2010).

2.3.3.2 Segregation

SCC should be designed to have a good resistance to segregation. This can be defined as the ability of concrete to remain homogeneous in composition while in its fresh state (Self-Compacting Concrete European Project Group, 2005). The viscosity of the paste in SCC is the highest among various concrete types due to its low water to powder ratio, this characteristic should inhibit segregation of fresh concrete (Okamura & Ouchi, 2003).

Segregation in SCC is not a problem if it is designed correctly and it can be tested with the sieve segregation resistance test (BS EN 12350-11, 2010). It is required that less than 20% of the mass can pass the 4.75 mm sieve.

Admixtures such as viscosity modifying admixtures can be added to the mix to increase cohesion and segregation resistance (Yang, 2004). Poorly designed SCC could have segregation issues, similarly to poorly designed NCC. Any tendency to segregation can have significant detrimental effects on the quality of the hardened concrete (Domone, 2007:1).

2.3.3.3 Bleeding

Bleeding in SCC is usually less than in NCC. This is mainly due the lower water content and the higher fines content. The higher fines content is a result of higher binder content, consisting of cement and cement replacers, as well as an increased sand content that is usually incorporated (Ramanathan, Baskar, Muthupriya & Venkatasubramani, 2013:465; Sari, Prat & Labastire, 1999:813).

As with segregation, a well-designed SCC mix will be cohesive enough to be handled without segregation or bleeding (Aslani & Nejadi, 2012:330).

The reduced bleeding can increase the risk of plastic shrinkage cracking. This increased risk can be mitigated through conventional curing practises if executed with due diligence.

2.3.3.4 Strength development and final compressive strength

According to the European Guidelines for SCC, the strength development of SCC is similar to that of NCC. The document concludes that maturity testing will be an effective way to control the strength development, whether accelerated heating is used or not (Self-Compacting Concrete European Project Group, 2005). This shows that no major site management, regarding strength tests, is required when SCC is used. The curing times and other strength development related managerial decisions would stay unchanged.

This statement is confirmed by the EFNARC guidelines document. It states that SCC can be designed to fulfil the requirements of EN 206 regarding density, strength development, final strength and durability (EFNARC, 2002:32).

Other guidelines and research literature even state that SCC can typically achieve a slightly higher compressive strength, compared to NCC with a similar water-binder ratio. This is due to the improved interface between the aggregate and the hardened paste (Ready Mixed Concrete Association of Ontario, 2009).

2.3.3.5 Plastic settlement

SCC should be designed to have sufficient resistance to segregation and to be stable, but just as with NCC, plastic settlement cracking can occur above the reinforcement bars. Admixtures such as viscosity modifying agents, together with the appropriate powder content can decrease the risk of plastic settlement cracks (Self-Compacting Concrete European Project Group, 2005).

The occurrence of plastic settlement cracks can be reduced with well-designed SCC due to the higher flowability and better uniformity. The increased flowability ultimately causes the cracks to be filled. This will not be the case if the specific SCC mix is prone to segregation.

2.3.3.6 Plastic shrinkage and creep

Since SCC has less bleeding, the evaporation of surface water must be controlled more diligently. Proper curing can prevent plastic shrinkage cracks from forming, but SCC will inherently be more susceptible to this form of cracking (Miao, Tian & Liu, 2009; Wallevik & Níelsson, 2003).

A higher volume of cement paste in SCC leads to a slightly higher expected creep than with NCC according to the SCC best practice guidelines of Ontario. Shrinkage (autogenous and drying shrinkage) is similar to that of conventional concrete (Ready Mixed Concrete Association of Ontario, 2009).

This is contradictory to the European Guidelines which states that deformation due to shrinkage may be higher for SCC, but deformation due to creep may be lower. The value of the sum of deformations due to shrinkage and creep were found to be similar to that of NCC (Self-Compacting Concrete European Project Group, 2005). The EFNARC specifications also support the finding of higher plastic shrinkage, but note that creep might also be higher. The specifications suggest specifying these parameters when using or procuring SCC (EFNARC, 2002:32).

Due to the latter statement being in an accepted standard code, it is assumed an acceptable notion. However, care needs to be taken when these parameters might be crucial in the application of SCC.

2.3.4 Long term properties and structural durability

The mechanical properties of SCC have been well researched over the last decade and a half and fundamental cognitions of this material have been developed. Klug, Holschemacher, Wallevik and Nielsson (2003:596) did an investigation into the hardened properties of SCC and NCC to test whether one can use the conventional design rules for designing structural members created from SCC. They found the following:

- At the same water-binder ratios, the compressive strength and the development thereof is similar for SCC and NCC
- Splitting tensile strength tests on SCC frequently achieves better results than NCC
- The modulus of elasticity of SCC is clearly lower than that of NCC

However, all the deviations were found to be within the tolerance range used for NCC. They concluded that it is possible to design structural members made of SCC in the same manner and with the same guidelines as for NCC. They noted that considerations have to be taken regarding restrictions in the codes that prevent the most effective use of SCC. One such consideration is the slightly higher tensile strength of SCC, which can lower the minimum reinforcement requirements of a structural element (Klug, Holschemacher, Wallevik & Nielsson, 2003:596). This potentially applies to restrained members.

These findings are aligned with the findings of other researchers (Bennek, 2007:24; Van Keulen, 2000). They found that:

- The maturity method to predict the cube strength of NCC is also applicable for SCC
- The characteristic cube strength of SCC is at least ten percent higher than for NCC, with the same w/c ratio
- The ratio tensile strength / compressive strength is comparable with NCC
- The Young modulus is 10-15% lower after 18 hours and about 10% lower after 28 days
- The shrinkage and creep deformation together, are less than or equal to that of NCC
- The transfer lengths of pre-stressed strands are comparable or better than for NCC
- The water-penetration test results did not show much difference from NCC

2.4 International applications of self-compacting concrete

SCC has been used globally for a wide range of applications since its inception. The nature of the material lends itself to adaptions to suit most concrete applications. Some of the major milestones of SCC development and its implementation are discussed in this section. This is by no means an all-comprehensive list, but the discussion highlights possible utilisations of SCC in the South African construction environment.

2.4.1 Japan

One of the first and well-documented uses of SCC in Japan was the construction of the two anchorages of the Akashi-Kaikyo Bridge system in Japan that opened in April 1998 (Mehta, 1999:69). This bridge is a suspension bridge with the longest span in the world of 1 991 metres (Ouchi, 2000:29). SCC was used to accelerate the placement of the 290 000m^3 of concrete in the anchorages. The total construction time was reduced from 30 to 24 months (Jooste, 2009:18).

Another more recent application of SCC in Japan is the construction of latticework and tunnel linings. The use of SCC in tunnel lining construction prevents cold joints since it limits bleeding or laitance at the joints (Okamura, Ouchi, Wallevik & Nielsson, 2003:3).

2.4.2 Europe

In France, SCC is utilised by the ready-mix concrete industry to provide clients with a noise free product that can be used twenty-four hours a day in urban areas (Mehta, 1999:69). NCC can usually not be placed at night in the urban areas due to the noise involved with using vibrators and other placing equipment.

Sweden uses SCC in the construction of bridges, box tunnel monoliths, tunnel entrances, foundations and more. The usage of SCC by Sweden’s precast and ready-mix industry was about 10%

of total concrete usage in 2003 (Skarendahl, 2003:6). This figure was confirmed by the interviews and was still applicable in 2014 as will be shown in the following chapter.

In the Netherlands, SCC is particularly favoured in the precast industry. Some precast manufacturers choose to use only SCC in all their manufacturing processes (Walraven, 2003:15). Pre-cast slabs, beams, walls, columns, arches and bridge elements are all made from SCC. More recently, fibre reinforced SCC has been used in the production of thinner and lighter floor elements (Walraven, 2003:15).

SCC has also been implemented in Norwegian highway structures. It was used to improve working conditions, improve concrete surface finishes, to ease casting in low access areas of structures and to make the construction process safer (Frydendal et al, 2003:958).

In the United Kingdom, an official initiative to expand the use of SCC, as a means to replace NCC, has been put in place by The Concrete Society (Hurd, 2002).

2.4.3 North America

Apart from the uses already mentioned for the other countries, two examples of SCC usage in the US are notable. The first example occurred during the construction of the Trump Tower in New York City. Concrete between tightly reinforced elements had to be poured in sub-zero weather and the use of high-strength SCC was imperative for this construction (Hurd, 2002).

The second application in the US was the construction of houses in Houston. Here the exterior walls and slabs were cast monolithically using SCC. The exterior face was textured and stained to provide a brick-like resemblance and a foam core was cast inside the wall to provide insulation (Hurd, 2002:44).

Mixtures of a low compaction energy concrete, which is tentatively called slip-form self-consolidating concrete, has been developed at Iowa State University. This was done in response to several cases of premature cracking in slip-form paving due to internal vibration causing over-consolidation (Shah., 2009:3).

2.4.4 Other countries

An analysis of 11 years of case studies showed that out of 51 case studies the following reasons were given for using SCC (Domone, 2006:197):

- In 67% of the cases SCC had technical advantages over NCC
- In 14% the economic benefit was the reason for using SCC
- In 10% of the cases SCC was used in a novel form of construction such as steel-concrete composites, thin sections or pre-cast units
- The remaining 9% had unclear reasons or did not state any reason

Environmental benefits were also cited as a complementary reason for SCC usage in these cases. It is interesting to note that 77% of the applications in this analysis did not regard cost savings as a major incentive for SCC usage. This indicates that SCC will remain in use in the industry irrespective of the economic findings of this dissertation, since cost savings are not the only driving force that leads to SCC implementation. It is thus important to weigh the technical benefits against the economic impact of using SCC when it is implemented on a project site.

SCC has also been used for bonding old and new concrete when aging structures need to be strengthened or when existing structures have been damaged (Chalioris & Pourzitidis, 2012). In Mexico, SCC has been used in the pre-cast industry, as in many other countries mentioned already, to increase the productivity of the production processes (Shi, Yu, Khayat & Yan, 2009:893).

Other uses of SCC include the construction of rafts and retaining walls in and the construction of a nuclear power plant in India (SCC mitigated the risk of the fatal consequence of potential concrete workmanship errors). In Australia SCC is used for the construction of precast pits, mainly to eliminate noise pollution as the manufacturing plant is situated in a residential area. Australia also uses SCC to construct pre-stressed bridge girders to save on in-situ labour and to reduce concrete pouring time (Asmus, Christensen, Shi, Yu, Khayat & Yan, 2009:823).

According to an international research team who investigated numerous cases in various countries where SCC has been implemented, the focus should lie on future requirements. They state that SCC should have a bright future as momentum from industry and academia from all over the world builds up for the use of this material. The extensive and growing research, knowledge, awareness, standardisation and increasing project experience and confidence will also contribute to the future of SCC (Zhang., 2009:831).

2.5 Advantages and disadvantages of self-compacting concrete

As with any material SCC can provide an advantage when used for the right application. To know how to identify a scenario as being more favourable, one should be familiar with the advantages and disadvantages of the material. The following advantages and disadvantages have been identified from literature and from the interviews conducted with experienced industry participants (described in Chapter 3). Certain advantages and disadvantages are case specific, but the onus rests on the project team to determine which of these will be applicable for the project under consideration.

2.5.1 Advantages

- Increased speed of construction, such as the 20% time saving on the Akashi-Kaikyo Bridge (Jooste, 2009:18)
- Cost savings due to lower labour requirements (Damtoft, Lukasik, Herfort, Sorrentino & Gartner, 2008:115)
- Secondary labour cost savings due to accelerated overall project schedule (Geel, Beushausen & Alexander, 2007:11)
- Increased site productivity (Damtoft, Lukasik, Herfort, Sorrentino & Gartner, 2008:115; Zhang., 2009:831)
- Higher quality and aesthetically pleasing finishes are easier to obtain (Zhang., 2009:831)
- Improved structural durability due to better compaction (EFNARC, 2002:32)
- Overall better buildability of designs (Walraven, 2003:15)
- The responsibility of concrete quality is shifted off-site to the producer of the SCC (if ordered ready-mixed)
- Low noise levels on site (Yang, 2004)
- Low dust levels on site due to absence of concrete vibration activities (Walraven, 2003:15)
- Low wear of formwork due to absence of vibration (Mehta, 1999:69)
- Safer working environment (EFNARC, 2002:32)
- Freedom of shape in design (Geel, Beushausen & Alexander, 2007:11)

- Ability to encapsulate heavily congested steel reinforced sections with relative ease (Khayat, 1999)
- Higher strength concretes are possible while increasing the workability at the same time
- Less cement needed due to the addition of fly-ash. This also reduces the carbon-footprint since cement production is not environmentally friendly and fly-ash is an industrial by-product (Damtoft, Lukasik, Herfort, Sorrentino & Gartner, 2008:115)
- Overall energy savings during concrete placement (Damtoft, Lukasik, Herfort, Sorrentino & Gartner, 2008:115; Zhang., 2009:831)

2.5.2 Disadvantages

- Additional fines such as fly-ash or more cement are needed
- Moisture content should be supervised more diligently due to the sensitivity to moisture variations such as wet sand
- SCC is sensitive to aggregate changes
- The importance of the delivery schedule can produce additional risk and pressure
- Additional formwork requirements are needed due to hydrostatic pressures. This translates to higher formwork cost (Shah., 2009:3)
- Increased cost of raw materials due to the addition of superplasticiser and a higher binder content
- An overall paradigm shift is required in the supply chain to ensure all the stakeholders understand the impact of using SCC
- There can be an additional initial cost to change or upgrade the mixing lot
- Increased sensitivity to shrinkage cracks due to the increased fines content

2.6 South African applications of self-compacting concrete

The use of SCC has been steadily increasing around the world, but it is not regularly implemented in South Africa. It was only in 2002, during the construction of the Nelson Mandela Bridge in Johannesburg, when it was first used on a large scale in South Africa. It took fourteen years for South Africa to realise the potential of this product, a fact that indicates that there are extensive knowledge that still needs to be acquired by the South African industry (Jooste, 2009:18). The current SCC sales are about 1% of the total concrete sales, only a tenth of the 10% average in developed countries. This was concluded from the interviews with Lafarge.

In 2007, a study revealed that SCC was mainly used in South Africa for the construction in high-rise buildings due to the technical advantages of the material. Figure 9 shows the results of this study, there were 17 participants in the study and they reported using only small volumes of SCC (Geel, Beushausen & Alexander, 2007:11).

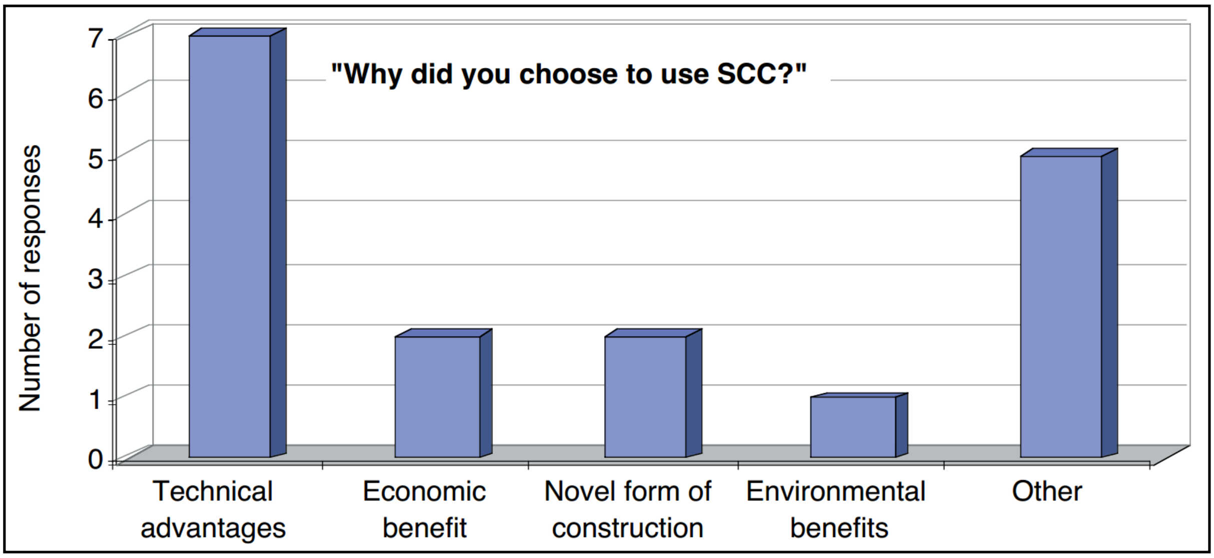


Figure 9: South African market review of SCC in 2007 (Geel, Beushausen & Alexander, 2007:11)

SCC gained some ground in the South African construction industry by 2009, as it became better known. SCC was used during the construction of the Bakwena highway bridge deck. The deck had to be cast in one pour and difficult access led to the use of SCC (Jooste, 2009:18).

The Soccer City stadium, south of Soweto, was also constructed using SCC in 2008. SCC made it possible to construct 140 slender columns that are asymmetric and eccentric with 860 kg/m³ of reinforcement steel (The Concrete Society of Southern Africa, 2013:12). It was stated, by George Evans from the Cement and Concrete Institute, at the *Self Compacting Concrete seminar roadshow – SCC 2013* that the construction was only possible with SCC.

SCC was also used in the construction of the Alexander Forbes headquarters, a winner of the 2013 Fulton Awards. SCC was used for the off-shutter concrete columns with dense reinforcement and a length of 8.5m. The columns formed an architectural feature of this project. SCC was also implemented to provide high quality off-shutter walls for the structure. Special high-tolerance box-outs were designed and manufactured for all the walls to accommodate the high formwork pressures associated with SCC (CSSA, 2013:20).

The 'Podium At Menlyn' utilized SCC in the construction of its facade walls. This structure was the winner of the Innovative Construction award at the 2013 Fulton Awards. The product of choice was Lafarge's Agilia Vertical SCC and 360m³ of SCC was used (CSSA, 2013:20).

The application of SCC in South Africa is thus growing and diversifying. The Alexander Forbes headquarters and Podium At Menlyn clearly show that the industry can indeed implement the material in larger and more complex projects. Not only was it used successfully, the awards it received certainly highlights the possible advancements that SCC can bring to a project. The industry has however only been gradually making the paradigm shift, with researchers and producers of self-compacting concrete and/or superplasticisers mainly driving the knowledge transfer. The precast industry of South Africa is in a good position to reap the rewards that SCC might hold (Geel, Beushausen & Alexander, 2007:11; Jurgens & Wium, 2007).

The financial cost of the concrete, the higher quality formwork and technical skills required were the main reasons given by interviewees for not using SCC in South Africa (as summarised in Appendix A). A local factor to be considered regarding the economic side of SCC usage is South Africa's relatively cheap labour. The low labour cost might cause slower implementation of SCC as the material cost of the product is significantly higher than that of NCC. The South African tender process where the lowest bid is often awarded the tender, places significant weight on the financial impact of SCC usage, lowering the importance of the possible technical benefits that can be realised.

This study therefore provides a method for financial comparison. This method can aid the construction industry in the decision making process of implementing SCC and in the cost management process when using SCC.

2.7 Elements of a techno-economic analysis

A techno-economic analysis is essentially a modelling technique, used in research, which combines process, market and input cost information to predict future cash flows. This is usually done to derive a predicted return on investment (Walwyn, 2013).

This description can be greatly elaborated on, some other researchers describe the concept in terms of what it is and what it is not (Knoll, 2012:5):

"What is it?

- *Business case modelling taking into account the technical dependencies and constraints during the process of cost and revenue calculations*
- *Long term business planning supporting strategic decisions and medium term operations and management decisions*
- *Periodic model runs with adopted input for result consolidation, operations controlling and decision valuation*
- *Sensitivity analysis reveals focus areas/elements for optimization*

What is it not?

- *No replacement for network planning*
- *Normally not inventory based*
- *No real-time or short term monitoring or controlling"*

Thus, it can be stated that a techno-economic analysis aims at quantifying the economic feasibility of a technology, the results should enable a user to analyse the economic aspects of new technologies and associated business models (Salmien 2008).

The techno-economic analysis framework was used in this research to execute a cost comparison between the use of SCC and NCC at a specific South African construction site. This is done to identify the total cost difference between the materials, as well as the sensitivity of the cost constituents. The identification of the major cost constituents is a key outcome used to interpret the overall financial implication of using SCC and to optimize cost management strategies.

A distinction between structural elements such as walls, slabs, columns and beams was made to identify the cost influence of using SCC on the various elements. Better medium term operational and managerial decisions can be made by comparing the size of the different cost constituents between elements.

2.7.1 Typical structure of a techno-economic analysis model

A techno-economic analysis is a technique that is based on data that is extracted from an inherently risky source. It incorporates this risk and/or variability into the model to enable the modeller to do *what if* analyses. The technique is used in fields such as finance, project management, energy, manufacturing, engineering, research and development, insurance, oil and gas, transportation and the environment (Palisade Corporation, 2014).

Typical information that is used in a techno-ecconomic analysis can be described as follows (Walwyn, 2013):

- Product information (what is the product and what market will it serve)
- Process technology information (how will it be made/implemented/delivered to the market)
- Raw material information (what material is needed and what will it cost)
- Operating cost, direct and indirect (overheads and personnel cost)
- Capital and R&D cost (what investments are necessary)

An overview of the structure and execution methodology of a techno-economic analysis can be seen in Figure 10:

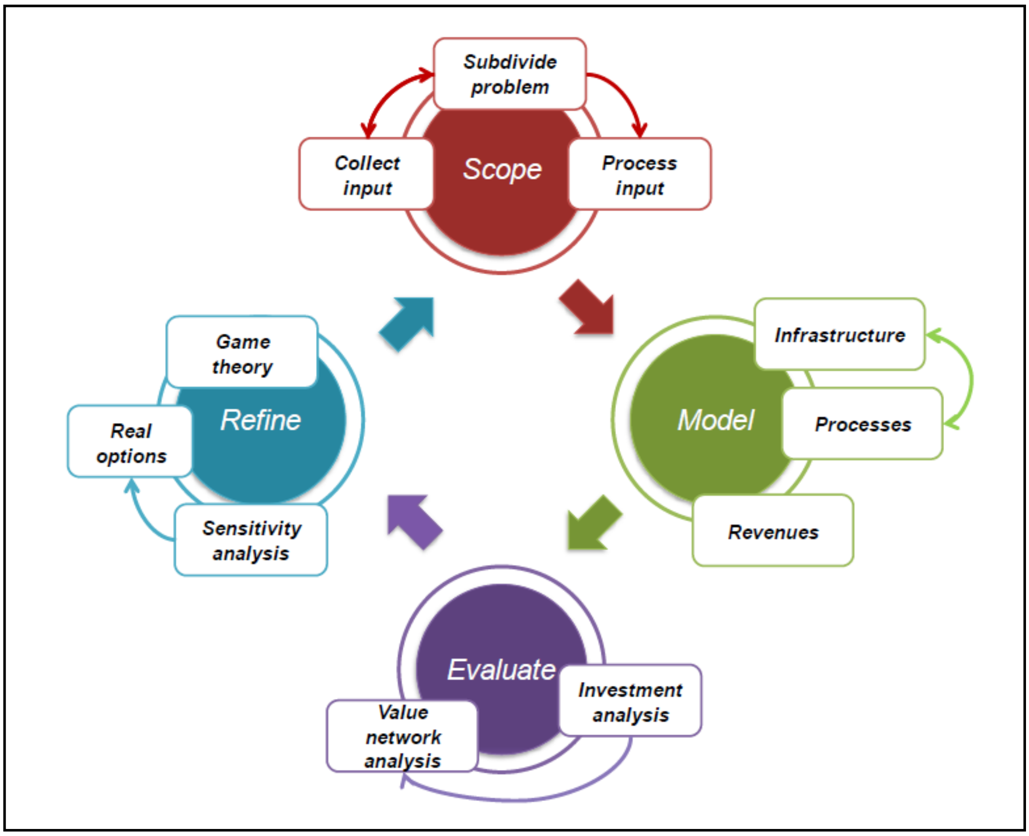


Figure 10: Techno-economic analysis methodology (Verbrugge, Casier, Van Ooteghem & Lannoo, 2008:1)

This is a general overview and certain aspects such as game theory will not be included in the study. The results interpretation is however based on a static analysis, a Monte Carlo analysis and the sensitivity analysis that supplements it.

The scope of the model was identified through the literature studies and the interviews. The model is a computer based financial model based on static cost calculations and on case study information. Further evaluation of the uncertain input data was then performed by means of a Monte Carlo analysis on the information extracted from the particular case study. The model was further refined to enable the user to extract summarizing information and to do a sensitivity analysis.

The Monte Carlo simulation method is used to model reality (uncertainty of input parameters) and to produce a series of scenarios (model states) by substituting selected probability distributions for the input parameters that are subject to inherent uncertainty. Hundreds or thousands of iterations can then be performed, using a different set of random values from the prescribed input probability distributions. The Monte Carlo simulations produce distributions of different possible outcome values. Probability distributions are a more realistic way of describing scenarios with inherent uncertainty. A Monte Carlo simulation shows the user how likely a result is, in addition to what a possible result is (Palisade Corporation, 2014).

According to the developers of the @Risk software, Monte Carlo simulation provides the following advantages over deterministic analysis:

- Probabilistic results, a likeliness of each outcome is added to each possible outcome value
- Graphical results make it easier to convey results to others
- Sensitivity analysis can easily show which inputs had the biggest effect on the bottom-line results
- Scenario analysis is easily performed, this enables the user to identify which values interacted with which inputs when outcomes of interest occurred
- Correlation of inputs can be modelled and can so capture interdependent relationships between input variables (Palisade Corporation, 2014)

Further details about the Monte Carlo analysis, and why it was chosen for the heuristic modelling, will be provided in Chapter 4, *Modelling approach and model outline.*

2.7.2 Inputs to a techno-economic analysis model

The techno-economic analysis is a stepwise procedure with various inputs at every step. One possible structure of the basic steps and information evolution are shown in Figure 11.

The model is built to provide a user with insight into the opportunity and/or risk through the integration of probability and scenario analysis. The techno-economic framework is used to extend the static model (demonstrated here as a Net Present Value model) through integrated Monte Carlo and opportunity analysis.

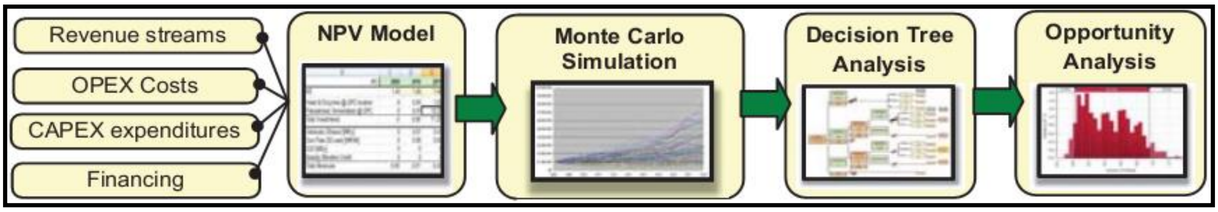


Figure 11: Modelling overview (Strategy Analytics Research Knowledge, 2013)

The revenue streams, operating costs and capital costs will be the major inputs of the model constructed for this research. Expenses are categorised into formwork, labour, material and rework expenses. This information will then be modified to represent a static result that represent the cost and cost breakdown of using SCC and NCC respectively.

Statistical data is then added to the model to create the Monte Carlo simulation. From this, the final distillation of the results can proceed. For this dissertation, Excel was used to construct the static model that represents the expenses of the case study, while the @Risk software was utilized to perform the Monte Carlo analysis by applying statistical distributions to certain inputs of the static model to make the model dynamic. This software was also utilized in the sensitivity analysis and is discussed in Chapter 4, *Modelling approach and model outline*.

2.7.3 Output from a techno-economic analysis

Since a techno-economic analysis quantifies the economic feasibility of a technology, the results should enable a user to analyse the economic aspects of new technologies and associated business models (Salmien, 2008).

These economic aspects include possible overall cost benefits, breakdown of cost implications, and certainty of the calculated results. The identification of high-influence cost parameters is another valuable output of a techno-economic analysis. This is not an all-comprehensive list of the outputs, but it is a summary of the information pursued through this research. More detail will be presented in Section 4.2.2.

2.8 Chapter summary

After the development of SCC in Japan, in response to a lack of skilled construction workers, the technology spread to Europe and then to North America and the rest of the world. Guidelines and specifications have been published by EFNARC and various individual countries. In South Africa, the design of SCC can be based on these documents, or on SANS 10100-2. The SANS codes do however not provide guidelines for SCC specifically but the fundamental guidelines of NCC can be applied in SCC mix design as well.

The material properties of SCC have been thoroughly researched and it is well published, the material is suitable to apply to any construction project that desires to use concrete materials. The concrete mix contains more fines than NCC and the addition of superplasticiser is the only additional element in the production of SCC. The long-term properties of SCC have also proved to be sufficient for construction use. The long-term properties of SCC can be expected to exceed that of NCC in certain categories.

Internationally, SCC has been incorporated by most developed countries such as Japan, China, the European countries and those of North America. This technology has been successfully implemented in a wide variety of projects including commercial structures, bridges, tunnel linings, residential property and special high strength applications such as skyscrapers. The material has been tested in large, complex projects and proved suitable for successful concrete construction.

Advantages and disadvantages of SCC, as with any material, should be understood before it is implemented. The material has improved workability and can lead to improved durability of a structure, but it can be more expensive and it requires higher skilled personnel to produce.

South African application of SCC is lagging behind that of the developed world. The industry has however, harnessed some SCC advantages and SCC usage has been growing in South Africa in both the industry and the research fields. The South African industry has applied SCC successfully in the construction of large commercial properties, bridge decks and in the precast industry. There might still be certain advantages that the industry can harness from SCC since South African sales are a tenth of that in certain developed countries when compared to the total concrete sales per annum in a country.

A techno-economic analysis on SCC entails both an investigation into the technical aspects of the material (as covered by the literature study and the interviews) and an investigation into the economic impact of implementing the technology on site. The economic impact will be investigated through the cost modelling of a case study. The case study and the costing model developed for this research will be used to identify the major cost factors, the sensitivity of these parameters and a risk evaluation of implementing SCC at the specific project. A computer based Monte Carlo analysis was identified as a means of incorporating variability into the techno-economic investigation.

3 INTERVIEWS AND PARAMETER CLARIFICATION

3.1 Introduction

Interviews were conducted as a part of this research to supplement the various knowledge areas that form the foundation of this research regarding the implementation of SCC. Most interviews were conducted in person and a small number of interviews were conducted telephonically.

The knowledge areas were first defined and an interview protocol for each of the eleven interviewees was developed based on their role in industry. The interviewees were selected based on their work in industry and their ability to enrich the required knowledge areas. The industry participants consisted of contractors, consultants, clients, commercial SCC suppliers, superplasticiser manufacturers, quantity surveyors and formwork specialists. The list of the industry participants are given in Appendix A.

Interviews were chosen over other information gathering techniques, such as surveys and questionnaires, due to the enhanced efficiency and access to information. The absence of a rigid pre-set structure of questioning and the adaptability of personal conversation is the major advantage that interviews have over other information gathering techniques. The predefined protocol was used to ensure that all the required topics were covered and digressions were then allowed to provide additional information.

The interviews were approved as an information gathering techniques by the Faculty Ethics Screening Committee of the Engineering Faculty of Stellenbosch University.

3.2 Knowledge areas covered by interviews

The knowledge areas that were covered by the interviews were chosen to supplement the identification of the critical performance areas (CPA's) that are of interest in the economic analysis. These areas could then be used to identify the key performance indicators (KPI's) which are calculated by the model. The interview information was also used to compile the risk register, to identify the perception about labour requirements associated with SCC, to form a knowledge base about the SCC market in South Africa and to identify the reasons for the slow uptake of SCC by the local construction industry.

The following topics were covered during the interviews, not all the themes were covered by all the interviews, but all the items on the list were covered by one or more interviews:

- If SCC is not used on their projects, what are the reasons?
  Otherwise:
- What are their experiences in terms of cost, time, quality and ease of use
- What is the impact of SCC on construction processes
- What decision criteria are implemented when deciding to use SCC or not
- Are there additional design requirements when implementing SCC
- What challenges has arisen from using SCC
- What labour requirements have to be considered when using SCC
- What are the cost impact on labour and materials if SCC is implemented
- What are the formwork requirements and impacts if one utilizes SCC

- What other cost impacts have you realized when using SCC
- Is there examples where SCC cannot be used instead of NCC
- How does a labour minimizing technology impact your tender requirements
- How has the market for SCC developed in the last 10 years
- What changes are expected in the SCC market in future

The parameters and results used in the model were more clearly defined through the discussion of these topics.

3.3 Information gathered

The conclusions drawn through the interviews are summarized in this section. The detailed report on the individual comments of the interviewees can be seen in Appendix A. The information is discussed in terms of the defined knowledge areas stated in Section 3.2.

3.3.1 Cost impacts on materials, formwork and labour

Material

The concrete material cost will probably rise if the decision is made to implement SCC. This is due to the higher binder content in a SCC mix, relative to a NCC mix. The higher binder content means that the cement content is higher and this leads to an overall increase in price. The addition of superplasticiser is another additional cost that will increase the concrete unit price. This price difference can be reduced by using cement extenders such as fly-ash or slag. The cost of the skilled labour involved in mixing SCC will be included in the margin if SCC is ordered from an external supplier. It was also noted that the price difference between SCC and NCC would be different in the Northern parts of South Africa than in the Western Cape and other coastal regions. The mining activities and industry in the Northern regions leads to a high availability of fly-ash and aggregate, this surplus lowers the market price of concrete and leads to a smaller price difference between SCC and NCC.

Formwork

The opinion regarding formwork was that the price per square metre would increase since SCC formwork should resist full hydrostatic pressures. The percentage price increase of formwork for wall elements was predicted to be the highest of all element types. A decrease in the large rework expense associated with NCC off-shutter concrete can make SCC more economical and advantageous when building according to these concrete finishing specifications. The formwork cost of horizontal applications was noted to be comparable with that of NCC, but the risk associated with formwork leakage and total material loss was emphasized for horisontal elements. If custom formwork has to be designed, the formwork expense will rise notably and the extent of such a rise will depend on the design. Any formwork that must resist hydrostatic pressures will be more expensive than standardised NCC formwork systems.

Labour

The views regarding the cost influence of SCC on labour differed between the interviewees. The suppliers of SCC noted that it could lead to a 50% reduction in the labour involved with concrete works. The contractors noted that this saving would only realise if the correct managerial steps are taken and the labour levelling (management) on site is done effectively. Another view was that the labour savings would not be significant in South Africa, because the labour in South Africa's construction industry is relatively cheap in comparison to first world countries.

These insights helped to define the structure of the cost comparison model that will be discussed in the next chapter.

3.3.2 Other cost impacts

Numerous other expenses, besides material, formwork and labour expense, are impacted when SCC is implemented on a construction site. Cost savings through the reductions in overheads, including insurance costs, were mentioned as a consideration if a construction schedule is accelerated by using SCC. Rework savings on densely reinforced structures and the elimination of the need for screeding slabs were also mentioned. Additional expenses if SCC is implemented include the use of higher skilled labour to ensure the proper production of SCC and watertight formwork. Risks such as formwork failures and moisture variation were highlighted and how the financial impact of the risk realisation can differ if SCC is used.

The carbon footprint of construction activities was mentioned as a non-financial impact of SCC usage. The higher cement content in SCC might increase the carbon footprint of the concrete mix, but it will have to be weighed against factors such as the possibility of increasing the cement extenders and lowering the energy use during placement.

3.3.3 Experiences regarding total cost, time, quality and ease of use

Cost

The general opinion regarding SCC implementation was that it would increase the overall project cost. This cost increase is the nett effect of the expense changes in the costing subcomponents such as formwork, labour, material and time saving.

The expected expense changes of the individual subcomponents varied between the interviewees. For example, while certain participants expected an increase in formwork cost due to the increased strength requirements, others meant that SCC might lead to a saving on formwork cost due to a quicker turnaround time of the shutters. These statements were tested through the modelling of a case study in this dissertation.

None of the participants who used SCC in the past had any well-defined calculation method to quantify the total cost impact for the implementation of SCC. The calculations are fragmented and focussed on the cost subcomponents rather than the total cost impact.

Time

It was noted that time savings have been realised by using SCC. The time saving in the precast yard was mentioned for the construction of heavily reinforced sections such as precast columns. The general opinion was that the casting of bulk elements, such as raft foundations, could be accelerated the most by implementing SCC (such as the Akashi-Kaikyo Bridge anchorages discussed in Section 2.4.1).

Quality

The interviewees were generally convinced that SCC will lead to a higher quality finished-products in specific applications. These applications include, but are not limited to, ground level floors, lift shafts, piling, water retaining structures, off shutter architectural concrete and sections with limited access. The possibility of connecting SCC with a Green Star rating was mentioned as a possible method of providing incentive for SCC usage when building an environmentally friendly structure.

One of the SCC suppliers was of the opinion that SCC can accommodate vertical drops better and this property will lead to a higher quality finished product in applications such as pile and column construction. The slightly increased relative density of hardened SCC due the improved compaction was expected to enhance the contractors' ability to meet durability specifications. The durability specifications used by SANRAL for their bridge construction projects was specifically mentioned.

Ease of use

The heavy precast industry has already implemented SCC to a notable extent due to the ease of using SCC. The reduced risk of rework and the ability of SCC to incorporate more admixtures add to the ease of use of the material. The additional admixtures make a transport period of up to six hours possible for SCC.

The negative comments included poor consistency in concrete quality received from the suppliers of SCC and formwork failures due to hydrostatic pressures that develop when the prescribed concrete placement rates are exceeded. Formwork companies can assist in mitigating this risk through management or by assisting in the formwork design process if they are involved from an early stage.

3.3.4 The impact of SCC on construction processes

The interviewees highlighted an extensive range of impacts of SCC on different construction processes. Some of the impacts are element specific and others influence the risks involved with specific construction techniques.

Johan Hartman, from Element consulting, highlighted the construction of high columns (4m and higher). These columns are usually constructed by doing two casts. The use of SCC can eliminate the need for casting over two days and so eliminate a cold joint in the column. Single casts can lead to more entrapped air on the exterior facades of the columns, but according to Hennis van Zyl from Lafarge, this can be prevented by using a high quality shutter release agent. The possibility of casting larger slabs in one day was also highlighted as this can change certain schedule relationships and lift certain constructability related constraints. The positioning of the reinforcement for piles can also be done prior to concrete placement if SCC is used and so eliminate the need to drive in the reinforcement cage after concrete placement.

The risk of poor compaction on site can be shifted off site to the concrete supplier if SCC is used. This risk shift can be especially useful if there is a lack of skilled concrete labourers on site or if high quality finishes are specified. The possibility of shifting the risk of formwork failure off-site to the formwork company was also mentioned as a consideration that can make SCC more favourable. Another risk that is mitigated by using SCC is that of water addition to the concrete mix by site personnel. This potentially occurs if the concrete has low workability, but this problem is inherently removed by SCC's material properties. Additional attention to curing practises on site is needed when using SCC due to the increased susceptibility of SCC to shrinkage cracking.

The contractor Francois Vermeulen from Stefanutti Stocks commented on the carbon footprint of SCC. He mentioned that the South African environmental law does not yet dictate strict carbon emission documenting for construction activities, but it might be dictated in the future. The impact of SCC on the overall environmental impact of a project can thus become influential in the near future.

SCC can influence the logistical organisation of a project by increasing the scheduling possibilities if high volume pours are done on site, especially if more than one concrete truck can be used simultaneously during the cast. For example, any number of trucks can discharge simultaneously (assuming sufficient access) and there is no need to increase the labour force or concrete placement equipment used on site.

3.3.5 Challenges and additional design criteria when implementing SCC

The additional challenges involved with implementing SCC, above those of NCC, were also discussed in the interviews. The realisation of the risk of total material loss when the formwork leaks or fails was highly commented on. The challenge is to mitigate this risk through design, construction and management of the formwork systems.

The higher moisture sensitivity of SCC is another challenge that should be managed during construction. This includes stricter supervision during the concrete mixing operations (regulating moisture in the sand and aggregate and using more sensitive water measuring equipment) and during the curing operations.

The lack of knowledge regarding the intricate workings of the superplasticiser and the sensitivity to poor quality formwork and release agents are other challenges that has to be overcome in order to successfully harness the potential of SCC.

The formwork design should be done to minimize displacements during concrete placement. Vertical formwork displacement can result in openings between the formwork panels and can lead to material loss. The formwork should be of sufficient strength to support hydrostatic pressures.

The high characteristic strength of SCC can lead to non-optimal designs where the strength outperforms the specifications. If the regular, lower strength formwork is used, the rate of pour should be closely monitored and controlled to prevent the development of high hydrostatic pressures.

3.3.6 Decision criteria for implementing SCC

Contractors

The criteria on which the choice to use SCC is based varies across the breadth of the industry, with contractors, consultants and clients showing very different motives when considering the use of SCC. Contractors reported on using SCC mainly to construct elements with difficult geometries, dense reinforcement or difficult access. The contractors might also use it if they need to do a large, time constrained pour. Generally, it seemed that their interest in SCC is limited to the prevention of rework on difficult sections that is expected with the use of NCC (the rework will cost more than the additional price of SCC). It was mentioned that any nett overall saving due to the implementation of SCC would be enough incentive for the contractor to use the technology. The focus on construction cost is caused by the industry’s lowest bid tendering process and this forces the contractor to prefer the least expensive methods if no other details are specified.

Consultants

The consultants took different views on the matter. One approach was the deliberate avoidance of the decision, since a structural engineer only specifies strength and allows the contractor to decide on the rest of the material details. However, for consultants who design bridges or water retaining structures, for whom the constructability and durability plays a major role in the design, it might be beneficial to consider SCC if it can improve the durability or constructability of such a structure.

Clients

Clients can specify SCC through the architect if they prefer off-shutter concrete. Other reasons that might lead a client to specify SCC is an environmental incentive, better structural integrity or for a faster schedule that might lead to a quicker turnaround on capital. This however requires that they have more knowledge about the product. Jan van Rensburg from the Department of Public Works for the Western Cape commented that the department would definitely consider it if they knew more about SCC and its advantages. In future, one might expect the client to specify SCC and carry the additional cost, since they might benefit the most in the long and short term if SCC is implemented.

3.3.7 Where can NCC not be replaced by SCC

The general opinion from the interviews was that in most cases SCC could replace NCC if the user possesses the correct knowledge and skills. The lack of appropriate skills were commonly said to be the main reason for failed SCC application.

Another difficulty with SCC is when an element is designed to have an inclined finish (e.g. for drainage), this finish is challenging to achieve with SCC due to its self-levelling characteristics.

SCC is a concrete that generally has characteristic compressive strengths of 40 MPa and more. This makes it inefficient in low cost, low strength concrete applications. SCC is thus overdesigned at low strength applications and more uneconomical than for higher strength applications.

3.3.8 Labour requirements and their effect on SCC usage

The general opinion from the industry representatives was that contractors would require a smaller labour force when using SCC. The contractors interpret this as a negative factor because they think they are obliged to create work by legal prescriptions or certain community expectations. Generally, the contractors do not consider the shift of the labour force from unskilled on-site labour to skilled labour in the supplier's operations. One correspondent noted that communities could disrupt site activities for not employing enough local labour. This is not a legal prescription but it has been mentioned as a consideration. This should not be a limit for contractors since it is an unlawful intervention and it will not be considered in this research.

Jan van Rensburg from the Department of Public Works for the Western Cape and programme manager of the Capital Works Programme meant that there is no reason for contractors not to employ technologies that are more efficient. He said although labour intensive projects can be specified through a tender, it will not prevent the use of a more efficient technology. In the Western Cape, tender approaches vary between different departments but all their tenders are done according to Annexure F of the CIDB conditions of tender. Most of the tenders are done according to the second and fourth CIDB methods(except for the four CIDB methods) are illegal. He said that implementing a labour reducing technology, which is cost-effective, at a site that is under their administration, would not lead to any negative effect on a tender application. He also commented that there are currently no legal prescriptions regarding labour for the implementation of the Expanded Public Works Programme (EPWP). This might be different for other employers, but labour prescriptions are based on personal or company preference and not a result of legally binding policies.

Another matter that became known was that most labour prescriptions are done in terms of percentages. Typically, the project conditions of tender might state that a certain percentage of the labour force must be employed from the local community. This does not affect the size of the total labour force and has no implication on the choice of using labour reducing technologies.

It is shown in Chapters 6 and 7 that the labour expense reduction associated with SCC is small and not of significance when deciding whether to implement SCC.

3.3.9 The SCC market over the last decade and the expected future

The development of the SCC market in South Africa and the expected future trends were discussed with the SCC and superplasticiser suppliers. When SCC entered the South African market it was accepted with an initial excitement, this subsided when the unit price of SCC came into consideration. Many companies see SCC as a value-added product rather than a market disruptive technology and this has led to disappointment about the growth in the market for the suppliers of SCC.

SCC is mostly used in the South African market by the precast industry for off-shutter concrete and for concrete structures with dense reinforcement or complex geometries. The market is divided between users who use ready-mix SCC and those who prefer to produce their own SCC at their own batch plant. Many users still prefer pumping concrete to SCC due to the better understanding of the product and a general tendency to avoid new or 'bleeding edge' technology. Bleeding edge technology describes a new technology that has not been thoroughly tested yet and for which some knowledge gaps still exist in the industry.

It was reported in the interviews that internationally, suppliers such as Lafarge, is experiencing SCC sales of about 10% of total concrete sales in some developed countries. In South Africa, it is reported to have reached a plateau near 1%. Again, this might be due to the cheap labour in South Africa and the perception that the implementation of a labour reducing technology might create unwanted challenges or be detrimental to the outcome of a tender application.

The expected market growth for SCC is currently low due to the overwhelming number of new concrete technologies that have entered the market in the last decade. Lafarge Agilia (South Africa) aims to focus on the high strength concrete market for future growth in SCC sales.

3.3.10 What reasons have been given for not implementing SCC

The reason for not implementing or prescribing SCC differs between consultants, contractors and clients. This fragmentation of the market may possibly prevent a holistic approach to the use of SCC in the South African industry. Increased material cost is unlikely to be taken on by a contractor in a market where tenders are awarded to the lowest bidder and when the prescribed specifications can be met at a lower construction cost. The clients' lack of knowledge about the benefits such as faster capital turnaround or higher structural integrity that SCC might realise, prevents them from prescribing SCC on the project.

Other factors that prevent contractors from using SCC is the lack of knowledge about the technology and bad experiences with the concrete that originates from a lack of knowledge or inconsistent SCC batches that they received from suppliers in the past.

From the consultant's perspective, two views were identified. The first was the deliberate avoidance of the decision, since the type of concrete used on site has a low impact on their work. As long as the concrete meets the specified performance parameters, such as characteristic strength, they will avoid further prescriptions. The second view was that SCC has not been implemented, since the need for it has not yet become apparent. This is because consultants generally work on hourly rates and do not concern themselves with the productivity of the site, which is the contractor's responsibility.

From this information, one can see that due to the fragmentation of responsibilities the incentive to implement SCC is diminished for each party. If the client does not have knowledge of the possible potential, they will not specify SCC. If the consultant does not inform the client or require SCC for constructability, they will not prescribe SCC and then the contractor cannot carry the increased cost of SCC due to the lowest-bid tender procedures.

3.4 Chapter summary

In this chapter, a summary was provided of the information that was gathered through the interview phase of this research. The information that was reported on was distilled from the interviews and it supplements the described knowledge areas in Section 3.2. Table 3 shows the summarised findings from the interviews.

Table 3: Interview findings summary

Knowledge area	Sub-sections	Remarks and observations
Cost impact on material, formwork and labour	Material	General increase expected due to increased cement content
	Formwork	General increase expected due to hydrostatic pressure accommodation
	Labour	General decrease expected due to increased workability and self-compacting properties
	Other cost impacts	Overhead savings expected due to an accelerated schedule and equipment savings
Experiences with regard to total cost, time, quality and ease of use	Total cost	Unclear and fragmented (this was the investigation of this research)
	Time	Decrease in placement time
	Quality	Rise in quality is expected
	Ease of use	Easier execution of concrete works
Impact of SCC on construction processes	Structural elements	Impact varies between elements and geometric characteristics of a specific element type
	Construction risks	Risk additions and changes occur with SCC implementation

Knowledge area	Sub-sections	Remarks and observations
	Task relationships	Different construction task orders are possible with SCC usage
	Environmental impact	Environmental impact might require further consideration and investigation
Challenges associated with SCC implementation	Main challenges	Lack of knowledge and increased cost were identified as the main challenges of SCC implementation
Additional design requirements for SCC	Main design criteria	Additional formwork design requirements are necessary to accommodate hydrostatic pressures
Decision criteria used when considering SCC implementation	Contractors	Cost and the prevention of rework on complex sections or when there is difficult access to an element
	Consultants	General avoidance of prescribing a concrete technology, except if it can improve durability or constructability
	Clients	Environmental incentive, better structural integrity, aesthetical reasons or a faster schedule can lead to SCC specification
Applications where SCC cannot replace NCC	General difficulties with SCC	Low cost, low strength concrete applications or when inclined finishes are specified.
Perceived labour requirements associated with SCC usage	Industry perceptions versus client	Industry participants interpreted the labour requirements as a challenge while a client said SCC implementation will not be detrimental to tender documents
SCC market in South Africa	As experienced by suppliers	The sales reached a plateau after the initial market excitement subsided due to the high material unit cost
Reasons for not implementing SCC	Contractors	The inability to carry the increased material price due to the lowest-bid tender award structure
	Consultants	Deliberate avoidance of specifying a concrete choice for contractors or the absence of a need to implement SCC
	Clients	The lack of knowledge about the potential benefits of implementing SCC
	General	The technology is not implemented due to the fragmentation of the responsibilities and incentives between the different parties

This information guided the research. It aided in the identification of the various cost parameters as well as the industry interpretation of the risk and labour requirements. The model structure refined through the discussions with the industry representatives through their suggestions about an applicable cost calculation breakdown. This will be the topic of the following chapter.

4 MODELLING APPROACH AND MODEL OUTLINE

4.1 Introduction

The proposed modelling approach and model outline used to simplify the economic comparison between NCC and SCC usage is provided in this chapter. The objective was to construct a cost comparison model that can be used as a tool when approaching the decision of whether or not to implement SCC at a specific South African construction project.

The modelling approach and outline is discussed to clarify how a comparable metric can be calculated. An important additional consideration discussed in this chapter is the way in which the cost constituents should be broken down to ensure insightful results are obtained, which can be acted on. The model should be applied to a specific project and it is not meant to calculate a generic answer for all South African construction projects.

The modelling is discussed in three phases. First, the general approach and reasons for taking this approach is discussed. This is followed by an explanation of the actual structure of the model (how it works and how the specific information was sourced). Lastly, the results representation is discussed. This is not the results of the specific case study, rather how one can calculate and present the results to ensure effective interpretation.

In this chapter, attention is given to the calculation method, rather than to the actual input numerical values that were used or the values of the obtained results.

The values of the input parameters can be easily adjusted if the model is structured correctly. The specific values of the input parameters are discussed in Section 5.2.3. The results of the case study, as calculated with the proposed methodology, are given in Chapter 6.

4.2 Modelling approach (Static and Heuristic)

The modelling was done in two phases with a static model created first. The model is static since it does not incorporate any variance and all the input variables are single data points. This was done to simulate the value chain that exists with regard to concrete placement.

Variance is added to the model in the second phase. The variance is added to create the heuristic model that supplements the information of the static model. This variance within the data simulates possible variations in the value of uncertain input parameters. It enhances the insight that the model can provide to a user. Table 4 shows the role of the two phases in acquiring the information through the calculation procedure. These two phases will be discussed individually.

The ideal is to perform static deterministic calculations as far as possible. The uncertain parameters of the static model are then statistically analysed, by means of a Monte Carlo analysis, to solve the problem in a heuristic manner. The overall results are a combination of static (certain) results and probabilistic (uncertain) results.

The uncertain input parameters are modelled as static values in the first phase and then modified with statistical distributions in the second phase. The results obtained will thus be static (including the uncertain input parameters) and then modified into a probabilistic result (the answer is then presented as a distribution of possible outcomes rather than a single value). This will become apparent in Chapter 6.

Table 4: Role of static and heuristic modelling in the calculation procedure

Information required	**Cost impact and cost impact breakdown of using SCC**	**Possible variation in cost results due to inherent uncertainty**
Input parameters and required information relationship (between inputs and outputs)	Results based on single value input parameters (assume fixed input data)	Results include the possible variation in the values of uncertain input parameters
Model part created to obtain the required information	**Static model**	**Heuristic model**
Input characteristics	Fixed value inputs	Variable inputs (variability defined by a statistical distribution of possible values)
Mathematical calculation method	Static deterministic calculations	Statistical/stochastic calculations by means of a Monte Carlo simulation
Result characteristics	Fixed value results	Resulting distributions

4.2.1 Static modelling approach

The first step in the cost comparison was to investigate and identify the value chain, or the different actions that take place in concrete construction that might incur a cost. This chain was mainly constructed from the information in the literature and it was supplemented by the interviews. The chain is shown in Figure 12. This value chain will be similar for most concrete placement activities at a construction site.

The second step was to simulate this value chain, or capture it, with a static model that consists of small and easily measurable data points. For this research, the disposal cost and the maintenance cost were excluded from the model. Since it can be assumed that the hardened properties of the two materials are similar.

Net present value calculations should be considered if one evaluates longer projects for which the time value of money might have a considerable impact. In this research, it is excluded to keep the focus on the method of calculation and because the investigated case study has a schedule of less than a year. The model structure can however accommodate the addition of net present value calculations.

Prior to the discussion of the value chain, and how it was approached in the static modelling, the following nomenclature should be established:

- The results extracted from the model will be presented as Key Performance Indicators (KPI's). In this research, a KPI is a measurable value that can be used to base a decision on. In this case, the decision of whether to implement SCC for a specific application.
- These KPI's are calculated based on the information in the Critical Performance Areas (CPA's). These areas represent the different construction cost constituents of an element.
- The different element types (slabs, beams, columns and walls) are also grouped together to enable the identification of trends associated with different element types. The groups of element types are referred to as element classes, or KPI classes, in this research.

The nomenclature will become more apparent when it is discussed in Section 4.3.

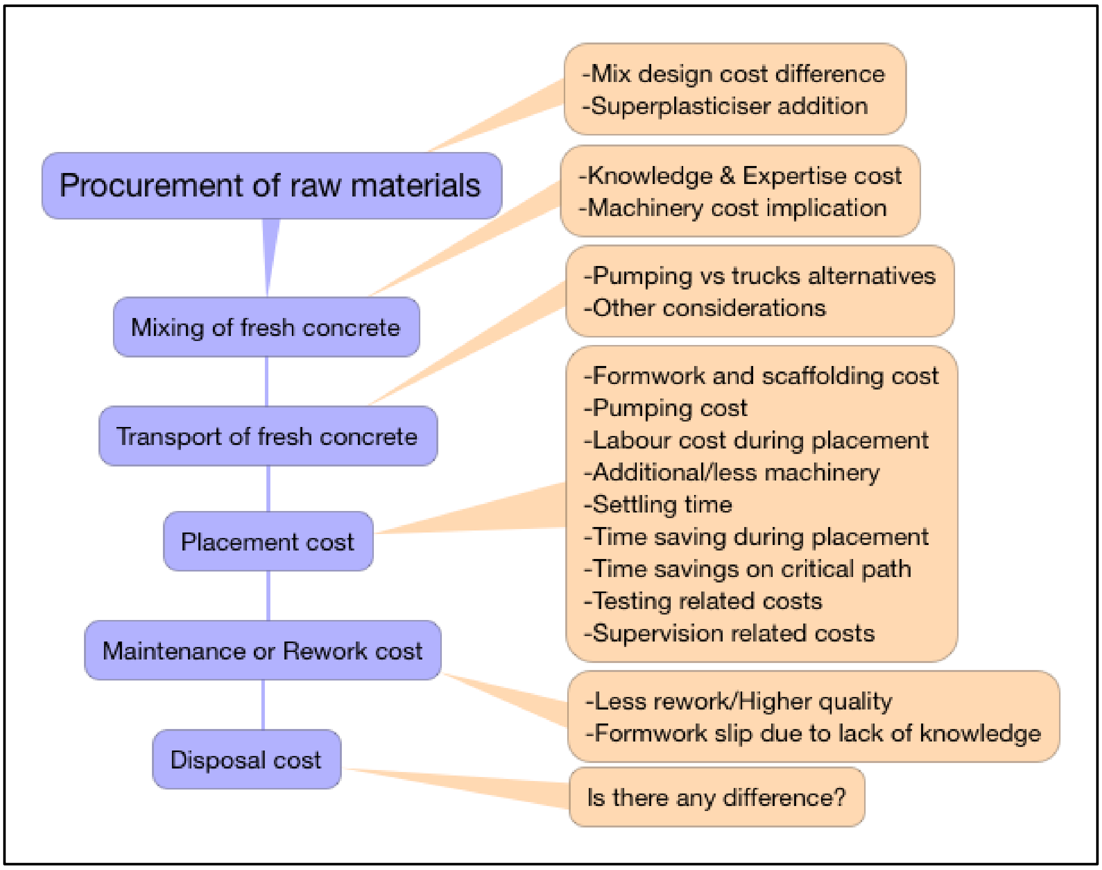


Figure 12: Value chain of concrete placement

The quantification of this value chain can be done if two conditions prevail, the first is that the user should know how the cost breakdown is done and the second is the availability of the required rates and cost figures. These rates are sometimes strategic to a company's success and they can be reluctant to share such information. The breakdown can be done according to the predefined structure for the model to enhance the ability of data organisation. The development of this cost implication model, based on the proposed predefined structure, is the primary objective of this research.

Figure 13 shows the proposed structure of the model (static in this figure). This structure can be used to build the static cost comparison model. For this research, the information that was used as input data was obtained from the case study's project documents as will be discussed in Chapter 5. The literature and interviews supplemented the data where necessary. Quotes were also used to populate the model for variables such as concrete cost, if externally supplied, and formwork renting cost.

The input data consists of all the information that is required to do the calculations. These can easily be sourced for a user's own project. The structure should be divided into slabs, beams, columns and walls, as these different elements will compare differently in the Critical Performance Areas (CPA's) as listed in Figure 13. The calculations can then be done to assign a construction cost for each element, as well as the breakdown of the cost into the five CPA's.

The model is structured so that any or all KPI's can be extracted and viewed for the overall project cost and for the cost of each element type. The construction cost can be extracted for a single element in a project as well, but this has limited informative value from a decision-making perspective. The cost breakdown is then summarized and presented visually to show the effect of using SCC. A project cost dashboard can then be used to convey the financial impact to the different project participants.

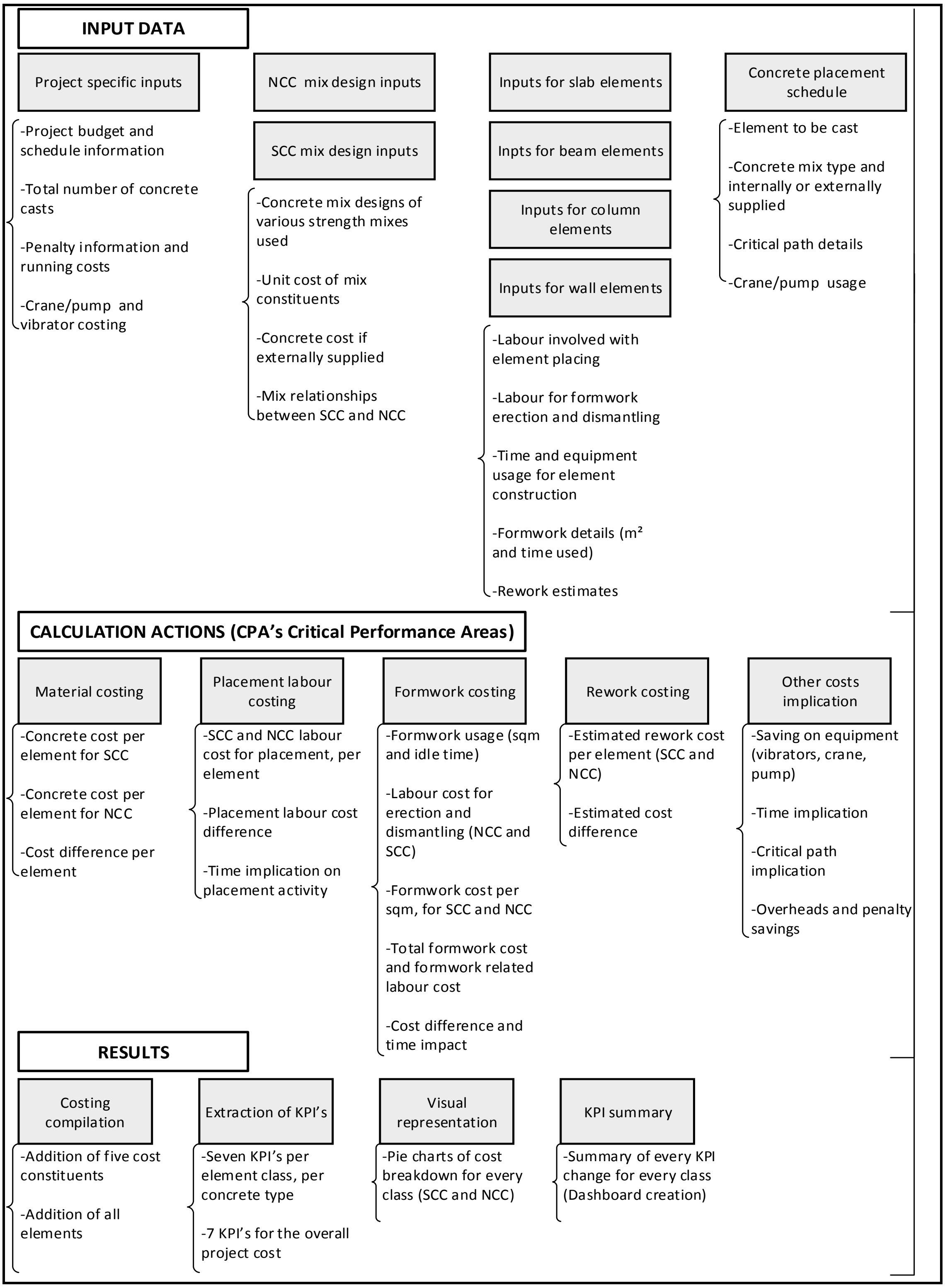


Figure 13: Breakdown of the model structure

4.2.2 Heuristic modelling approach

The second modelling phase is the addition of variability to the static model. This variability is added to simulate possible changes that might realise in input values. A heuristic approach was chosen to accelerate the calculation technique. Since the cost estimation of civil and structural engineering projects are not precise, it will not add notable value to aim for precise figures that attempt to constrain the calculations further. The objective is to create a quantification technique that is reliable enough to consider when a decision has to be made on whether or not to implement SCC at a South African construction project.

Due to the intended use of the results that are generated by the model (to assist in decision-making), a Monte Carlo analysis was chosen to simulate the variability and uncertainty in the input data. This method was chosen over competitors such as fuzzy logic, for two main reasons (apart from the disadvantages of fuzzy logic mentioned below). A short digression is necessary to introduce fuzzy logic as well as the disadvantages that disqualified it as a quantification technique.

Fuzzy logic is a multi-valued logic that deals with vague and indecisive ideas. Fuzzy logic is said to be similar to human thinking and interpretation and it is said to give meaning to expressions such as "often", "smaller" and "higher". It takes into account that everything cannot have absolute values and follow a linear function (Godil, Shamim, Enam & Qidwai, 2011:24). Fuzzy logic can use words from natural language instead of numbers for calculation and decision-making (Šafarič & Rojko, 2006:). The following disadvantages led to the disqualification of using the fuzzy logic approach to do the heuristic modelling in this research (Šafarič & Rojko, 2006:).

- It is impossible to prove the stability of the fuzzy control system. When it comes to proofs which can be found in literature, stability is often proved on a 'crisp' system which is only a deformed picture of the fuzzy, while methods from the classical system theory are used
- There is no systematic approach to fuzzy system designing. Instead, empirical ad-hoc approaches are used
- Fuzzy systems are transparent (understandable) only for simple problems
- Statisticians represent the opinion that the probability theory is enough to notate linguistic knowledge and that fuzzy logic is, thus, not necessary

Since a discrete cost is always the result after project completion, it is unrealistic to approach the heuristic part of this techno-economic analysis with a quantification technique that assumes a 'fuzzy outcome'.

The advantages of a Monte Carlo analysis make it suitable for this problem and two main reasons led to the use of a Monte Carlo analysis for the heuristic modelling part of this research.

The first reason is the time efficient data gathering techniques associated with a Monte Carlo analysis and fewer participants that are required to generate the data used to populate the heuristic part of the model. The second reason is the relative ease with which the results of a Monte Carlo analysis can be interpreted. Even if a decision maker does not have any knowledge about a Monte Carlo method or is relatively low skilled in terms of mathematical education, the Monte Carlo results can be explained with ease.

A sensitivity analysis is performed on the static model to lower the number of inputs that is included in the Monte Carlo analysis to do the analysis efficiently. The focus on time-efficiency during model population, simulation and interpretation renders it as a heuristic modelling approach.

The sensitivity analysis is performed on the relevant KPI's to extract the most influential input parameters of any KPI under consideration. The results of the sensitivity analysis are used to identify those input parameters that are uncertain and that should be included in the Monte Carlo Analysis. This is done with the TopRank software developed by the Palisade Corporation, the same developers than that of @Risk. This software performs the sensitivity analysis and identifies those parameters that fall into the range of effect specified by the user. For this research, the following ranges were used:

1. $\Delta max_{input\ i} = \pm 10\%$, must lead to:
2. $\Delta min_{KPI\ y} = \pm 1\%$

This means any input variable is an influential input if it changes by more than ten percent and the change leads to a change of one percent or more in any output KPI. The top ten relevant inputs are then listed for every KPI. One can choose any of the KPI's and apply the applicable distributions to their uncertain input parameters. The sensitivity of the KPI with regard to the input parameters is then presented as a tornado graph. The list of extractable KPI's is given and discussed in Section 4.3.

It is useful to apply the Pareto Principle (Reh, 2015) at this stage; this is known as the 80-20 principle. Generally, a low number of input parameters (twenty percent according to the Pareto Principle) have the majority of the influence on an output parameter (eighty percent in theory). If one can identify the key parameters of a KPI, it is more time efficient to focus on applying the correct distributions only to them.

The Monte Carlo analysis was performed using the @Risk software package, which can be added into Microsoft Excel, enabling the Monte Carlo analysis on the static model. This software was chosen due to the relatively easy to use user-interface and the availability to download it for a trial period. A Monte Carlo analysis can also be done in Excel without this software, but this requires some additional time investment. More detail regarding a Monte Carlo analysis is provided in Section 5.2.4.

The static model is converted into the heuristic model by applying statistical distributions to the uncertain input parameters, thus forming the Monte Carlo analysis. The results obtained from the Monte Carlo analysis are then post-processed. The input data and results can be represented graphically as statistical distributions to show opportunities, or lack thereof, and what the certainty is associated with each possible opportunity.

The KPI's and cost breakdown comparison of the material options can then be summarised into a suitable format for presentation. This will be done in Chapter 6 with the results of the investigated case study.

4.3 Model structure

As discussed previously, the model is structured and discussed according to the inputs, calculations and results. The inputs are used to calculate the five CPA's (Critical performance areas), which are:

1. Material costing
2. Placement labour costing
3. Formwork costing
4. Rework costing
5. Other costing

The other costing are those expenses that can be saved on concrete placement equipment, as well as savings on overheads and/or penalties due to a reduction in placement time. Each of the five CPA's was quantified for every element that was cast. Once for NCC implementation, and once for SCC implementation ('other costs' was only quantified for the use of SCC, relative to NCC). The total cost per element is then calculated for NCC and for SCC to enable a comparison. The total estimated time impact was included as a KPI because the time impact can also influence the outcome of a decision about an appropriate construction technique. A summary of all the KPI's that can be extracted from the 5 CPA's is shown in Table 5.

The following formula was used to calculate the construction cost of every element:

$$T_{SCC} = M_{SCC} + L_{SCC} + F_{SCC} + R_{SCC}$$

$$T_{NCC} = M_{NCC} + L_{NCC} + F_{NCC} + R_{NCC}$$

With:

$$T = Total\ element\ cost\ (R)$$
$$M = Material\ cost\ per\ element\ (R)$$
$$L = Labour\ cost\ for\ element\ placement\ (R)$$
$$F = Formwork\ cost\ per\ element\ (R)$$
$$R = Rework\ cost\ per\ element\ (R)$$

The subscript SCC and NCC refers to the concrete type. The implication of other costs, represented as (A), will have a negative value due to its definition being an additional saving due to the use of SCC, such as equipment cost savings and overheads savings. The total cost implication of using SCC for a specific element can then be calculated as:

$$\Delta TC = T_{SCC} - T_{NCC} + A$$

The time impact of SCC, due to faster placement, was documented throughout the calculation procedure.

The summary of the input sheets, used for the calculation, can be seen in Appendix B. Table 5 is a summary of all the KPI's that can be extracted from the calculations and the CPA's from which they originate.

Table 5: Summary of extractable Key Performance Indicators (KPI's)

Elemental breakdown (KPI classes)		Critical Performance Areas (CPA's)					Additional performance areas	
		Material cost	Placement labour cost	Formwork cost	Rework cost	Other costs implication	Total cost	Time impact
	Overall project specifics	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Slab elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Beam elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Wall elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only
	Column elements	SCC and NCC	SCC and NCC	SCC and NCC	SCC and NCC	SCC only	SCC and NCC	SCC only

There are sixty KPI's which can be extracted from the model, depending on the required information. The sixty KPI's are subdivided into the five classes as shown in the table, each class containing twelve KPI's (five KPI's for NCC and seven KPI's for SCC).

The Monte Carlo analysis can then be performed after the main influence parameters have been identified for the KPI under consideration. The choice of the distribution type to be used in the Monte Carlo analysis depends on the type of uncertainty associated with the specific influential input parameter that has been identified. The expected uncertainties are dependent on the project geometry. An example of choosing the Monte Carlo parameters is discussed in Section 5.2.4, after the introduction of the case study.

The modelled mathematical relationship between the input data and the output information is summarised in Figure 14. This structure can be used to construct and tailor the model according to the needs of a specific project. The shown structure represents the quantification of the cost difference between using NCC or SCC for a single element or concrete cast. If all the concrete casts or elements are quantified in this way, their sum will represent the cost impact of using SCC for the entire project.

Figure 14 shows the modelled relationship between the parameters while the model is structured as shown previously in Figure 13. The two figures describe the entire static model.

The sensitivity analysis isolates the most influential input parameters so that any input information that is based on uncertain data and that are influential on the model results can be identified and varied to simulate the uncertainty. The simulation of uncertainty is done with a Monte Carlo analysis and it enables the results to be presented as a collection of possible outcomes instead of a singular value.

The resulting distribution that represents all the possible outcomes and the likelihood of their realisation can be used to enhance management and cost reduction efforts. The KPI's shown in Table 5 are a summary of all the ways in which the resulting information can be extracted and grouped according to the needs of a specific user or project participant.

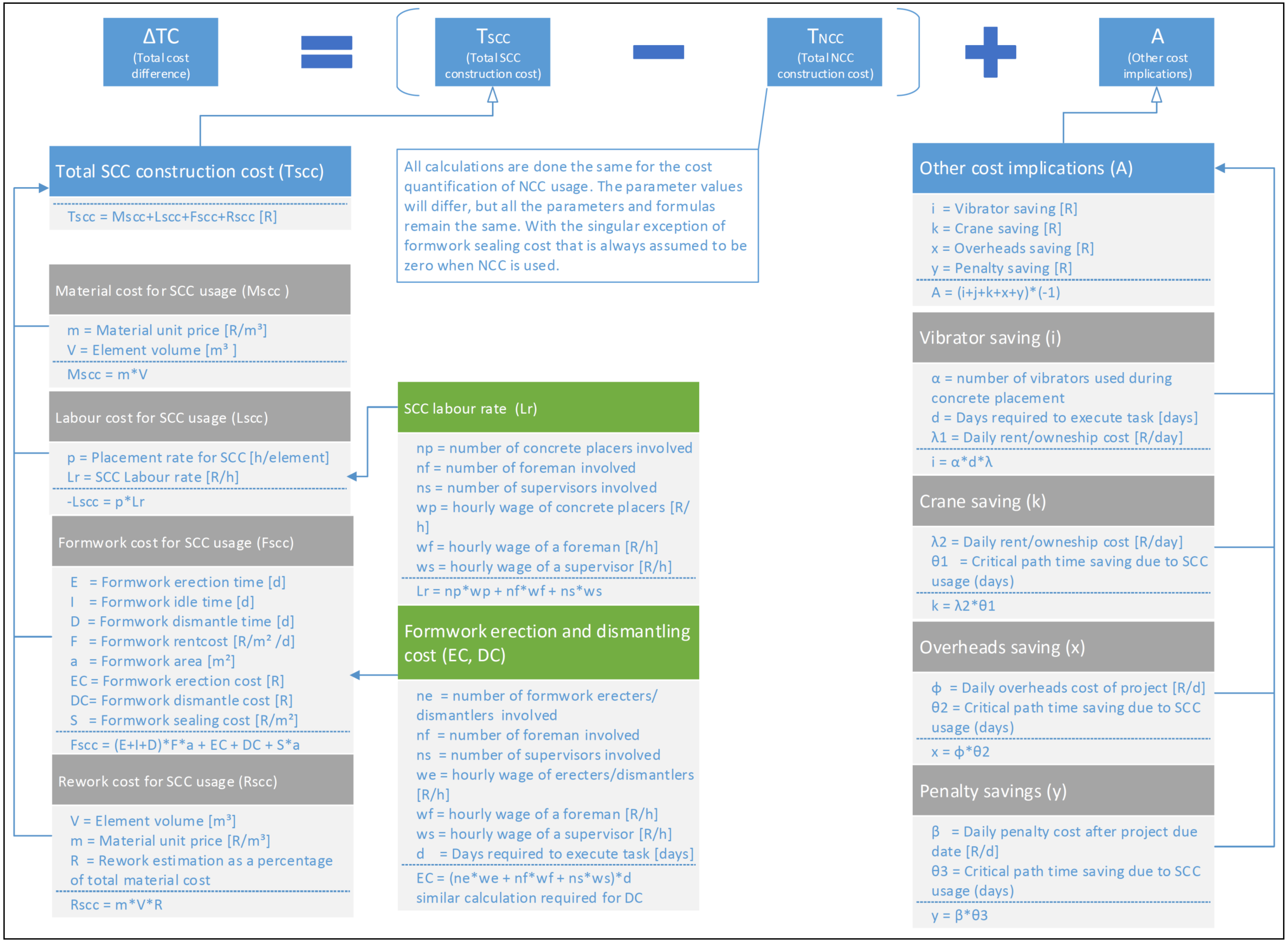


Figure 14: Mathematical relationships in the model

4.4 Representation of results obtained

The model results can be divided into different classifications, based on the type of information they convey. The different information types and the proposed method of presentation are listed below. This is how the results will be given in Chapter 6.

- Total cost breakdown, into the 5 CPA's, for every KPI class (Pie chart showing total cost, and each CPA's cost contribution)
- KPI change summary to show the effect on every KPI if SCC is implemented (Bar chart showing the relative change that SCC implementation realises)
- Total cost difference and its elemental composition (Pie chart, showing the total cost difference, as well as the different contributions of every element type to this difference)

The details regarding KPI sensitivity, the Monte Carlo input distributions and the resulting KPI output distributions are included in the results. These details can be used in the following ways to ensure that a holistic conclusion can be drawn from the data.

- The KPI sensitivity can show a user where to invest their efforts to save the most resources.
- The Monte Carlo input distributions show how the relevant uncertainties have been modelled
- The resulting distribution, combined with the KPI sensitivity and input distribution characteristics, are used to make an informed decision about the implementation of SCC.

The level of detail that the user applies in terms of distribution allocation and variance definition will influence the resulting distribution. A higher level of detail, such as applying distributions to more input parameters and/or defining a distribution of single input parameter more stringently, will however not always increase the accuracy of the result, as explained earlier (due to the uncertain nature of costing estimates). It is better to identify the most influential and uncertain input parameters, focus on their correct definition, and use that calculated answer to base a decision on. This process will be shown in Chapter 5 and 6 when the case study is introduced and its results are discussed.

4.5 Chapter summary

The modelling approach and model outline are introduced in this chapter. The methodology can be employed to calculate the cost impact of implementing SCC at a South African construction project.

The static modelling should be done first in order to capture the value chain associated with concrete placement on a construction site. The input data required for the modelling was defined and the quantification procedure of the CPA's was explained.

The heuristic modelling approach was discussed, as well as an explanation for why a time effective calculation method (heuristic method) was chosen to simulate uncertainty in the model. The application of the Monte Carlo analysis was chosen due to the effectiveness of data collection, the clarity of the visual representation of the results and the information it provides. The mathematical approach of identifying and extracting the highest influence input parameters was explained, as well as the consideration of the Pareto Principle. The application and integration of the Monte Carlo analysis, with the static model, was also introduced in this chapter.

The model structure can be broken down into the input data, the five CPA's that should be quantified and the sixty resulting KPI's that can be extracted from the CPA's. It is not necessary to evaluate all the KPI's, only those required by the specific user should be extracted and added to the applicable results summary.

A suggestion on how to present the results was discussed. This includes the representation of the cost breakdown into the five CPA's, the KPI change summary and the total cost change associated with the implementation of SCC. The main advantage of presenting the results in this manner is the ease with which it is interpreted

The model structure can be used on any project where a need exists to quantify the use of SCC. This method is adaptable and the results obtained can support the client and the project management team in understanding the financial influence of implementing SCC. The KPI summary can easily be converted into a dashboard, which can be used for reporting purposes.

5 SPECIFIC CASE APPLICATION

5.1 Introduction

The case study was done to test the model to quantify the decision of implementing SCC at a South African construction site. The chosen project was the construction of a bridge (Bridge Nr. 5895) over the Modder River near George (on R404, next to Fancourt Estate). The case study evaluation enables the demonstration of the value of the results representation method as well.

The project description is provided first in this chapter. It presents the general information and geometry of the project and the data used to populate the cost comparison model. The description is followed by the details and construction considerations. The specific values of the parameters and reasons for their use in populating the model are then presented.

The reasons why this project was suitable to use as a case study are discussed, followed by a list of shortcomings of the project as a case study for a techno-economic analysis of SCC versus NCC.

The whole bridge was a concrete structure, built in-situ. All the concrete works made use of NCC.

5.2 Project description and data capturing

5.2.1 General information and geometry

The bridge project is located West North West of George in the Western Cape. The bridge is situated on the R404 and the bridge construction site is situated next to Fancourt estate. Figure 15 shows the locality of the project.

Figure 15: Case study locality map (Google Earth)

The case study was done by means of a site visit, a project drawing and document investigation and through interviews with the consultant and contractor on site.

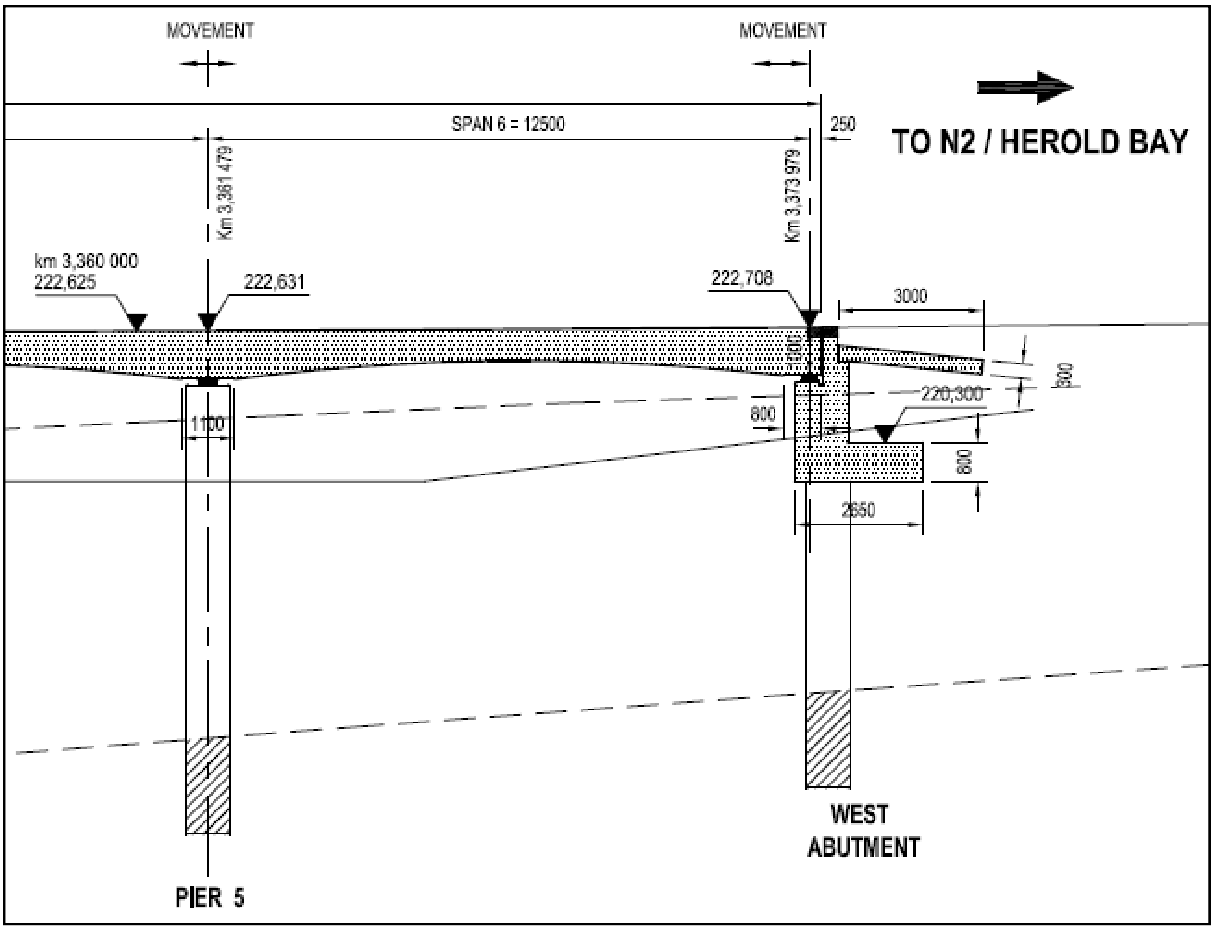


Figure 16: Longitudinal section of span 1, on the western end

Figure 16 shows the western end of the bridge. The bridge consists of six deck slabs, all similar to the one in the figure. Piles support the bridge structure and the whole structure was constructed by means of in-situ NCC construction. The bridge deck had a slight superelevation since the two roads that it connects are not aligned. Drawings that are more detailed can be found in Appendix C (courtesy of SNA Civil and Structural Engineers (Pty) Ltd.).

The structure was broken down into basic structural elements in order to use the proposed calculation method. The structure was broken down into the following elements:

- 4 concrete types (based on strength and aggregate characteristics)
- 10 slab element types
- 6 column element types
- 10 wall element types

Forty concrete casts were executed and the total volume of concrete used was 1223 cubic metres. Appendix C provides a more detailed list of how the project was broken down to prepare the data for insertion into the model.

5.2.2 Details and construction considerations

The concrete placement for the project was done by pumping the concrete into the formwork, or discharging it directly out of the truck and into the formwork mould.

In Figure 17, some construction activities can be seen. Note that the use of SCC will only change two of the images. The slump test will be replaced by a slump flow test and the need for vibration to enhance the concrete compaction will not be required. If SCC was used, it would appear even more flowable than the vibrated concrete seen in the top right corner of the image.

Figure 17: On-site construction activities
(Left: Concrete placement by pump, Top middle: Regular slump test,
Bottom right: Fresh concrete after pump discharge, Top right: Fresh concrete after vibration)

Note the six labourers involved in the placement. If SCC was used, there would only be one labourer to guide the end of the concrete placement pipe. The concrete placement cost would have remained the same if SCC was implemented and if the same pump was used.

For this project, the piling and the steel fixing were sub-contracted. The construction of the piling is however still included in the costing model as if built under the same contract. If SCC was used for the construction of the piling, it could have reduced the risk and complexity of the task and allowed the main contractor to construct the piles using his own team (Note: Often the piling contractor takes the risk for the foundation and the main contractor would not have preferred taking the risk).

Another factor to be considered is the construction of the bridge deck. According to the drawings and the designer, there is no structural reason that prevents the whole deck to be cast in a single pour. The reason for doing it over six non-consecutive days is the slow NCC placement rate. SCC would have lifted this constraint. If the batch plant was able to supply enough SCC, the whole deck could have been cast simultaneously and a notable time saving would have been achieved.

After the construction of the piles, sonic testing was done to ensure sufficient concrete compaction. This could have been eliminated if SCC had been implemented.

The concrete shutters used for the other elements (not piles) were reused four times on site. If SCC was used, this might have led to some problems regarding concrete finish and surface air voids if the shutter release agent was not of a sufficient quality. An insufficient concrete finish quality or a reduction in shutter reuse can both incur an additional cost.

The choice of using a pump mix for the deck concrete was mainly due to the higher workability requirement. Since pumping was the placement method of choice, SCC would have been suitable as a concrete choice as well. The use of SCC would have had two noticeable impacts at this site if one considers construction and constructability (besides faster placement and others mentioned previously). In Figure 18 the poor compaction that occurred in the corners of the deck can be seen, the use of SCC would have eliminated this compaction problem. This occurrence was observed in more than one place on the deck. This increased quality would have been a positive impact of SCC. However, formwork leakage is evident on the right hand side of Figure 18. This leakage would have been more severe if SCC was the concrete of choice. As noted by the interviewees, it could also have led to major material loss.

Figure 18: Possible SCC impacts on construction (Left: Poor NCC concrete compaction in the formwork corners, Right: Formwork leakage at a shutter connection underneath a bridge deck slab)

It is evident that the implementation of SCC would have had an impact on the construction processes and supervision on site. The advantages have to be weighed against the risks and costs involved in order to make the decision to implement the technology or not. Factors such as these would be included in the decision criteria and it shows that the decision to implement SCC is not only based on financial aspects. Rework can be another decision criterion to consider. The rework advantages might outweigh additional SCC costs such as an increased material price. The decision will depend on the extent of rework that a contractor generally experiences due to poor concrete compaction. This will typically be the case with inexperienced contractors constructing an element with off-shutter concrete specifications.

5.2.3 Specific parameter values for model populating

The model, as explained in Chapter 4, requires a number of input parameters. These parameters are based on site-specific information, design and certain market and labour force characteristics. The values of these parameters will vary between projects and contractors. The values used in this case study were sampled from various sources as will be explained in this section. Where all the information of a site is available, the population of the model will be time effective. It is however not the focus of this research to pursue the precise values of each parameter, but rather to test the calculation method with realistic values. The Monte Carlo analysis adds variance to uncertain input parameters to incorporate a higher number of possible scenarios in the final answer.

5.2.3.1 Labour

For the labour inputs to the model, the team compilation of the different construction activities was received from the contractor on site. The contractor made available the productivity rates of these workers and the time required to construct different elements. This is site-specific information. The placement rate of concrete was also measured on site and verified with the contractor. The labour cost, or hourly wages, was sourced from the South African Forum of Civil Engineering Contractors (SAFCEC, 2014). SAFCEC published a summary of all the minimum wages for the different task graded labourers. These were assumed the industry norm. The plant and equipment usage for the different construction activities were also sourced through the site-visit.

The major reduction in labour expense when SCC is implemented is due to faster concrete placement. It was assumed that the use of SCC would halve the concrete placement time. The interviewees reinforced this assumption, as discussed in Chapter 3. SCC suppliers noted that the placement time would be at least halved. The labour force was also assumed smaller, with only one concrete placer utilised with SCC placement for every four required with NCC.

5.2.3.2 Formwork

The formwork rates were obtained through quote requests from formwork specialist companies such as PERI and Form-Scaff. The formwork rates varied between SCC and NCC. This is due to higher strength formwork that is required to accommodate the hydrostatic pressures associated with the use of SCC. The following formwork values were considered for the case study.

- For horisontal applications, there was no difference in the formwork cost
- With columns the difference depends on the formwork choice. Certain column boxes can be used for both concrete types, if standard sizes are used, then the cost difference is minimal. If a column box has to be built up for a custom design, the price can easily double. PERI commented that they have column boxes ready for most sizes if NCC is used, but they will have to build a box from their Vario formwork system if SCC is used (only the piles in this case was modelled as columns and due to the permanent steel formwork that was used, no cost difference was modelled)
- For walls, the NCC formwork could be built using the PERI Domino system (about R75 per m^2/week), but the PERI Vario system will have to be used for SCC (R300 per m^2/week, late 2014). Form-Scaff quoted the same formwork irrespective of concrete choice, but noted that the rate of pour has to be controlled with SCC, thereby compromising the time saving benefit (This means that they probably do not design to accommodate hydrostatic pressures)

The formwork rates used for SCC in the model were mostly the more expensive rates to be conservative. All the assumed formwork idle times (the number of days that the formwork supports the structure while the concrete gains strength) were as specified by the applicable SANS code (SANS 2001-CC1, 2007). The code prescribes 4 days minimum for slabs when supports are left in, 2 or 7 days for beams, and two days for columns and walls. All these figures were used, but for the slabs, the formwork was not removed on site after 4 days due to restricted access. This was compensated for by increasing the amount of time destined for formwork erection on the deck slab elements. This increase will be elaborated on in Section 6.4.1.

5.2.3.3 Materials

The concrete and other material costs were also sourced by the researcher through industry quotes. This includes unit prices of constituent materials, admixture costs and ready-mix concrete costs. All the quotes showed an increase in material price for SCC, relative to NCC. This supports the expectations of the interviewees.

5.2.3.4 Rework and other cost parameters

Rework for NCC was assumed as 0.25% of the total concrete cost. This assumption was based on the reports given by contractors who were interviewed.

The penalty cost at this specific site was R15 000 per day and the last 5% of casts were assumed, for comparison purposes, to take place in the penalty period. The prevention of the penalties in the last 5% of the casts is used to calculate the financial saving that can realise due to a time saving (The saving is calculated as prevented penalties). If the assumption is made that the project will finish on time and not incur any penalties, this variable can be defined as 0%.

The overhead costs of this project were not available, but this figure can be incorporated into the model in the same way as the penalties. It should be calculated as a cost saving due to an accelerated schedule.

The cost associated with the equipment used for concrete placement depends on the chosen placement technique. If pumping is used, the cost will remain the same due to the constant volume of placed concrete (pump cost is based on concrete volume and pump establishment cost). If a crane is used for concrete placement, the time saving that can be realised through faster placement can be translated into an equipment expense reduction (reduction in the renting time of the crane).

Other factors such as earthworks, stone pitching and other finishing tasks that stay the same regardless of concrete choice, are not included in the calculations.

5.2.4 Applicable distributions for the Monte Carlo analysis

Probability distributions have to be assigned to the uncertain single point input estimates of the model to enable the execution of a Monte Carlo simulation. The static model can be visualised as a formula, this is shown in Figure 19. The addition of the probability distributions, to the uncertain input parameters (x_i), changes the model to the scenario shown in Figure 20.

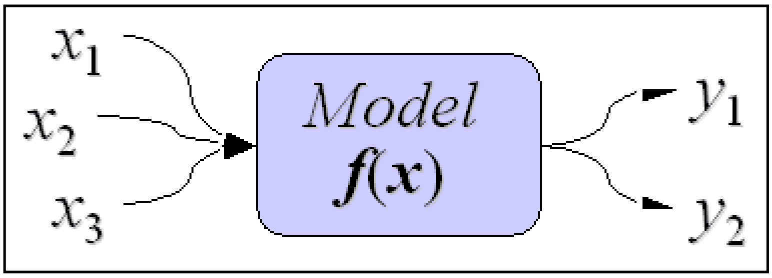


Figure 19: Static/deterministic model representation (Wittwer, 2004)

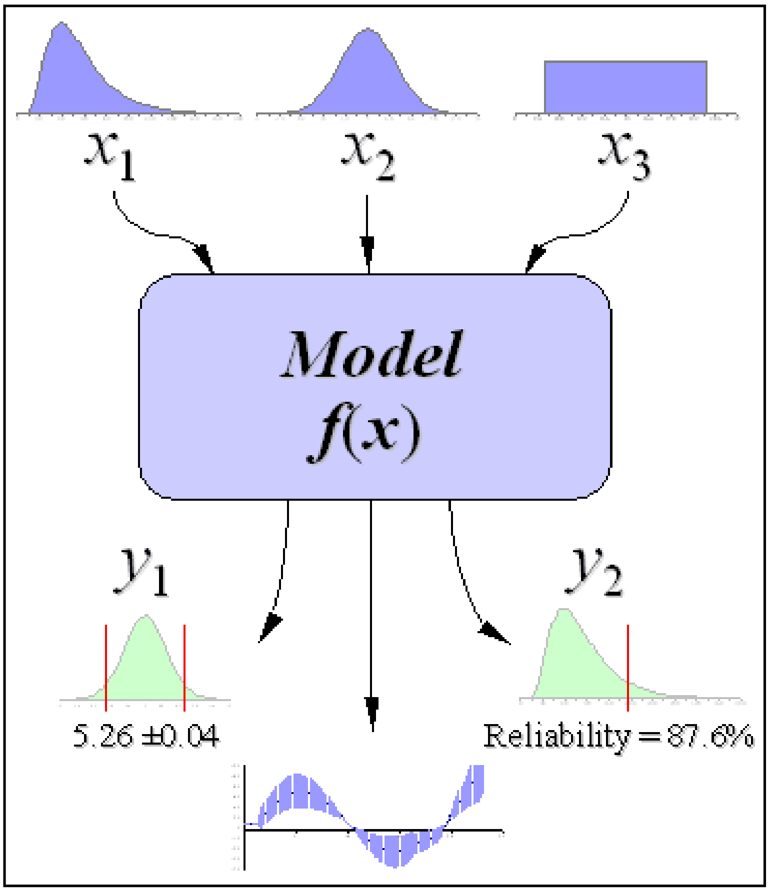


Figure 20: Heuristic/probabilistic model representation (Wittwer, 2004)

In a Monte Carlo analysis, the resulting output value of an iteration is calculated by drawing a sample value out of the statistical distribution of each input parameter (x_i) and calculating the answer (y_i) with the predetermined model ($f(x)$). The input value is generated by a random number generator. Ten thousand iterations are done to create a set of ten thousand possible answers. This answer set is then presented as a statistical distribution (10 000 possibilities for every y_i). The resulting distribution shows the effect of the uncertainties described by the input distributions on the calculated answer. The answer is thus a set of ten thousand possible outcomes that can realise within the framework of the predefined possible changes in the input values

The parameters that are assigned probability distributions are identified as explained in Section 4.2.2, through the sensitivity analysis. The total cost difference of the overall project was chosen as an example KPI. For the overall cost, the ten main influence input parameters, identified through the sensitivity analysis, are listed in Table 6. The distributions assigned and the reasons for the specific distribution choice will vary for every input parameter. The chosen distributions are dependent on the inherent nature of the parameters and the availability of information.

Table 6: Total cost influence parameters and distributions

Total cost influence parameter	Distribution type	Reason
Mix1 SCC external supply cost	Single point	Lack of variable quotes
Mix1 NCC external supply cost	Uniform	Cost choice based on quotes
Mix2 SCC external supply cost	Single point	Lack of variable quotes
Number of NCC formwork erectors for Slab1	Single point	Fixed due to contractor strategy
Formwork Erect Time NCC Slab1	Normal	Human activity with limited variance
Formwork Erect Time SCC Slab1	Normal	Human activity with limited variance
Mix3 SCC external supply cost	Single point	Lack of variable quotes
Number of SCC formwork erectors for Slab1	Single point	Fixed due to contractor strategy
Total number of concrete casts	Single point	Fixed due to project geometry
Mix4 SCC external supply cost	Single point	Lack of variable quotes

Only one data point was available for the externally supplied SCC mix costs. From the three companies that received a quote request, only Lafarge Agilia provided quotes for SCC. The externally supplied NCC costs were given a uniform probability distribution with limits between the highest and lowest quotes received. It was assumed that in negotiating a price, all the outcomes between these two values had an equal probability to realise.

The formwork erection times were assigned normal distributions with small standard deviations. The rationality is that human dependent activities vary in such a way that it can be represented by a normal bell-curve probability distribution (Hendrickson & Au, 1989; Mubarak, 2010). Due to the standardized procedures of erecting formwork, the variance was accepted to be low. It should be noted that the reason for the formwork erection time of slab1 being one of the major contributors towards total cost, lies in two distinct reasons.

The first reason is that the element ‘Slab 1’ represents one deck span of the bridge, and there are six spans in the model. Due to this project geometry, ‘Slab 1’ has the biggest contribution towards the total formwork cost of any element. Formwork is a major cost contributor towards the whole project.

The second reason is the limited access to the formwork that avoided the formwork removal after the period specified by the SANS code. The result was an increase in formwork rent. This was captured in the model by extending the time it took to erect the formwork structure. This method of capturing the cost might lead to confusion regarding nomenclature. However, the final formwork expense and the breakdown thereof into the five CPA’s will remain the same (this addition of time to the formwork erection estimate will not change the final values of the results).

The total number of concrete casts was kept as a single data point. It is a predetermined variable based on project geometry. There is no reason for it to vary. It is identified as an influential input parameter due to the mathematical relationship with the overheads and penalties savings. The overheads and penalty savings are calculated based on an estimation of the percentage of concrete casts done in the penalty period. The model then calculates which casts incur a saving based on the total amount of concrete casts. It is important to ensure the accuracy of the assumption regarding the percentage of casts done in the penalty period (if any). This assumption is varied in the model rather than the total number of concrete casts. The applicable input distributions are shown in Section 6.4.3.

The interviews, site-visit and literature were used in the process of determining and validating these probability distributions. If all the input information in the static model is known to be correct, the distributions and Monte Carlo analysis will only provide limited additional information. If there is uncertainty regarding the input parameters, the distributions gain importance in the analysis.

The model input values were chosen to be realistic to ensure a realistic example of the calculation method. Parameter values and distribution definitions will change for every application or project. The methodology of the calculation will however remain constant. The construction of this constant methodology is the primary objective of the research.

Specific and statistical detail regarding the input parameters and the probability distributions that were used will be provided in Chapter 6, when the results are discussed.

5.3 Project suitability as a case study

This specific case study was chosen due to various suitability factors that made it ideal for the investigations performed for this dissertation. These advantages are listed below to demonstrate the suitability of the specific case in quantifying the decision to implement SCC at a South-African construction project:

- All concrete works were done in-situ
- Good availability of the required information
- Some access to the quantities and project schedule
- Access to the construction team information
- Most element types exist in the structure
- All existing element types have more than one form of manifestation in the structure
- Concrete placement is done with pumping techniques which are also suitable for SCC (No cost difference)
- A site visit was possible to enhance the comprehension of the researcher (the bridge was still in the final construction phase)
- Low columns and walls ensured no change in the construction task relationships needed to be modelled for these element types
- The project was of adequate size to draw meaningful conclusions and model it in the required timeframe

5.4 Project shortcomings as a case study

Although this case is suitable for verifying the calculation methodology and insightful results can be calculated from it, there are some shortcomings. These shortcomings are mainly exclusions of aspects that will be encountered on different projects or the shortcoming originates from a lack of information for this specific case. This includes:

- Absence of beam elements in the structure
- Absence of off-shutter concrete specifications
- Absence of large volume, ground level, elements which might incur a noteworthy time saving

- Absence of elements with complex geometries
- Lack of large changes in the construction processes due to SCC implementation
- Lack of specific productivity rates, wage information, material costs and other site-specific input values

These challenges and shortcomings relate to the choice of the case study, different cases will have different shortcomings. It is important to investigate and document these shortcomings prior to investigating the use of SCC and modelling the costs.

5.5 Chapter summary

In this chapter, the case study of a bridge construction near George, in the Western Cape, was introduced. The project geometry and the elemental breakdown were defined. The incorporation of the project into the costing model was then described. The project consisted of 40 concrete casts and 1223 cubic metres of concrete.

The construction implication that would have realised if SCC had been implemented was evaluated.

The sourcing of the input parameters that are used in the model was listed and the parameter values were given. The values of these input parameters were chosen as realistic as possible with the available information. The focus however, is on the calculation method and the conclusions that can be drawn from the results. For an industry application, the values of the input parameters should be readily available.

The suitability of this bridge construction project as a case study was discussed. This includes the variety of element types that exist within the structure, and because the whole structure is built with in-situ concrete construction. This simplifies the accurate comparison between concrete technologies and eliminates certain considerations that are indirect cost influencers (such as variable task relationships or equipment expenses that are associated with the concrete placement technique).

The shortcomings of this specific case study were also listed. These include the absence of beam elements, the lack of complete access to the project details that are used as input parameters and the lack of certain SCC specific uses (such as off-shutter concrete and complex geometries).

The case study has now been introduced and the relationship and implementation of this information into the model has been explained. The following step is the extraction of the results. This is the topic of the following chapter.

6 RESULTS COMPARISON AND DISCUSSION

6.1 Introduction

The economic impact of implementing SCC at a specific South African construction site is presented in this chapter. These results are extracted from the model explained in Chapter 4. The model was populated with the information gathered through the interviews and the case study. The results address the primary objective of this dissertation: to construct a cost comparison model for the use of SCC versus NCC on a South African construction project.

The results discussion contains four categories. The first category is the overall static results. These results quantify the financial impact of implementing SCC at the construction site of the specific case study. The overall project KPI's (Key Performance Indicators) is discussed, as well as the total cost difference between the concrete types and the cost contribution of the different element types.

The second category contains the static results of the different structural element types (slabs, columns and walls for this case). This information shows the difference in the contribution of each cost constituents for walls, columns and slabs. The impact of SCC on a generic element type is represented by this result. The elemental cost breakdown is a result that can be used as a reference for other projects. The impact of using SCC is expressed as a change in the elemental KPI values (a change in the size of the contribution of a particular cost constituent), this is shown and evaluated in this category.

The results in the first two categories are calculated with the static model. The third and fourth categories cover the preparation and results of the heuristic model.

The third category contains the results of the parameter sensitivity analysis. The results of the sensitivity analysis are calculated from the static model, but the sensitivity analysis is the first step in the construction of the heuristic model. The main influence parameters are evaluated as an initial action. The KPI's are filtered, based on the Pareto Principle, to identify those KPI's that should be included in the Monte Carlo analysis. The results of the sensitivity analysis are shown as tornado graphs for the evaluated KPI's.

The last category is the results of the Monte Carlo analysis. The input distributions are discussed first, as well as their statistical characteristics. This is followed by the details regarding the Monte Carlo analysis setup procedure and the resulting KPI distributions. The value and interpretation of the distributions are discussed at the end of this category.

These four categories are the quantification of the economic part of the techno-economic analysis, which is the topic of this dissertation. Each category describes the value of the specific results, where they are useful and to whom they are useful.

All the results should be considered in two ways, what does the calculated value mean and why is it useful. The meaning of the calculated value is obvious, but the value of the proposed calculation method will become evident by analysing the type of answer obtained.

The first consideration can be based on the actual results that were obtained from the case study and the interviews. The calculated results are used to show the insights that the proposed calculation method and result representation method leads to (the second consideration). It also shows the impact of SCC on a specific South African construction project and highlights those impacts that are not necessarily bound to the specific case. These results can be used to make managerial decisions and to identify those areas where SCC can be applied beneficially.

All the values discussed in this chapter are rounded to the nearest hundred rand and/or half percent, this can be accepted due to the uncertain nature of cost estimation in itself.

6.2 Overall static results

In this section, the static results (no variance in the input values) of the case study are evaluated. The discussion is segmented into the seven overall project KPI's that are extracted from the static model. These seven KPI's are the material cost, placement labour cost, formwork cost, rework cost, other cost implications, time impact and the total cost. It should be noted again that the focus needs to be on both the value of the calculation method and the actual obtained results. This distinction will be continuously made throughout this chapter.

Each KPI is discussed individually and the KPI values for NCC and SCC are compared. The comparison and the conclusions drawn from it are then discussed.

6.2.1 Material cost

For the overall project, the material cost increased with SCC implementation. The increase in the material cost for the investigated case study can be seen in Table 7. The results were calculated with the input parameters explained in Section 5.2.3.

Table 7: Material cost impact for the overall project

OVERALL PROJECT	
Concrete type	**Material cost**
NCC	ZAR 1,584,500
SCC	ZAR 1,938,800

The material cost is one of the seven KPI's that is extracted (for the overall project) to quantify the cost impact of implementing SCC at a construction site. The material cost KPI for NCC usage and for SCC usage is shown in Table 7. These two KPI's are compared to provide the user with insight into the material cost impact of implementing SCC. The comparison shows the importance of a competitive price for SCC if it is to be implemented on a project. This cost difference and the fact that material cost contributes to more than 70% of the total calculated cost (for this project) would have guided a project team's cost reduction efforts to reducing the unit price of SCC.

A material cost increase of 22.5% would have realised if SCC were implemented to construct the investigated bridge. This increase in the concrete unit price quoted for SCC, relative to NCC, is due to:

- The change in the volume fractions of the SCC mix constituents (a higher binder/cement content and the addition of superplasticiser)

- The labour cost of additional expertise requirements for SCC production (this is included in the profit margin of ready-mix SCC, as identified through the interviews)

The expense of the higher cement content can be reduced by the addition of cement replacers and extenders. This can be useful for further research, especially since the South African codes place a limit on the percentage of cement extenders that can be used, such as a maximum of 35% fly-ash (SANS 50197-1, 2000).

This second factor mentioned can be alleviated if the concrete is self-supplied. The existing site personnel can absorb the production supervision responsibilities (additional expertise requirement).

6.2.2 Placement labour cost

The calculated concrete placement labour cost for the whole project decreased significantly with SCC usage. Table 8 shows the values as calculated for the case study.

Table 8: Placement labour cost impact for the overall project

OVERALL	
Concrete type	**Placement labour cost**
NCC	ZAR 39,600
SCC	ZAR 8,300

The placement labour cost KPI's for the overall project is another important piece of data used to interpret and quantify the financial impact of implementing SCC in a South African construction project. The following figures summarize the impact of implementing SCC on the placement labour cost.

- A 79% reduction in placement labour cost can realise if SCC is implemented
- This 79% reduction is equal to a R31 300 saving
- The total concrete works related construction cost was calculated as R2 098 700 for NCC usage
- The savings on placement labour is only a 1.5% saving on the project cost
- The saving is outweighed by the other cost increases such as material and formwork cost

The large percentage reduction in labour expense is not a sufficient reason for implementing SCC. This reduction is frequently used as an argument for the promotion of SCC, but it would be of little value for the investigated case. This insight can provide a decision maker with valuable information when considering SCC usage. The 79% reduction in concrete placement labour cost corresponds to the estimates of the interviewees. The assumption that one labourer is needed (if SCC is used) for every four when NCC is used, together with the accelerated placement time, leads to this reduction in costs.

In South Africa, labour is relatively cheap in comparison with the developed world. The interviewees identified this as one of the possible reasons for the less intensive usage of SCC when comparing South Africa to developed countries. It should be noted that the calculated results only account for the labourers involved in the placement of the concrete. Other labour costs, such as the expense of a floating team, might also be saved when using SCC on other projects. These labour expenses were excluded from the case study because minimal manual concrete finishing was done on the investigated bridge.

If labour related risks such as strikes or labour shortages are a major threat to a project, SCC can be used to minimise these risks by reducing the size of the labour force.

The bulk of the bridge (the large elements used in the structure), together with the simple geometric design, necessitates relatively few man-hours per cubic metre of concrete placed (in comparison to small repetitive element construction found typically in a precast construction process). The calculated results will differ if smaller elements are cast with a more labour intensive construction process. Labour expense will contribute a higher percentage of the total cost when constructing smaller elements and so raise the significance of a labour cost reduction.

6.2.3 Formwork cost

The total calculated formwork cost of the overall project showed an increase with SCC implementation. Table 9 shows the calculated formwork costs of this project.

Table 9: Formwork cost impact for the overall project

OVERALL	
Concrete type	**Formwork cost**
NCC	ZAR 428,700
SCC	ZAR 516,200

The formwork cost KPI's, for the overall project, are important in the interpretation of the financial impact of implementing SCC at a South African construction site. As predicted by the interviewees, the formwork cost shows an increase with SCC implementation. The formwork cost impact should be understood in order to effectively focus cost reduction efforts. Formwork cost reduction efforts should not be the same for every element type since the impact on formwork cost differs between element types.

Horisontal elements, such as slabs and beams, do not show a cost increase (except if the formwork has to be sealed). Vertical applications, such as columns and walls, do show an increase in formwork cost. This increase is due to the higher formwork strength requirements to support the hydrostatic pressures associated with SCC. The hydrostatic pressures are generally not problematic with horisontal applications due to the small depth of the element.

Formwork cost is highly dependent on the geometric characteristics of the individual elements in a structure. The larger the element depth, the larger the cost increase will be for the specific element. The higher quality formwork required if SCC is used and sealing the formwork to prevent material loss might incur additional expense. Sealing the formwork is not always necessary, if the formwork is well designed and if it is constructed to fit tightly together, this expense might be avoided.

The calculated formwork cost rose by 20% if SCC is implemented in the investigated case study. The increase is only due to the increase in the formwork cost of the wall elements. This will be explained in detail in Section 6.3.

The total formwork cost contributes a large percentage of the total calculated cost of the whole project (20.5% of R2 098 700 - NCC). The percentage that the formwork cost contributes to the total cost will change as the relative bulk of the underlying elements of a structure changes, similarly to material cost.

Very large elements have a lower outer surface to volume ratio than smaller elements. This means that the size of the formwork cost contribution will show an inversely dependent relationship with element size (formwork cost management becomes more important as elements get smaller).

Figure 21 shows this principle for a change in the cost composition of a square column with a varying cross sectional area and constant height (only formwork and material cost is shown due to their large contribution to the total cost). The same principle is shown in Appendix D for other elements with varying dimensions.

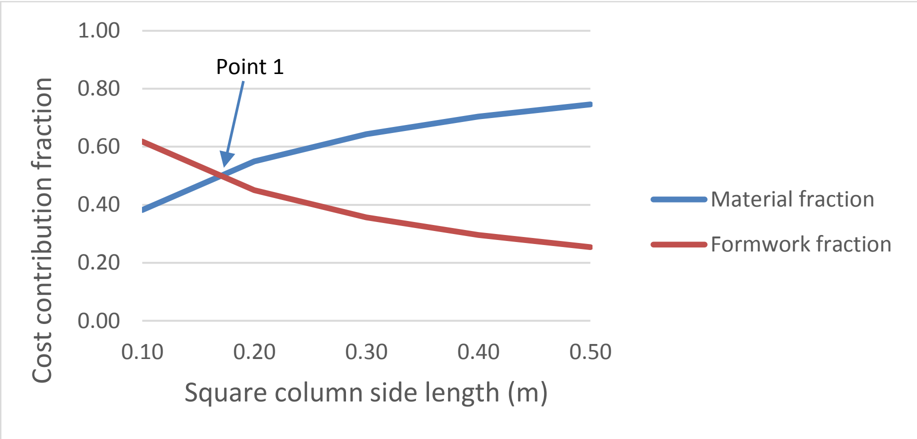


Figure 21: Change in the cost composition of a square column with varying base area and constant height

The formwork cost is more important in smaller elements than in large elements due to the higher cost fraction that is contributed by formwork in smaller elements (shown in Figure 21 left of point 1). This implies that the significance of an increased material price diminishes as elements get smaller. The finding is supported by the fact that SCC is more commonly used in the precast industry than for in-situ construction where larger elements are usually constructed. The increased unit price of SCC is less detrimental to the financial viability of SCC usage when smaller elements are constructed.

6.2.4 Rework cost

The calculated expense of rework done after the concrete has hardened showed a decrease if when SCC is implemented at a construction site. The overall calculated rework cost of the investigated case study is shown in Table 10.

Table 10: Total rework cost impact for the overall project

OVERALL	
Concrete type	**Rework cost**
NCC	ZAR 4,000
SCC	-

The rework cost KPI can provide valuable insight in the quantification of the cost impact of implementing SCC at a South African construction project. The calculation of the rework KPI is purely based on the estimation that 0.25% of the material cost can be added to the total cost to compensate for the rework done on NCC elements. The assumption that the value of the rework cost is 0.25% of the material cost was identified through the interviews. This was accepted for the case study due to the simple design and geometry of the bridge. It was noted that this figure could vary considerably between different concrete applications, with an increase expected as the geometry of an element becomes more complex.

The skill level and maturity level of the quality control techniques employed by a contractor will influence the rework expense. Concrete applications and specifications such as high quality off-shutter concrete, complex geometries or densely reinforced elements will increase the assumed NCC rework value.

The assumption that SCC has no rework due to its self-compatibility characteristic is based on the information gathered from the interviews. It was mentioned that rework due to poor compaction is eliminated if SCC is used.

The inclusion of rework in the model also affects the potential time saving that SCC can realise. Avoiding rework on elements that are on the critical path of a project translates into a time and cost saving.

The inclusion of a SCC rework assumption can be used if the need exists to quantify the risks involved with SCC implementation. These risks are identified in Section 7.4, but the quantification of risk is excluded from the scope of this study.

6.2.5 Other costs implication

'Other costs' showed a reduction if the proposed calculation methodology is adhered to and SCC is implemented at a construction site. The implication on other costs that would have realised for this case study if SCC were used can be seen in Table 11.

Table 11: Total 'other SCC costs implication' for the overall project

OVERALL	
Concrete type	**Other costs implication**
SCC-NCC	ZAR (42,000)

The other costs implication KPI is different from the previously discussed KPI's because it is not used by comparing two values between NCC and SCC. This KPI is only a single value, based on the expenses that are avoided if SCC is implemented (versus a change in a specific expense). The mathematical difference can be shown, relative to formwork for example, as:

$$KPI_{other\ costs\ implication} = \frac{\sum(implication\ on\ other\ costs)}{Total\ NCC\ project\ cost} * 100$$

Versus:

$$KPI_{Formwork} = \frac{Formwork\ cost_{SCC} - Formwork\ cost_{NCC}}{Formwork\ cost_{NCC}} * 100$$

Where the $'implication\ on\ other\ costs'$ are those expenses that only occur for one concrete type. With a positive value when they occur for NCC and a negative value if they occur for SCC.

This concept is important for the correct interpretation of the 'other costs implication'. Refer to Section 4.3 for further mathematical explanation of how the calculation of this KPI is done.

The 'other costs implication' is a combination of equipment savings (poker vibrators and cranes) and time saving. The time saving is quantified by means of a reduction in overhead costs (daily running cost of site) and a reduction in penalties.

The penalties reduction is based on the assumed percentage of the concrete casting that is done in the penalty period of a project. As with the rework assumption, the value of this assumption is highly variable. The assumed percentage is dependent on the complexity of the project, the experience of the contractor and the employed quality management processes on site.

The cost saving of R42 000 for the investigated project is mainly due to the absence of poker vibrators and the penalty savings. This is a 2% saving on the total project cost if calculated as explained. The assumption was made that the last 5% of the casts will be done in the penalty period. This is purely to illustrate the value of the calculation method and to highlight the need for this consideration.

Savings on overhead costs are excluded from the calculated results due to the absence of the required information. The reduction in overheads might have a significant influence on the final cost difference between the concrete types and should be included for a project if the information is available.

The value of the 'other costs implication' KPI will differ for each element type. This is because of the difference in equipment usage and labour intensity between elements. Smaller elements and those with easier access require less equipment for construction and the potential time saving is also less significant.

6.2.6 Time impact

The time required for construction will decrease if SCC is implemented on a construction site. For this case study, the calculated time saving for the whole project amounted to 14 days on an original construction duration of 277 days.

This is a 5% reduction in construction time and it is the time saved on concrete placement. This is notable and can translate into financial savings through reductions in overheads and penalties. The quantified financial impact due to a reduction in penalties is included in the 'other costs implication' KPI of this case study.

The increased workability of SCC is the main reason for the reduction in concrete placement time. It was assumed, based on the interview information, that SCC can be placed twice as fast as NCC. This was the most conservative estimate provided by the interviewees. However, the concrete placement is not a large contributor to the total project schedule and it can easily be accelerated for NCC through certain logistical decisions (such as increasing labourers or pumping the concrete rather than discharging it from a bucket with a crane).

Projects that are time constrained or which have fallen behind schedule will typically benefit from any time saving that can be realised on site. The increased material cost and decreased time requirements can be harnessed when tasks have to be accelerated ('crashed' in terms of project management calculations).

6.2.7 Total cost

The model results show an increase in the total cost of construction if SCC is to be used for this case study. The calculated values are shown in Table 12.

Table 12: Total cost difference for the overall project

OVERALL	
Concrete type	**Total Cost**
NCC	ZAR 2,098,700
SCC	ZAR 2,463,300

The overall cost implication of implementing SCC at a South African construction project is the highest level KPI considered. This comparison is a useful summary of all the other information and can be utilized by a decision maker who needs to use the total financial impact of implementing SCC as a decision criterion. The only drawback of this KPI is that it does not show the impact of SCC usage on the underlying cost constituents.

In a lowest bid tendering process a contractor might reject the use of SCC based on this KPI but a client can benefit from this information and specify SCC for reasons other than pure financial considerations. A client can only accept or reject the expected cost-benefit trade-off if it is quantified.

The increase in the total cost is due to impact of SCC usage on various underlying cost contributors and the size of the different contributions depends largely on the project geometry. As seen from the previous six KPI's, these cost constituents and their relative contributions to the total cost can provide other useful insights. (The previous six KPI's are the cost constituents of the total cost under consideration).

For the investigated case study, the increased cost is mainly due to the increase in material and formwork cost that outweighs the savings on the rework, labour and time. The total cost increase of 17.5% for the overall project (shown in Table 12) should be considered in relation with the cost-time-quality trade-off concept shown in Figure 22.

The information gathered from the calculated results, literature and interviewees suggested that the 17.5% cost increase has a basic economic justification. The increased price is paid for increased ease of use, better site conditions, a potentially more durable finished product and the other advantages of using SCC as listed in Section 2.5.

The increased cost can be attributed to the accelerated schedule as well. Figure 22 shows the well-known project quality triangle. This triangle shows the principle that a time acceleration and quality increase will incur higher costs, a concept which supports the findings of this research regarding the implementation of SCC at a construction site.

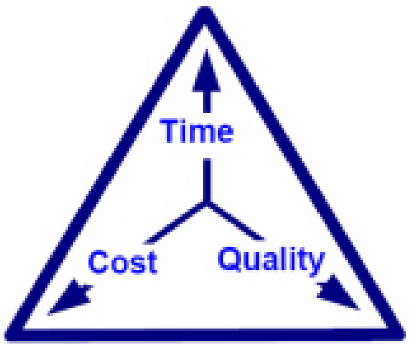


Figure 22: Project quality triangle (Jenkins, 2010)

The cost increase can be reduced by means of managerial and logistical decisions (aside from the methods that have already been proposed such as the addition of cement extenders). Complex structures that allow variations in the sequence of construction tasks can be used to test various task relationship options to identify the cheapest alternative. SCC usage increases the number of alternatives since more concrete can be placed in a specified timeframe and this can lead to alternatives that are more economical.

Possibilities of taller single cast columns (Soccer City Stadium discussed in *2.6*) and other large concrete casts can lead to labour and time saving if SCC is applied efficiently and if the schedule is planned accordingly. The reduction in material cost by the addition of cement extenders can further reduce the calculated total cost difference.

6.2.8 Visual representation

The results of the preceding sections can be presented visually and in a summarised format. This representation aids in the interpretation of the results. The results should be shown to a project participant in this proposed format. The total cost impact and the change in the individual cost constituents are both easily interpreted from two pie charts, as seen in Figure 23.

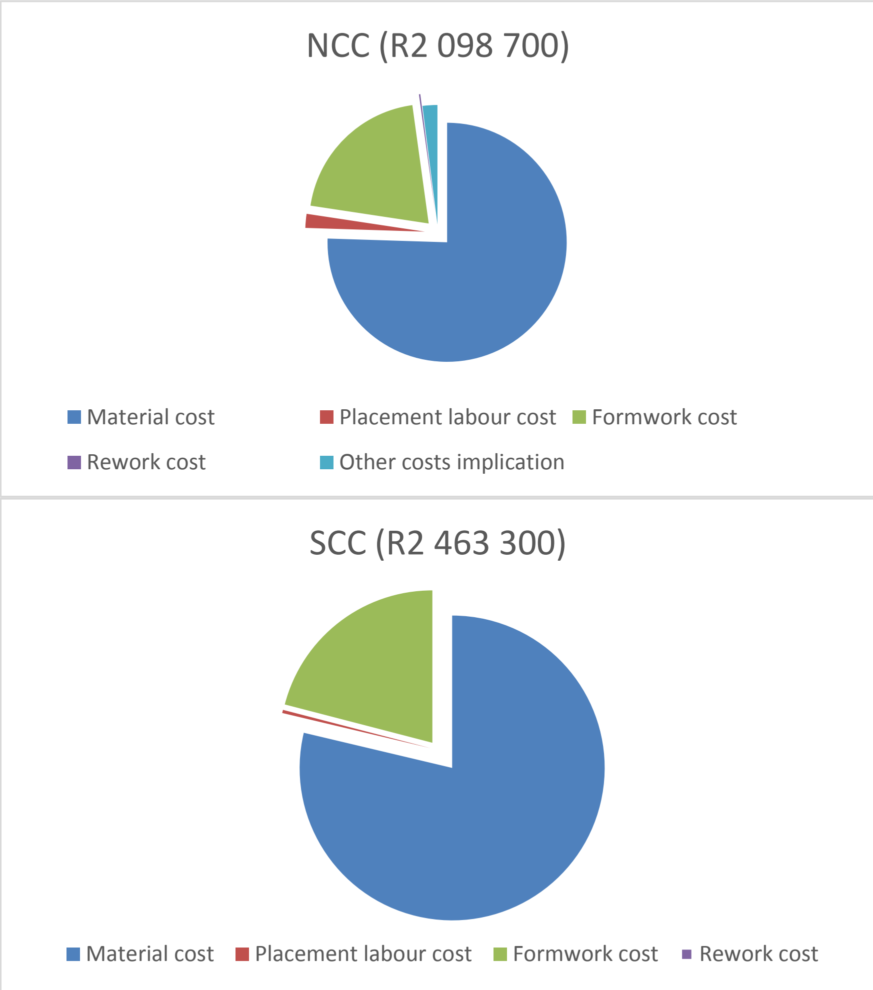


Figure 23: Visual representation of total cost comparison for the overall project

The information shown in the two pie charts in Figure 23 is the same as presented in Sections 6.2.1 to 6.2.7. This summary of the KPI's (for NCC and SCC respectively) is extracted from the model. The value of this format is in the clear presentation of the cost contribution of the individual cost constituents. A decision maker is enabled to easily assess the impact of SCC usage on each KPI and to interpret the impact relative to the total cost of the project.

For example, the impact of the assumption that there is no rework associated with the use of SCC is negligible. This is because of the negligible cost contribution (0.25% of material cost) of rework towards the total cost of using NCC in the first place. This provides the user with the knowledge that a 100% reduction in rework, a figure that might be used to convince an industry participant to use SCC, is in fact not substantial in terms of the total cost.

Decision makers can use this presentation method to investigate the justification of the cost-benefits trade-off associated with SCC.

The calculated cost difference of 17.5% between SCC and NCC (R2.1–R2.4 million) is represented by the increase in the diameter of the pie chart. The NCC cost is broken down into the five CPA's but the SCC cost does not include the 'other costs implication' as explained in 6.2.5.

The change in the cost composition is useful for a project team when identifying the focus areas for cost reduction efforts. The following observations can be made from Figure 23:

- There is a large reduction in the placement labour cost contribution. This is attributed to the improved workability of SCC in comparison to NCC and will be a generic result for the use of SCC in most concrete applications
- The implication on 'other costs' is not included as a cost constituent on the SCC chart, as explained in Section 6.2.5 (due to the definition of the KPI)
- Rework cost is negligible in both cases due to the assumption that 0.25% of the total concrete cost is representative of the rework expense associated with NCC (and SCC rework is 0%)
- The percentage cost contribution of formwork stays approximately constant, this means that total formwork expense will increase in the same order of magnitude as the total expense
- The decrease in rework and placement labour cost is outweighed by the increase in material cost
- Material cost is the largest cost contributor at more than 75% of the total cost.
- Any cost reduction in material will translate to a noteworthy saving on the total expense

The use of SCC would have been the more expensive option for this case study, but it would have saved time (and overhead savings are excluded from the calculations). The cost increase could have been reduced by negotiating better material unit prices or by investigating the use of cement extenders if the decision was made to implement SCC.

The South African industry has a lowest bid tender award structure and the fact that the case study's project team did not use SCC in reality supports the findings as explained in this section.

The total cost difference (17.5% or R364 600) can be divided into the contribution of each element type. The value of this division is the initial conclusion (whether or not to use SCC) that can be drawn from it if one understands the costs, benefits and risks involved with the different element types. The size of the individual contributions will be influenced by the project geometry and the concrete volume used for the respective element types. This breakdown can be seen in Figure 24.

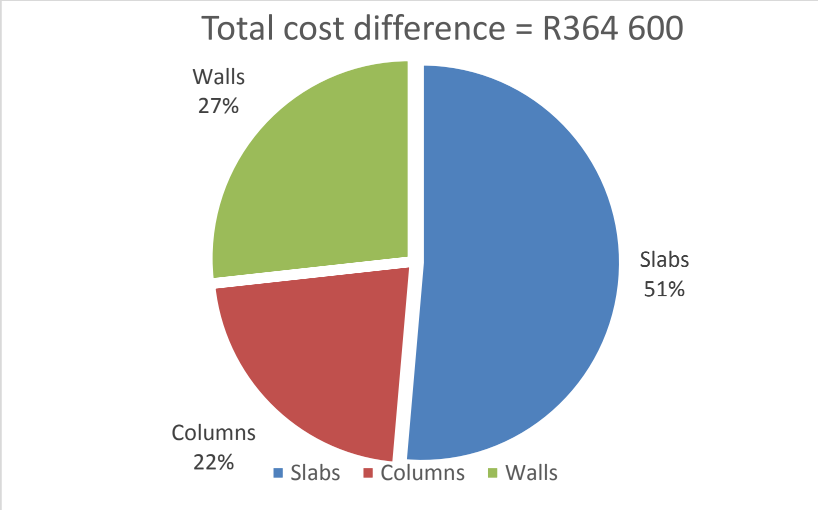


Figure 24: Breakdown of total cost difference into the element contributions

A large portion of the total concrete volume is used to construct the bridge deck slabs in the investigated case study. This is why slabs contribute to more than half the total cost difference. The relative contributions of walls and columns are also representative of the concrete volume used to construct those elements. This correlation emphasizes the significance of the material unit price. Figure 24 can be used to make an initial decision regarding the implementation of SCC, based on the preference or past experiences of the project team with using SCC in the construction of the respective element types.

The financial impact of using SCC on the individual elements is discussed in Section 6.3.

6.2.9 General discussion

By presenting the results as shown in this chapter, a project dashboard can be made as a visual summary of the financial impact of implementing SCC at a South African construction project. It enables the decision maker to effectively weigh the technical and time related advantages against the cost difference and to make a decision about the implementation of SCC.

For this case, the exclusion of the overhead expense calculations distorts the final answer in the following ways:

- The model indicated a 14 day time saving would be the result of SCC implementation
- The total cost increase associated with SCC usage is R364 611
- If R26 050 per day (R364 600/14) was saved on overheads due to the accelerated schedule, SCC usage would have lowered the total cost of the evaluated project

Cement extenders and logistical adaptations will reduce the cost difference. With this reduction, and the inclusion of the overheads calculations, SCC can potentially be utilised in applications where it is both cheaper and more beneficial in terms of technical advantages.

The model verification is important to ensure confidence in the calculated results. An expeditious investigation into the accuracy is explained below. This is not an exact verification but aims at verifying the orders of magnitude of the results.

- Material cost contributes 75.5% of the total cost and an increase of 22% in the concrete unit price was quoted for SCC in comparison with NCC
- Formwork cost contribute 20.4% of the total cost and an increase of 20% was calculated for the case study, based on the quotes received
- Both costs are easily verified as the cost per unit (R/m³ or R/m²/d) multiplied by the quantity used (m³ or m²)
  (multiplied by the formwork support time (days) for formwork cost)
- The material and formwork costs contribute 95.9% of the total cost and are easily verified, material and formwork showed an increase in the same order of magnitude
- The decrease in rework, labour and other costs (4.1% of the costs) reduces the total cost difference to 17.4% by their own large reduction (79%, 100% and 100% for labour, rework and other costs respectively)

This can be presented mathematically as: (using the same notation is used as in Section 4.3)

The total cost impact of implementing SCC was calculated as **an increase of 17.4%**

$$\frac{T_{SCC}}{T_{NCC}} = (1+\Delta T) = \frac{M_{NCC}}{T_{NCC}} * (1+\Delta M) + \frac{F_{NCC}}{T_{NCC}} * (1+\Delta F) + \frac{R_{NCC}}{T_{NCC}} * (1+\Delta R) + \frac{L_{NCC}}{T_{NCC}} * (1+\Delta L) + \frac{A_{NCC}}{T_{NCC}} * (1+\Delta A)$$

75.5% of the total NCC cost (Material) — An **increase of 22%** (1+0.22) in the average quoted unit price of concrete if SCC is used

20.4% of the total NCC cost (Formwork) — An **increase of 20.4%** (1+0.24) in the average quoted formwork renting cost if SCC is used

Both costs are easily verified as the cost per unit (R/m³ or R/m²/d) multiplied by the quantity used (m³ or m²)

95.9% of the total cost is easily verified and will increase with approximately 20-22% if SCC is used

The decrease in rework, labour and other costs (**4.1%** of the total NCC cost) reduces the total cost difference to 17.4 % by their own large reduction (**79%, 100% and 100% reduction** in labour, rework and other costs respectively)
*Note: The inclusion of overheads in A (other costs) will significantly change the weight distribution between the cost contributors

The weighted average between the material and formwork cost increase is thus a conservative estimation (20-22%) of the total cost increase calculated for this case study. (Note: The total project cost only refers to the total concrete related construction cost of the project and the applicable overheads and penalties).

6.2.10 Possible variations on other projects

Projects of different geometries will show different results in terms of the total cost difference and the cost constituent contributions. The change in results will depend on the element types used in the structure and their frequency of occurrence. The results of an office block, for example, will differ from the case study results due to the higher portion of concrete used for wall construction and the inclusion of beams.

The following changes are expected for projects with different geometries:

- Off-shutter and high-quality concrete finish specifications will increase the contribution of rework cost to total cost. SCC can be used if a contractor is inexperienced with these specifications

- The construction of smaller elements is more labour intensive (more man-hours per cubic metre of concrete used) than large elements. The phenomenon of labour becoming dearer and labour-savings more important can be expected when smaller elements are built.
- Projects with small and repetitive elements will show a higher labour cost contribution and a lower overall cost difference if SCC is implemented

These findings are supported by the regular implementation of SCC in the precast industry in South Africa, as identified through the interviews with South African SCC suppliers.

Considering the connection between element size and financial viability, hybrid-concrete construction projects can benefit from SCC implementation. The repetitive placement labour saving on small elements, manufactured in the precast yard, will lower the total cost of a project. A further reduction in costs can be expected since less formwork is used in hybrid-concrete construction.

6.3 Structural element contributions

The overall cost difference, as discussed in the previous section, is a good summary of the financial impact of using SCC on a project. This summary can be supplemented by investigating the cost breakdown of the individual element types. The breakdown of the element types provides additional insights on where SCC can be applied to maximise benefits and optimise costs. The elemental cost is a more generic result than the overall cost because it is not dependent on the project geometry and it provides a result that can be extended to other projects. The elemental breakdown is only dependent on the element geometry, which is similar between projects.

The slabs, walls and columns of the investigated case study is examined and discussed in this section. The aim is to identify how to maximise the benefits of using SCC while reducing the cost impact of the increased material and formwork cost.

The elements are discussed individually, by evaluating the effect of implementing SCC on the seven identified KPI's. This is followed by a general discussion about the results and the identification of variations that can be expected for other projects.

6.3.1 Slabs

The construction cost of slabs showed an increase if SCC is implemented. This is mainly because of the increased material price resulting from the higher cement content of SCC. The cost breakdown, into the seven KPI's can be seen Table 13.

These values are also represented by the two pie charts shown in Figure 25.

Table 13: Slab KPI comparison

SLABS		
Concrete type	**NCC**	**SCC**
Material cost	ZAR 1,097,400	ZAR 1,330,300
Placement labour cost	ZAR 20,700	ZAR 3,900
Formwork cost	ZAR 336,300	ZAR 336,300
Rework cost	ZAR 2,700	ZAR -
Other SCC costs implication	ZAR (26,000)	NA
Total Cost	ZAR 1,483,200	ZAR 1,670,500
Time impact [days]	NA	-5.9

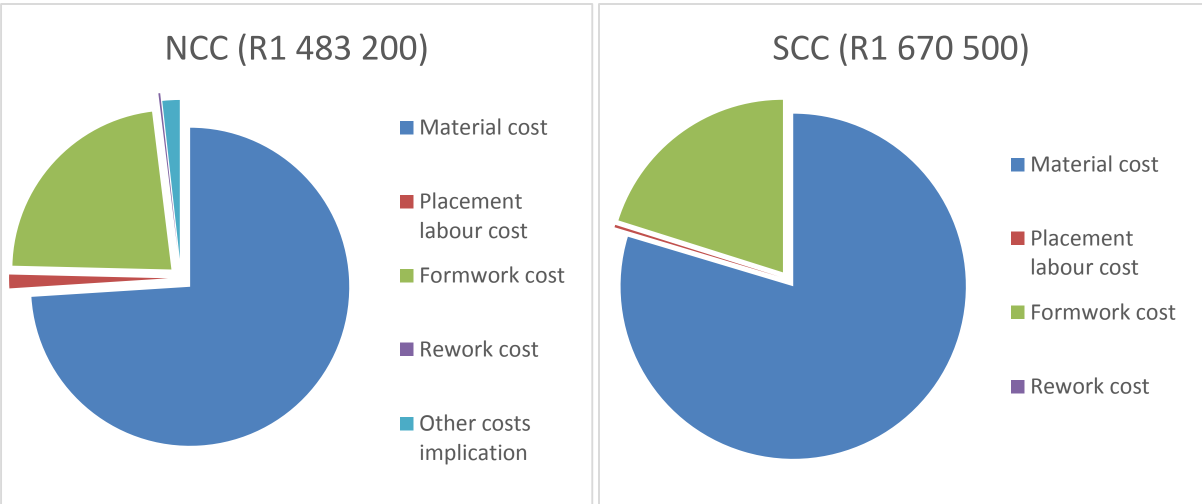


Figure 25: Cost implication for slab elements

The cost breakdown of the slab elements is similar to the overall project cost breakdown. This is because slabs are the biggest cost contributor to the total project cost. The cost increase is mainly attributed to the increased material price. The placement labour cost reduces to become insignificant when SCC is used. The increase in the material cost contribution outweighs the combined reduction of the placement labour cost, rework cost and 'other costs implication'. The increase in the percentage contribution of material cost to the total cost causes the percentage of the formwork cost contribution to reduce (formwork costs remain constant for horisontal applications; it thus contributes a smaller part to the increased total cost of SCC usage).

The large influence of the increased material cost contribution and the large contribution that material cost makes to the total cost (>75%) is due to the geometry of a slab. The low outer surface to volume ratio of a slab (compared to walls, columns and beams) causes the material price to be the most influential cost constituent. Refer to Appendix D for the comparison of the outer surface to volume ratios of the different elements.

The following additional observations can be made about the calculated results and can be used to interpret the financial impact of using SCC in the construction of slabs:

- The increase in material price is due to the increase in the unit price of SCC (attributed to the increase in the cement content in a SCC mix design)
- The large reduction in labour cost is insignificant due to the small contribution of labour cost towards the total cost
- Formwork costs remained constant (the small depth of horisontal elements do not cause sufficient hydrostatic pressure to require additional formwork strength)
- Rework cost and 'other costs implication' reduce when SCC is used (This is based on the model definition explained in Section 4.3)
- The results showed a 5.9 day time saving if the construction of slab elements were done using SCC (due to faster placement rates as sourced from the interviews)
- Realising this time saving on the overall schedule requires adaptations in the relationships between project tasks (it is a combination of small savings spread out over various concrete casting days)
- The resulting total cost increase of 12.6%, mostly due to the 21% increase in material cost, highlights the importance of unit price negotiations in the construction of slab elements

6.3.2 Columns

The calculated cost of constructing column elements increased for the use of SCC. This increase is mainly attributed to the increased material unit price of SCC. This reason is the same for slab elements and the overall project. The breakdown of cost into the seven KPI's can be seen in Table 14.

These values are also represented by the two pie charts shown in Figure 26.

Table 14: Column KPI comparison

COLUMNS		
Concrete type	**NCC**	**SCC**
Material cost	ZAR 377,900	ZAR 470,600
Placement labour cost	ZAR 8,200	ZAR 2,200
Formwork cost	ZAR 13,300	ZAR 13,300
Rework cost	ZAR 945	ZAR -
Other SCC cost implication	ZAR (5,900)	NA
Total Cost	ZAR 406,300	ZAR 486,100
Time impact [d]	NA	-3.00

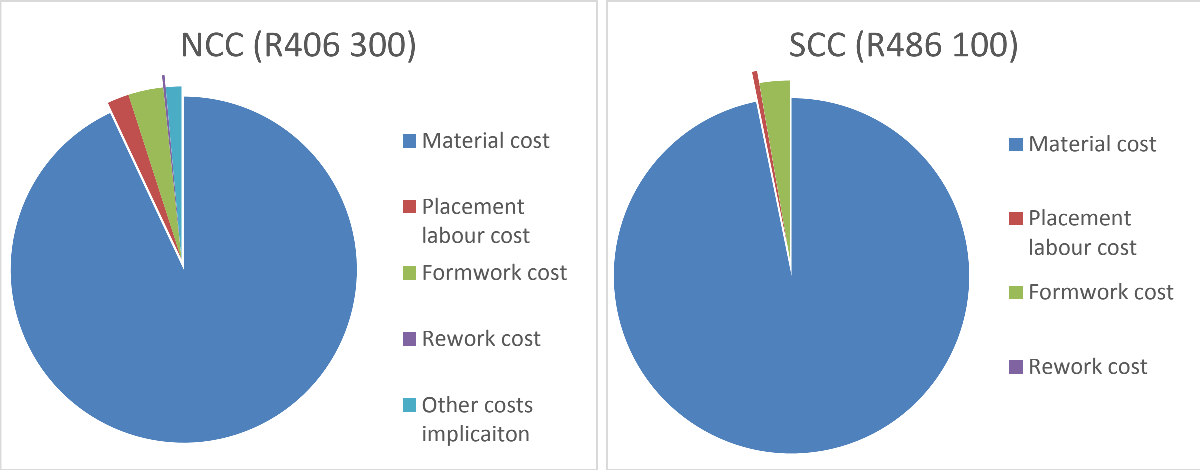


Figure 26: Cost implication for column elements

The cost breakdown of the column elements is different from the overall project cost and the slab elements cost breakdown. The cost increase is mainly because of the increased material price, which corresponds with the other elements and the interview expectations. The placement labour cost reduces to become insignificant when SCC is used. As with the slabs, the increase in the material cost contribution outweighs the reduction in placement labour cost, rework cost and 'other costs implication'.

The increase of the material cost contribution and the large contribution of material cost towards the total cost (>90%) is due to the geometry of a column and the shorter formwork idle time of vertical elements. Since the time that the formwork should support the fresh concrete is short for vertical elements (2 days), the formwork cost contributes less towards the total cost (relative to horizontal elements where the specified support time is longer). The reduction in the specified formwork usage time outweighs the higher outer surface to volume ratio that tends to increase the contribution of formwork cost to the total cost. Refer to D.1 in Appendix D for the comparison of the influence of the outer surface to volume ratio on the cost contributions of material and formwork costs for different elements.

The following additional observations about the impact of using SCC in the construction of columns are made from the calculated results:

- The small cost contribution of formwork cost to the total cost of columns is due to the specification of the time that the formwork has to support the fresh concrete
- The small volume of concrete used for column construction in the case study diminishes the influence of the column cost breakdown over the total project cost breakdown
- The increase in material price is due to the increase in the unit price of SCC (higher cement content in SCC mix design)
- The quoted unit price difference between NCC and SCC was larger for vertical applications (+25%) than for horisontal applications (+21%)
- The large reduction in labour cost (73%) is insignificant because of the small contribution that the labour cost makes towards the total cost of the column elements
- Rework cost and 'other costs implication' showed a reduction if SCC is used in column construction (This is based on the model definition explained in Section 4.3)

- The model indicated a 3 day time saving on the construction of column elements (due to faster placement rates as sourced from the interviews)
- Realising this time saving on the overall schedule will require adaptations in the relationships between project tasks (it is a combination of small savings spread out over various concrete casting days and that has to be consolidated)
- The resulting total cost increase of 19.6%, mostly due to the 25% increase in material cost, highlights the importance of unit price negotiations in the construction of column elements
- The formwork cost for columns remained constant (although columns are vertical elements that exerts significant hydrostatic pressures on the formwork if SCC is used)

The formwork cost does not change for column elements because the formwork suppliers noted that the standard column boxes are pre-designed to accommodate hydrostatic pressures, even when NCC is used. This was accepted in the modelling procedure, but it is not a universal case. Other formwork quotes varied notably if SCC is the material of choice instead of NCC. The justification of a particular supplier was that prefabricated SCC column boxes are not available and that SCC column boxes are built from the basic formwork building blocks. Thus, the NCC column formwork can be constructed from lower strength formwork systems than the formwork used to support SCC (due to the hydrostatic pressures associated with SCC). This resulted in a higher quote for the preparation of SCC column boxes. The first quote was accepted (no price difference) because it is cheaper and suitable for the project under consideration.

6.3.3 Walls

The calculated cost of constructing wall elements showed an increase with the use of SCC. This increase is mainly attributed to the increased material unit price of SCC and the increase in formwork cost due to higher strength requirements. The cost contribution of formwork to the total element cost is larger for walls than any other element in the case study. The breakdown of the costs into the seven KPI's can be seen in Table 15. These values are also represented by the two pie charts shown in Figure 27.

Table 15: Wall KPI comparison

WALLS		
Concrete type	**NCC**	**SCC**
Material cost	ZAR 109,200	ZAR 137,900
Placement labour cost	ZAR 10,700	ZAR 2,200
Formwork cost	ZAR 79,100	ZAR 166,600
Rework cost	ZAR 273	ZAR -
Other SCC costs implication	ZAR (10,000)	NA
Total Cost	ZAR 209,200	ZAR 306,700
Time impact [d]	NA	-5.1

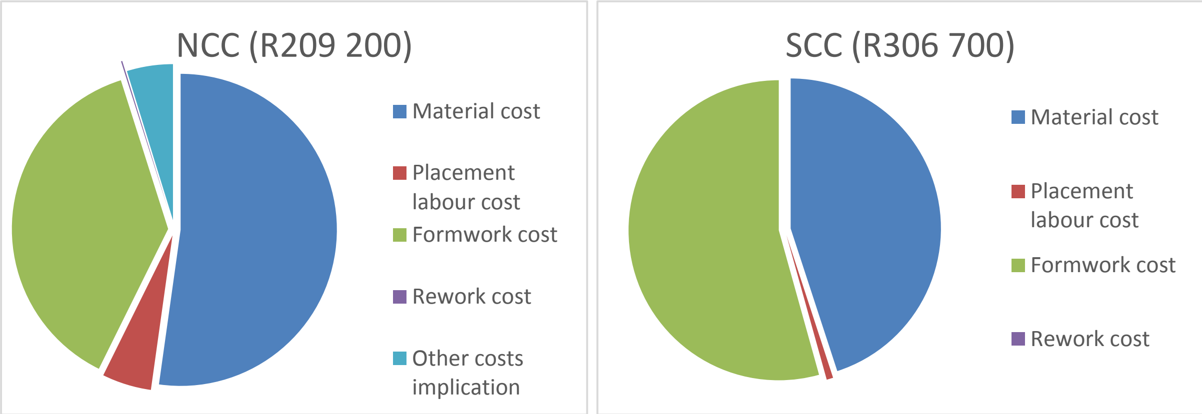


Figure 27: Cost implication for wall elements

The cost breakdown of the wall elements differ from the overall project cost, the slab elements and the column elements cost breakdown. The cost increase for walls is due to the increased material and formwork cost (rather than only material cost). The placement labour cost reduces to become insignificant when SCC is used. Contradictory to the previous elements, the increase in the formwork cost contribution (rather than the material cost contribution) outweighs the reduction in placement labour cost, rework cost and 'other costs implication'.

Wall elements are the only elements where the most significant cost increase is due to the rise in the formwork cost and not only the material cost.

The increase in the formwork cost contribution and the large contribution to total cost (38% for NCC and 54% for SCC) is due to the geometry of a wall (high outer surface to volume ratio) and the absence of standard pre-constructed formwork (such as standard size column boxes used in column construction). Refer to Appendix D for the comparison of the influence of the element size (outer surface to volume ratio) on the size of the formwork cost contributions of different elements.

The following additional observations were made about the calculated impact of using SCC in the construction of walls:

- The absence of standard pre-constructed wall formwork means the SCC formwork is built with a significantly more expensive formwork system than the NCC formwork (to accommodate higher hydrostatic pressures)
- Controlling the concrete pour rate can enable the use of lighter strength formwork, but the time saving associated with SCC is then lost (pour rate limits reduce hydrostatic pressure development)
- The small volume of concrete used for wall construction in the case study lowers the correlation between the cost breakdown of walls and that of the overall project
- The quoted unit price difference between NCC and SCC was larger for vertical applications (+25%) than for horisontal applications (+21%)
- Rework cost and 'other costs implication' reduce when SCC is used for wall construction (This is based on the model definition explained in Section 4.3)
- The results showed a 5.1 day time saving on the construction of wall elements (due to faster placement rates as sourced from the interviews)

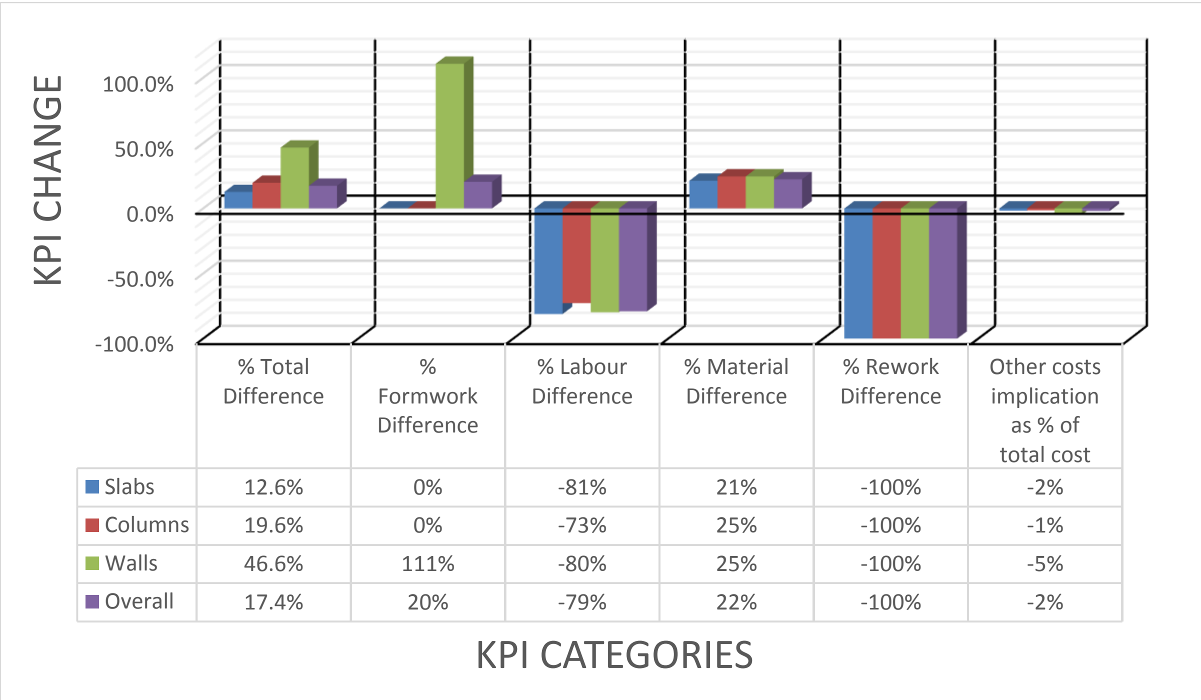
- Realising this time saving on the overall schedule requires adaptations in the relationships between project tasks (it is a combination of small savings spread out over various concrete casting days that needs to be consolidated)
- The total construction cost increase of 46.6% for wall elements is mostly due to the 25% increase in material cost and the accepted quote of a 111% increase in the formwork cost. These figures show the importance of material and formwork price negotiations in the construction of wall elements

6.3.4 General discussion

The value of the cost breakdown into the different constituents is the clarity that the breakdown provides about the following questions:

- **How large** is the cost contribution of every constituent towards the total cost (the total cost of an element or of the entire project)?
- **How and to what extent** does the size of the cost contributions **change** for each constituent when SCC is implemented?
- How can this information be used to **reduce the total project cost difference** when choosing to use SCC?
- **Which** results are based on **uncertain input variables** that should be included in the **Monte Carlo analysis** that forms part of the heuristic model?

The first point is addressed by the results presented in the pie charts. The second point is only to some extent addressed by the pie chart representation. The exact change that will occur for every cost constituent when SCC is implemented remains unclear. The KPI change summary shown in Figure 28 shows the exact calculated change of each cost constituent when SCC is implemented.



	% Total Difference	% Formwork Difference	% Labour Difference	% Material Difference	% Rework Difference	Other costs implication as % of total cost
Slabs	12.6%	0%	-81%	21%	-100%	-2%
Columns	19.6%	0%	-73%	25%	-100%	-1%
Walls	46.6%	111%	-80%	25%	-100%	-5%
Overall	17.4%	20%	-79%	22%	-100%	-2%

Figure 28: KPI change summary

The information about how and to what extent a cost constituent changes can be extracted from this KPI summary. The material cost difference for slab elements, the material cost difference for the overall project and the total cost difference of a slab will be evaluated as examples. The data table and the figure in Figure 28 show a 21% increase in the material cost of slab elements if SCC is implemented. This increase is a result from the model and it is based on the quoted unit prices of NCC and SCC as received from the concrete supplier.

The calculated material cost difference for the overall project is 22% if SCC is used, as shown in the data table of Figure 28. This figure is the weighted average of the change in the material cost of slabs, columns and walls (21%, 25% and 25% respectively). It is weighed in terms of the cost of the concrete volume used for each element type (based on the portion of the total concrete used to construct different element types and the cost of the specific mix design used in the construction of each element). The large portion of concrete used to construct slabs in the investigated project results in the 22% material cost increase for the overall project.

A 12.6% increase was calculated for the total slab cost of the investigated case study. This figure is also a weighted average. It is the weighted average of the cost difference in the formwork, labour, material, rework and 'other costs' as calculated for slab elements (0%, -81%, 21%, -100% and -2% respectively).

All the other changes in the different cost constituents (KPI's) can be analysed in the same manner in order to determine how and to what extent the expense will change if SCC is implemented. The KPI change summary should be evaluated together with the pie charts. The pie charts show the size (base value) of each cost constituent and the KPI change summary shows the exact change that can be expected if SCC is implemented.

The third point, how to reduce the total project cost difference with this information, can be addressed in the following ways:

- Based on the large contribution (pie chart information) of material and formwork cost, as well as the increase in the percentage cost contribution if SCC is implemented (KPI summary), cost reduction efforts should be focussed on these KPI's
- Formwork costs can be reduced by negotiating lower unit prices for renting the formwork
- Material costs can be lowered through unit price negotiations and/or the addition of cement extenders

Additional insights into cost reduction strategies and cost estimation techniques that were gained through the modelling process are:

- The labour intensity (man-hours per cubic metre of concrete placed) required to construct an element will indicate whether or not reductions in labour costs is worth pursuing (higher man-hours per cubic metre of concrete placed means a higher significance of labour cost reductions)
- The labour intensity usually rise as the size (volume) of an element reduces
- A small element with a high labour intensity will render reductions in labour cost the most significant
- The outer surface to volume ratio will indicate whether or not reductions in formwork costs is worth pursuing (as explained in Section 6.3.1)

- A larger outer surface to volume ratio indicates a larger contribution of formwork cost to the total cost and hence an increased importance of managing the formwork cost
- The prescribed time that the formwork supports the concrete while it is hardening will provide an additional indication of whether or not reductions in formwork costs is worth pursuing
- If the formwork support time is short, the percentage that the formwork cost contributes to the total cost is lower since the formwork is rented for a shorter time (e.g. vertical elements)
- The outer surface to volume ratio and the formwork support time should be considered together to make a final estimation on whether or not to pursue cost reductions for formwork
- Any reduction that can be realised in the material cost will significantly enhance the economic viability of SCC

The identification process of the uncertain input variables that should be included in the Monte Carlo analysis is the topic of discussion in Section 6.4.

6.3.5 Possible variations for other projects

The proposed calculation method for quantifying the decision to implement SCC is adaptable for most concrete construction projects. The structure of the static model is independent of the geometric characteristics of a project. This adaptability adds value to the proposed quantification technique and leads to visual results that can be interpreted with ease.

The calculated results are however dependent on project related constraints. The cost constituent results and the size of their contribution towards the total cost will vary notably between project types. The calculation method exposes these changes and enables better cost management if SCC is implemented. The following variation in results is anticipated for different project types:

1. The elemental cost breakdown will be similar between projects using the same element types, but the overall project cost breakdown will be similar to the most abundant element, by volume (for this case the overall project cost breakdown was similar to the slab cost breakdown)
2. The cost breakdown of structures where the vertical elements form a larger part of the total structure may show less correlation with slab elements due to the smaller concrete volume portion used for constructing slabs in these structures
3. Elemental cost breakdown variations can be expected if fundamental differences exist in the construction technique, such as:
    a. The reduction in the formwork cost of wall elements through formwork standardisation
    b. Using cement extenders to lower the material cost
    c. Using Hybrid Concrete Construction techniques (especially with small elements)
    d. Implementing precast element manufacturing processes
    (the efficiency of labour and formwork usage is improved)
4. Specialist concrete structures and elements such as water retaining structures will have a higher formwork cost contribution (due to specialised formwork systems). This can diminish the importance of an increased material price by increasing the importance of the technical advantages of SCC (avoiding construction joints, faster placement and improved durability due to better compaction).

6.4 Parameter sensitivity

A sensitivity analysis was performed on the overall project KPI's of the case study (as explained in Section 4.2.2). The overall cost difference is discussed in this section as an example, but any KPI listed in *Table 5: Summary of extractable Key Performance Indicators* (KPI's) can be used in this process. The distinction in the importance of the different KPI’s will be based on the project type and the potential benefits that can be realised by using SCC. The pursued benefits will differ for each project participant; a consultant might be interested in the cost of increasing the constructability while a contractor might be interested in limiting the rework expense.

The sensitivity analysis was done to identify those input parameters that have the largest effect on the output KPI’s. Three types of information can be extracted from the result of the sensitivity analysis:

1. Identifying the top ten input parameters that have the most influence on the output KPI under investigation
   (cost management can be enhanced by focussing on these parameters)
2. The sensitivity of the KPI with regard to these ten influential inputs and if it is possible to lower the expected cost by managing these inputs
   (cost management efforts can be further prioritised)
3. Identifying the influential input parameters that are based on uncertain data to include them in the Monte Carlo analysis
   (Enhancing the accuracy of the results that are used to decide if SCC should be used at a project)

The discussion in this section is done in the same order. This is done to show how the calculated information can be utilised by a project team.

6.4.1 Main influence parameters of the overall project KPI’s

The top ten influential input parameters, identified through the sensitivity analysis of the overall project KPI’s, are listed in Table 16.

Those KPI’s with less than ten listed input parameters are either dependent on less than ten input parameters in the model or less than ten input parameters can lead to a 1% change in the KPI value if its own value varies by 10% or less.

The Total Cost KPI listed in Table 16 is a comparison between SCC and NCC. This means that the total cost KPI in the table can be expressed as:

$$Total\ cost = Total\ cost_{SCC\ implemented} - Total\ cost_{NCC\ implemented}$$

The ten influential input parameters that are listed for the total cost KPI are those that influence the total cost **difference** between using SCC and NCC the most.

Appendix D contains the result of the sensitivity analysis (most influential input parameters) for every KPI of every element type discussed in Section 6.3. Only the total cost difference of the overall project (Total cost KPI) will be discussed in detail in this section. The other KPI’s can be analysed in the same way if they are important for prioritising cost management strategies. Refer to Table 23 in Appendix C for the structural element breakdown of the project (to see that Slab1 is the modelled slab element that represents the six bridge deck spans). The concrete mix detail and which mix is used in the construction of which element is also shown in Appendix C in Table 23.

Table 16: Main influence parameters for overall project KPI's

Overall Project KPI's	Most influential input parameters									
	1	2	3	4	5	6	7	8	9	10
Critical path timesaving	NCC formwork erection time Slab1	SCC formwork erection time Slab1	NCC concrete placement rate Slab1	SCC concrete placement rate Slab1	NCC concrete placement rate Column2	NCC concrete placement rate Column3	NCC concrete placement rate Column4	NCC concrete placement rate Column5	NCC concrete placement rate Column6	NCC formwork dismantle time Slab1
Total Cost	SCC unit cost Mix1 (externally supplied)	NCC formwork erection time Slab1	SCC formwork erection time Slab1	SCC unit cost Mix2 (externally supplied)	SCC unit cost Mix3 (externally supplied)	Total number of concrete casts	NCC unit cost Mix1 (externally supplied)	SCC unit cost Mix4 (externally supplied)	Number of NCC formwork erectors for Slab1	Number of SCC formwork erectors for Slab1
SCC Material Cost	SCC unit cost Mix1 (externally supplied)	SCC unit cost Mix2 (externally supplied)	SCC unit cost Mix3 (externally supplied)	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	
NCC Material Cost	NCC unit cost Mix1 (externally supplied)	NCC unit cost Mix2 (externally supplied)	NCC unit cost Mix3 (externally supplied)	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	Slab1 element volume	
SCC Placement labour cost	NCC concrete placement rate Slab1	NCC concrete placement rate Column2	Number of SCC concrete placers for Slab1	Number of supervisors required for Slab1 SCC placement	Number of foreman required for Slab1 SCC placement					
NCC Placement labour cost	NCC concrete placement rate Slab1	Number of NCC concrete placers for Slab1	Number of skilled labourers for NCC placement of Slab1	Number of semi-skilled labourers for NCC placement of Slab1						
SCC Formwork cost	SCC formwork erection time Slab1	Formwork Area of Slab1	Number of SCC formwork erectors for Slab1	Number of SCC formwork foreman for Slab1	Number of SCC formwork supervisors for Slab1	Formwork support time of fresh concrete Slab1				
NCC Formwork cost	NCC formwork erection time Slab1	Formwork Area of Slab1	Number of NCC formwork erectors for Slab1	Number of NCC formwork foreman for Slab1	Number of NCC formwork supervisors for Slab1	Formwork support time of fresh concrete Slab1	NCC formwork dismantle time Slab1			
Rework cost	NCC unit cost Mix1 (externally supplied)	Slab1 element volume	NCC unit cost Mix2 (externally supplied)	NCC unit cost Mix3 (externally supplied)						
Other costs implication	Total number of concrete casts	Percentage of casts done in penalty period	NCC formwork erection time Slab1	SCC formwork erection time Slab1						

The following observations can be made regarding the total cost difference KPI and the influential input parameters identified in Table 16 for this KPI:

- Five of the ten most influential input parameters are material unit costs (this is supported by the static results presented in Section 6.2.8)
- The SCC unit cost of externally supplied Mix1 is the most influential input parameter with regard to the total cost difference (Mix1 is used to construct the bridge deck, the element for which the most concrete is used in the case study)
- Mix 2, Mix 3 and Mix 4 are less influential because a smaller volume of these concrete mixes are used on site (compared to the concrete volume used in constructing the bridge deck)
- The total number of concrete casts are influential to the total cost due to the savings in overheads and penalties that are dependent on its value*
- The SCC and NCC formwork erection time of Slab1 influences the cost due to the renting of formwork and the labour used in erecting it**
- The 'number of formwork erecters for NCC and SCC' identified as influential parameters, is based on the team compilation of the formwork erection team of Slab1. These costs are also included in the formwork erection calculations**

*The penalty saving is based on the assumed percentage of the concrete casts that is done in the penalty period (PP). The formula used to calculate the penalty saving can be seen below. Note the dependency on the total number of concrete casts (n) and the assumed percentage (PP). Although the percentage assumption can and should vary, the total number of casts is fixed by design. The uncertainty in the inputs can be modelled by adding variance to the assumed percentage of concrete casts that are done in the penalty period (PP), rather than the scheduled number of casts (n).

$$Penalty\ saving = \sum_{i=0}^{i=r-1} (T_{n-i}) * PC$$

And:

$$r = n * PP$$

With:

PP	=Percentage of concrete casts assumed to be done in the penalty period	[%]
n	=Total number of concrete casts in the project	
r	=Number of casts that is done in the penalty period	
PC	=Penalty cost per day	[R/day]
T_n	=The saving on concrete placement time associated with placement n	[days]

**The contribution of the formwork erection time is misleading. It was used in the model differently than the name suggests. The figure should only represent the time required for erecting the formwork. Additional time was added to this since the formwork on site could not be removed after the specified time that it should support the fresh concrete. An access problem caused the formwork to be rented for longer than necessary. The additional time that the formwork supported the structure was modelled as ten days for every bridge deck span. The cost of the additional ten days was accepted due to the additional formwork renting cost that was accepted on site. (This is the best parameter to adapt for this site complication; if assumed applicable to both materials, the net effect on the total cost difference is zero)

Only the five material costs can be altered through cost management and cost reduction efforts. This analysis should be done for every KPI that is important to a specific decision maker. It is done to identify the areas where costs can be saved and those areas that should be monitored closely in order to prevent unexpected expenses.

6.4.2 General representation

As discussed earlier, the value of a sensitivity analysis is in the extraction of the following information:

1. Identifying the top ten influential input parameters that affect the output KPI under investigation
2. The sensitivity of the KPI with regard to these ten influential inputs and if they can be altered
3. Identifying the influential input parameters that are based on uncertain data and which should be included in the Monte Carlo analysis

By presenting the results of the sensitivity analysis as a tornado graph, as seen in Figure 29, the first two information types are easily extracted. A tornado graph shows the list of the influential input parameters, as well as the sensitivity of the output KPI to their variance. This was calculated as explained in Section 4.2.2.

Continuing with the overall project cost difference as an example, the results of the sensitivity analysis on this KPI is shown in Figure 29. In a similar way, this can be done for any other KPI if the need should exists.

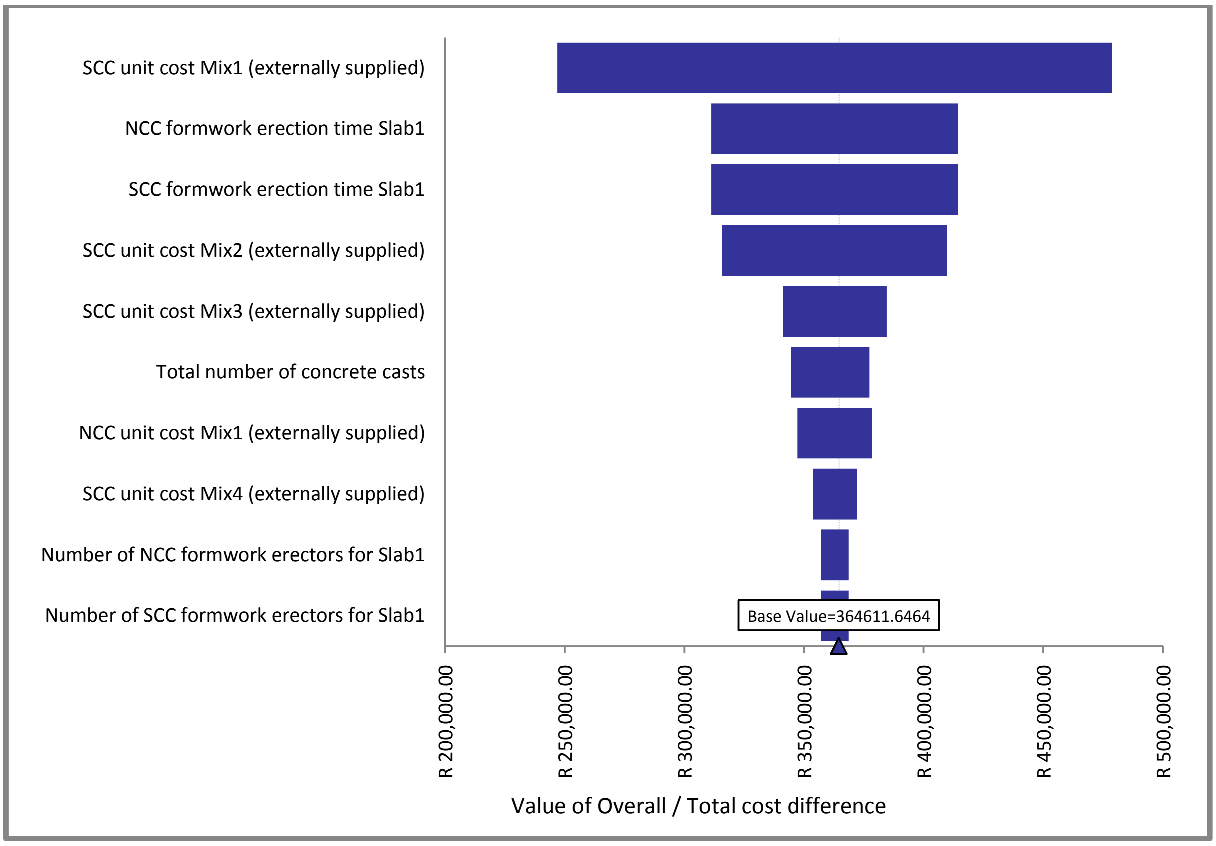


Figure 29: Tornado graph of overall project cost difference (impact by inputs)

The following observations are relevant to the results of the sensitivity analysis on the total cost difference of the overall project, shown in Figure 29:

- A 10% reduction in the material unit price (from R1565 to R1408.50 per m³) of SCC Mix1 (used to construct the bridge deck) causes a 32.3% reduction in the cost difference (R364 611 to R246 972)
- A 10% reduction in the material unit price of SCC Mix2 (used to construct the piling columns) causes a 13.4% reduction in the cost difference (R364 611 to R315 825)
- If a **10% cost reduction in all SCC unit prices** can be achieved it will **lead to a reduction in the cost difference of approximately 55%** (32.3% for Mix1 plus 13.4% for Mix2 plus 6.41% for Mix3 plus 3.01% for Mix4)
- The two formwork erection rates should be disregarded (for the sensitivity analysis) due to the irregular use of the parameter in this case study*
- The large cost contribution of slab elements towards the overall project cost difference (51%, as shown in Section 6.2.8) is highlighted by the fact that six of the ten influential input parameters are related to the construction of Slab1, the six bridge deck spans

*It should be noted that if the access problem was anticipated and the formwork could have been removed earlier, the overall cost would have been less. The cost **difference** would however remain the same (since the formwork cost for slab elements is the same, irrespective of material choice).

These insights are the fundamental reason for doing the sensitivity analysis and are used to show the impact of different decisions and potential opportunities. All the identified KPI's can be evaluated in this manner.

6.4.3 Input identification for the Monte Carlo analysis based on the Pareto Principle

The final information that can extracted from the sensitivity analysis is the identification of the uncertain influential input parameters, which should be included in the Monte Carlo analysis.

Three considerations aid in identifying the input variables that should be included in the Monte Carlo analysis of a KPI. An input parameter should be included if all of the following statements are true:

1. The input parameter can be altered and is not part of a specification
   (labour teams can be altered but are specified by the contractor and thus not included)
2. The source information of the input value is uncertain
3. The input parameter is influential (according to the sensitivity analysis) to the KPI under consideration

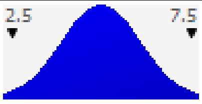
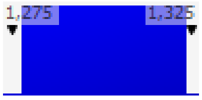
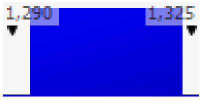
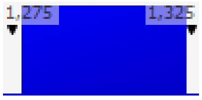
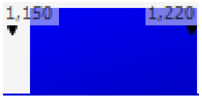
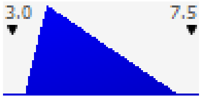
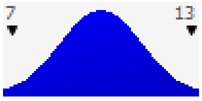
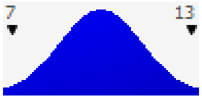
The reduction in the number of parameters to be included in the Monte Carlo analysis ensures a simpler and more accurate analysis. The accuracy of the results is improved by ensuring that variations in predefined values such as element volumes (set by design) do not influence the final distribution of the possible cost difference. This simplification and elimination of unnecessary input parameters in the Monte Carlo analysis is the heuristic approach, as discussed in Section 4.2.2.

The total cost difference of the overall project will again be used as an example. The choice of input variables is based on three consideration (as explained above), together with the Pareto Principle. The Pareto Principle, or the 80-20 rule, states that eighty percent of the influence can be attributed to twenty percent of the input parameters. This is similar to the 50% reduction in the total cost difference if a 10% reduction in SCC unit prices can be achieved.

The input variables identified in Section 5.2.4 were included as variable inputs. The percentage of concrete casts done in the penalty period and the formwork idle time for the bridge deck slabs were included due to the uncertainty associated with them for this case study. Table 17 shows the input distributions and their statistical characteristics.

Refer to Section 5.2.4 to see the discussion on how a Monte Carlo analysis works and why the distributions in Table 17 were chosen.

Table 17: Input variables statistical distributions characteristics

Name	Graph (values shown represents the axis)	Function	Min	Mean	Max
Percentage of concrete casts that is done in the penalty period		Normal distribution	-∞	5.00	+∞
NCC unit cost Mix1 (externally supplied)		Uniform distribution	1280	1301.00	1322
NCC unit cost Mix2 (externally supplied)		Uniform distribution	1295	1308.50	1322
NCC unit cost Mix3 (externally supplied)		Uniform distribution	1280	1301.00	1322
NCC unit cost Mix4 (externally supplied)		Uniform distribution	1160	1189.50	1219
Time that formwork supports the fresh concrete		Triangular distribution	3.5	4.83	7
NCC formwork erection time Slab1		Normal distribution	-∞	10.00	+∞
SCC formwork erection time Slab1		Normal distribution	-∞	10.00	+∞

The statistical distributions should be chosen and assigned with due diligence. If there is uncertainty regarding a distribution choice, it is advisable to run two Monte Carlo analyses with the only difference being the distributions to see what the impact is on the resulting distribution.

Only the total cost difference KPI for the overall project was investigated in the Monte Carlo analysis for the specific case study. The differences in the KPI choice for evaluation will depend on the project stakeholders and their specific interest.

- Clients will be interested in the overall cost KPI's to assess the cost increase relative to the possible technical advantages associated with SCC

- Consultants can use the overall KPI's, together with the elemental KPI's to assess the cost of design considerations. The sensitivity analysis can be used to formulate construction guidelines that will minimise costs
- Contractors will benefit from the elemental cost breakdown. The lowest bid tender award system forces them to build in the most economical way. The cost of different elements and their sensitivity can be used to provide the maximum technical advantages at minimum cost

To summarise; the following considerations can assist in choosing the data (inputs and KPI's) that should be included in the Monte Carlo analysis:

- Can the input data be altered? (data such as element volume is fixed by design and cannot be altered)
- Is there uncertainty in the source of the input data? (items such as construction time can be uncertain while formwork renting cost may be certain)
- Does the input parameter have a large influence on the KPI? (does a 10% variance in the input parameter lead to at least 1% change in the KPI value)
- Is the specific project participant interested in the value of the chosen KPI? (contractors might be interested in the cost KPI's while clients might be interested in the time KPI's)

If all four statements are true then the KPI and the relevant input parameters should be included in the Monte Carlo analysis.

6.5 Resulting distributions

This section deals with the results of the Monte Carlo analysis. The Monte Carlo method allows the inclusion of uncertainty in a mathematical model. The inclusion of the uncertain input parameters enables the model results to be expressed as a range of possible values that can realise, instead of a single figure. The results are expressed as probability distributions and this enables the user to determine a domain in which the answer will realise for a specified confidence interval.

This is particularly useful to the parties involved in the financial planning of a project. It can provide them with a basis for estimating the additional costs that can be expected, as well as provide them with an indication of what funds should be allowed for contingency provisions.

The Monte Carlo analysis was carried out using the Palisade @Risk software on the static Excel model. The model was populated with the information of the case study near George. All the KPI's can be analysed with a Monte Carlo analysis, but the overall cost difference between SCC and NCC implementation will be discussed as an example. The overall cost difference will be of interest if the overall financial implication of implementing SCC at a South African construction project needs to be evaluated.

Ten thousand iterations were performed in the Monte Carlo analysis. The eight parameters identified in Section 6.4.3 (Table 17) were the input parameters that had statistical distributions assigned to them. The applicable output KPI's (Table 5) were then calculated using the varying input values. Note that the beam element KPI's shown in Table 5 are not included in the case study.

Figure 30 shows the resulting distribution for the total cost difference of the overall project.

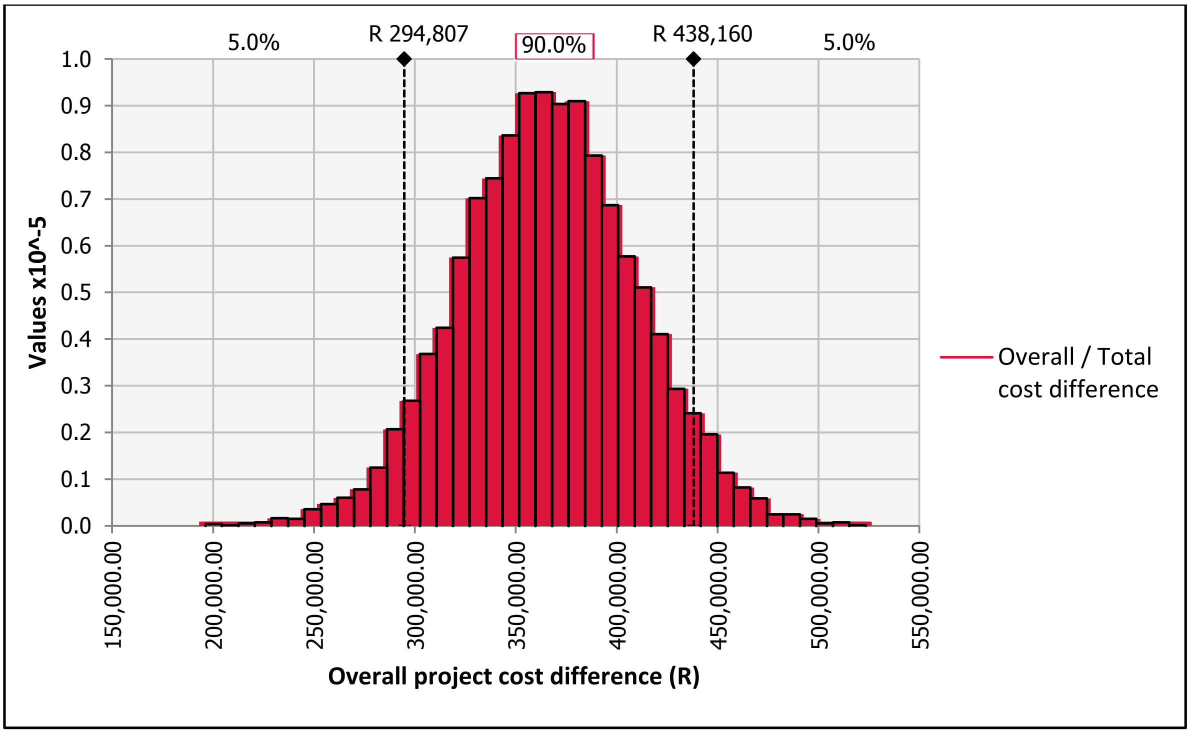


Figure 30: Total cost difference of overall project: Monte Carlo analysis results

For this case study and the assumed input distributions, it can be seen that the cost difference for the overall project is represented by a normal distribution. If a 90% confidence interval is required, the estimated cost impact of using SCC is an increase of between R294 800 and R438 200 (14% and 21%).

The geometry of the resulting distribution is similar to the two distributions assigned to the formwork erection times for SCC and NCC respectively. This correlates with the finding of the sensitivity analysis that showed these two parameters to be the second and third largest influencers of this KPI.

It should be noted that the lack of quotes for SCC material prices affected this specific output negatively. If the model is applied to a project where all the information is freely available, the resulting distribution will have higher variance due to the uncertain material unit costs. The contrary is also true, if the material prices are fixed by the time the model is executed, the result would be similar to the shown distribution.

The additional time that was added to the formwork erection time estimates raised the influence of this parameter above its normal state. The expense of renting the formwork was increased because of the restricted access that prevented the formwork from being removed after the specified support time had passed.

All the other KPI's and their respective output distributions, if dependent on any of the varying inputs, are shown in Appendix D.

The resulting distribution shown in Figure 30 can be used as part of a risk assessment for the implementation of SCC. It can help a project team to decide if they are willing to accept the uncertainty associated with using SCC for a specific concrete structure or element.

It is useful to analyse specific concrete casts to identify which elements are most suited for SCC use. The sensitivity of the individual concrete casts can be of interest to precast manufacturers or other organisations that construct small elements and who are looking for a method of optimising the cost-quality-time trade-off.

This method of analysing a specific KPI with the included variance in the input parameters can be done for any KPI of interest.

6.6 Chapter summary

This chapter reported on the fulfilment of the primary objective of this research. The various results that are needed to acquire the proper insights when considering the implementation of SCC at a South African construction project were discussed individually. The value of each result was discussed, as well as how it should be interpreted and who could benefit from the results. The case study was used to show how the impact of SCC can be quantified and how the results can be used and visualised. A distinction was also made between those results that are project specific and those that can be extended to other projects.

From the static results it is concluded that an overall cost increase is expected when SCC is used. This increase is mainly due to the increase in the cement content of SCC due to the higher binder content. Formwork cost is also expected to increase since higher strength formwork is required to accommodate hydrostatic pressures. These two costs contributed the most to the total construction cost of any element. The cost of rework, placement labour and other costs such as penalty and overheads are expected to decrease with the implementation of SCC. The time required for construction is also expected to decrease if SCC is used. This is mainly because of the accelerated placement time that is made possible by the flowability and self-compatibility of the material. The representation of the results is best done with a combination of pie charts that show the cost breakdown and a bar chart that shows the KPI change summary. The cost increase of SCC can be interpreted as a time-cost-quality trade-off that can potentially realise a higher quality finished product in a shorter time but at an increased cost.

The cost breakdown of the individual element types are not dependent on the project geometry and can be extended to other construction projects. This case study analysed the cost influence of implementing SCC on slabs, columns and walls. All three elements showed an overall cost increase. The increase in slab and column elements is mainly attributed to the increased unit price of SCC, while that of walls is mainly due to the increase in formwork cost. The overall project cost breakdown will be similar to the element type for which the highest portion of the total concrete volume is used in construction.

The sensitivity of the static results was then evaluated in order to identify the input parameters with the most influence on the output KPI's. For this case study, the unit price of SCC and of formwork cost had the largest influence on the total cost difference. The high formwork expense was due to the additional time that the formwork supported the bridge deck because of limited access for formwork removal. The high unit price of SCC is due to the increased cement content due to the higher binder content in the mix design. A 10% reduction in the unit price of SCC for Mix 1 and Mix 2 was shown to halve the total cost difference between SCC and NCC usage.

The resulting distributions of the output KPI's, as calculated with the Monte Carlo analysis, was evaluated in order to assign a confidence level in the answers calculated with the static model. The Monte Carlo analysis yielded a 90% confidence that the total cost increase of SCC usage would be between 14.0% and 20.9% (R294 800 and R438 200) on a base value of R2 098 700 for NCC usage. The resulting probability had a bell-shaped distribution.

Any KPI can be evaluated with the proposed calculation method. The choice of which KPI to evaluate depends on the role of the project participant and the uncertainty associated with the input data.

These results and the proposed calculation method can be used to quantify the financial implication of the decision to implement SCC for a construction project.

7 LABOUR REQUIREMENTS AND RISK EVALUATION

7.1 Introduction

The high unemployment rate and the need for focus on job creation in the South African economy are well established. This focus has given rise to many job creation policies over the years that aim to alleviate unemployment and to reduce inequality in the country. Some of these policies, and the incentives with which they are enforced, have limited the uptake of mechanising technologies and other cost reduction strategies on construction projects (especially if the labour force size is reduced by their implementation). These requirements, policies and expectations were interpreted as an obstruction to implement SCC by the interviewees. The first part of this chapter covers the challenges that the interviewees identified, assesses its influence in the current industry and provides a proposed compliance strategy if SCC implementation is needed for a project.

The discussion considers the impact of the labour prescriptions for consultants, contractors and clients respectively, since they are each impacted differently by the policies. The perceived issues regarding a labour reducing technology are discussed first, followed by the legislative requirements and the policies from which the legislation originates. The true legislative requirements and its effect on the decision to implement SCC are also discussed.

The aim of this part of the research is not to construct an all-encompassing compliance strategy to serve as a workaround for the restrictions established by these policies. The aim is to investigate the perceived influence of the policies on a construction site and the validity of these perceptions. The information can be used by a project team to develop a specific compliance strategy for a project.

The risks that were identified through literature, interviews and the case study are also presented. These risks are evaluated qualitatively to investigate the possible effects and mitigation strategies. Only the qualitative risk evaluation is included in the report and it is suggested that a risk quantification process be done for individual projects. The risk identification and qualitative evaluation is included to contribute to a holistic approach that can be utilized if the decision is made to implement SCC at a South African construction site.

The work presented in this chapter addresses the secondary objective of the research.

7.2 Identified labour requirements and issues

7.2.1 Issues and requirements identified through interviews

As discussed in Section 3.3.8 contractors in the South African construction industry showed an awareness of policies and legislation that they interpreted as an obstruction to implement new technologies if it will lead to a smaller labour force.

The general impression from the interviews (as shown in Section 3.3.8) is that the industry is aware of the legislation, but the labour prescriptions and policies are not fully understood and often misinterpreted as a prohibition on mechanising technologies. The policies should be interpreted as an incentive for job creation rather than a prohibition on the use of more efficient technologies. This statement will be elaborated on in Section 7.2.3.

The following labour related aspects were identified through the interviews conducted for this research:

- Consultants are generally less affected by the labour issues associated with the use of SCC when compared to contractors and clients (This is because the labour on site is the responsibility of the contractor and labour prescriptions are enforced by the client)
- Certain governmental policies do affect the consultants through the prescribed design criteria regarding labour utilization
- The design criteria prescriptions for consultants, as prescribed by the EPWP, have not been fully implemented at present
- The South African Government is one of the largest clients of the construction industry and the driver of the national job creation policies (This leaves the industry highly susceptible to the influence of governmental policy)
- The lowest bid tender award structure and lack of SCC knowledge slows the SCC market uptake down further (construction cost is a higher priority than a further increase in quality)
- National government drives job creation policies while local government award most of the construction work in their respective areas
  (This may create inefficiency in the implementation of the policy)

The implementation, execution and true impact of these policies will be discussed in Section 7.2.3.

It is useful to refer to the static results of this research for perspective on the impact on labour if SCC is implemented. The labour saving was calculated as R31 301.46, only a 1.49% saving on the total calculated project construction cost. The labour employed in concrete placement (where the labour savings occur) is only a small fraction of the labour employed on a whole construction site. The inclusion of overheads and other non-construction related expenses render the R31 301.46 insignificant.

With the original entrance of SCC into the South African market, the labour reducing effect of SCC implementation on a project was used as a strategic marketing argument (refer to interview summary in Appendix A). This strategy might be one of the reasons why contractors overestimate the labour saving associated with the use of SCC. The saving on labour expense was calculated as significantly less than that proposed by the original proponents of the technology.

7.2.2 Legislative requirements and applicable policies

The two main policies that affect the labour usage on a South African construction project are the Expanded Public Works Programme (EPWP) and the National Development Plan (NDP). These two policies are evaluated and discussed in this section of the report. These policies are both national government policies and their influence on the construction projects are usually supposed to be enforced by the actions of local government.

7.2.2.1 Background

Expanded Public Works Programme

The EPWP is a government initiative that should “provide poverty and income relief through temporary work for the unemployed to carry out socially useful activities” (Department of Public Works, 2013). The EPWP was launched in 2004 and the implementation is currently still in progress. The programme is set to run until 2021 in five-year cycles and the programme is currently in the third phase of implementation according to the original timeline. It aims to employ workers on a temporary or ongoing basis either by government, by contractors or by other non-governmental organisations under certain conditions. The programme creates work opportunities in four sectors, but only the first sector is important for this research. This sector is the infrastructure sector and work opportunities are created here through "increasing the labour intensity of government funded infrastructure projects under the Infrastructure sector" (Department of Public Works, 2013).

This sector aims at using labour-intensive methods in the construction and maintenance of public sector funded infrastructure projects. Labour intensive infrastructure projects should do the following according to the terms of the EPWP (Department of Public Works, 2013):

- Use labour-intensive construction methods to provide work opportunities to local unemployed people
- Provide training and skills development to locally unemployed people
- Build cost effective and quality assets

The first and third points can be contradictory if a labour minimising technology provides financial benefits, independent of whether the financial benefits are confined to the construction phase or spread over the lifetime of the asset.

The Department of Public Works (DPW) carries out the implementation of the EPWP in the infrastructure sector. The DPW defines the labour intensity of a project as the percentage that the value of the unskilled labour wages contributes to the total expenditure of the project.

The EPWP is a programme that aims to reduce unemployment and it is one of the platforms used to achieve the enabling milestones of the National Development Plan (NDP). The Department of Public Works is the lead role player in implementing the EPWP in line with the NDP. Conclusions that were drawn from the interview with the programme manager of the capital works programme at the Western Cape Department of Public Works will be discussed in Section 7.2.3.

National Development Plan

The NDP is the reference and foundation for other government developmental policies and it sets two main aims for 2030. "*The elimination of income poverty and the reduction of inequality"* (The Presidency, 2012/2013).

To realise the two aims, numerous enabling milestones have been established of which only one can potentially affect the implementation of SCC at a South African construction project. This milestone is to increase employment in South Africa from 13 million in 2010 to 24 million in 2030. To reach the milestones the government has identified critical actions, three of these critical actions can affect the construction industry (The Presidency, 2012/2013). These three actions are discussed in the following section of this chapter.

7.2.2.2 Relevant documentation

Three critical actions, from the complete list in the *National Development Plan 2030, Our future – make it work: executive summary,* are worth mentioning since it can influence a South African construction project. These three action items call for the development of the following (The Presidency, 2012/2013):

- A strategy to address poverty and its impacts by broadening access to employment, strengthening the social wage, improving public transport and raising rural incomes

- Boost private investment in labour-intensive areas, competitiveness and exports, with adjustments to lower the risk of hiring younger workers
- Public infrastructure investment at 10 percent of gross domestic product (GDP), financed through tariffs, public-private partnerships, taxes and loans and focused on transport, energy and water

All three action-items promote either the expenditure on construction projects or the increased focus on job creation, or both.

The critical actions are set in place to achieve the high-level aims of the NDP set out by national government. The largest part of the responsibility of realising these aims lies with local government and one of the ways to execute the critical actions is the implementation of the EPWP. The execution of the EPWP is overseen by the respective provincial Departments of Public Works.

The NDP implementation strategy should thus be investigated by analysing the guidelines on the implementation of the EPWP. Two documents are worth consulting to identify the impact of the EPWP on the construction industry. These documents are the *Guidelines for the Implementation of Labour-Intensive Infrastructure Projects under the Expanded Public Works Programme (EPWP) (2005)* and *EPWP Large Projects Guidelines (2012).*

Both documents cover the proposed methodology of implementing the EPWP on a construction site, as well as the proposed contractual adjustments that have to be made by consulting engineers and contractors. The contractual adjustments are made to enforce the implementation of the programme on a construction project. The *EPWP Infrastructure Implementation Manual (DPW 2008)* can also be consulted regarding the prescribed contractual adjustments.

The following comments are worth highlighting about the first document (Expanded public works programme, 2005):

- Labour-intensive construction methods are required, by national government, to be implemented at projects involving:
  - Low-volume roads and sidewalks
  - Storm water drains and trenches having a depth of less than 1.5 metres
- These structures are expected to be economically and technically feasible for the application of labour-intensive construction methods
- The construction guidelines must conform to the Public Finance Management Act requirement for assessing the cost-effectiveness of capital projects
  (A policy cannot be enforced if it is not cost efficient)
- A design checklist is provided to increase the labour-intensive works at a project. It aims at ensuring that cognisance of labour intensive works are taken during the design phase (such as limiting the weight of pre-manufactured elements to 320kg)
- An additional skills requirement is added to the contract regarding the implementation of labour-intensive works
- Labour-intensive construction is defined as *"Methods of construction involving a mix of machines and labour, where labour, utilising hand tools and light plant and equipment, is preferred to the use of heavy machines, where technically and economically feasible"*

The following are applicable to the guidelines set out for large projects (Department of Public Works, 2012):

- In this document, seven infrastructure project related activities are identified as possible activities where labour-intensive construction should be implemented
- All the identified activities, together with their subordinate tasks, are low cost activities which will have minimal influence on the decision of implementing SCC on large structural elements
- The onus of designing and implementing labour-intensive tasks are put on the consultants and the contractor
- Monitoring and reporting requirements set out by the EPWP prescriptions for large projects are included in this document

All the identified policy requirements seem to have a very small impact on the ability to implement SCC at a South African construction project. This is contradictory to the supposed effect of these requirements as described by the interviewees in Section 3.3.8.

7.2.2.3 Supposed effect vs. real prescriptions

The interviewees interpreted the policies discussed in the previous section as a constraint on the use of SCC in South Africa. Although there were certain exceptions, this was the general conclusion drawn from the interviews. The opinion was that a tender would be less competitive if less labour is used.

The following effects are more specific and based on the information gathered from the policy documentation:

- Increased requirement for skills development on a construction site
- Small adjustments to procurement techniques have to be implemented
- Adjustment to specified construction techniques must be made to enable labour-intensive construction
- EPWP related monitoring and reporting requirements have to be adhered to
- A larger unskilled labour force has to be used for tasks that are specified as labour intensive

If the project is not government funded, a contractor has none of the constraints mentioned above. Commercial structures that are complex in design and privately funded will have no policy restraints for SCC implementation. The choice of concrete type will not be influenced by complying with the identified prescriptions.

The policies do not affect the consultants if the choice is made to use SCC. They are expected to comply with specific skill requirement prescriptions and documenting prescriptions that should prove they took cognisance of labour intensive tasks during the design phase. This documentation will be expected regardless of the concrete material choice.

Governmental clients will drive the implementation of these policies and thus be unaffected by them, except for the increased administrative attention that will be required.

7.2.3 General approach of the South African economic and socio-political legislators

The interview with a representative from the Western Cape Department of Public Works highlighted important factors about the job creation policies contained in the EPWP and the NDP. The policies are not set out to discourage technological advancements, but to give work to the poor. This should be the core focus and the policies will not obstruct the implementation of SCC at any construction site if it is more cost efficient or if it provides a required technical advantage.

The Department of Public Works in the Western Cape confirmed that using SCC on a construction project would not detrimentally affect a tender. The tendering process is done as prescribed by the CIDB and the tender process has just been revised without the inclusion of any EPWP clauses that can obstruct SCC implementation on a project.

One of the focus areas for phase three (the current phase) of the EPWP is to increase the scope of infrastructure maintenance. This will provide labourers with longer duration work opportunities and place more emphasis on the monitoring and evaluation of assets created (Parliamentary Monitoring Group, 2014). This shows a holistic focus that does not create jobs by limiting the implementation of new technologies during the construction phase of a project. The focus is rather on creating sustainable maintenance orientated jobs.

The EPWP and NDP focus on skills development and long-term enhancements. Schedule acceleration and the execution of more construction projects is in its own a better focus than the number of labourers employed per task. Faster schedules and more projects can lead to more employment opportunities per year in total.

The EPWP is currently in phase 3 of planning and implementation, while the NDP is in its first planning cycle. Both policies have not yet been implemented fully and the conclusions of the discussion and results in this chapter might change as this implementation progresses. The labour reductions due to SCC implementation should not currently be a concern for any project party.

It was mentioned that a client might consider specifying the material, even at an increased price, to ensure a higher quality finished product. This can only be done if the client knows about the technical advantages of SCC.

The perceived obstructions of SCC implementation due to labour reductions seem to be overestimated. The overestimation is possibly a result of the chosen advertisement method used for introducing SCC to the South African construction industry. The advertisement and SCC introduction techniques placed a major focus on the reduction in labour cost that SCC can realise.

The labour cost reduction on the concrete placement labour was calculated as minimal for the investigated case study (1.49% saving on the project cost). Especially when the complete labour force expense of a project is considered. Lastly, the tasks that are prescribed as labour-intensive construction activities will not affect the majority of concrete works on construction sites and is thus irrelevant when choosing the concrete type that must be used.

7.3 Proposed compliance strategy

The NDP and EPWP are both still in a planning phase and the required documentation and skill development requirements will be further defined in the future. In order to fulfil those requirements associated with a labour-intensive project, certain prerequisite actions will have to be taken but none of the identified prescriptions will significantly influence the decision of whether or not to implement SCC at a South African construction site.

While these requirements will be further developed in the future, there is no justification to assume that the policies will obstruct the use of SCC. The policy requirements and SCC implementation are two independent considerations and the use of SCC should not be disregarded due to the associated labour reductions. This statement satisfies the secondary objective of this research.

7.4 Risk identification

The risks that were identified through the literature study, the interviews and the case study were compiled into a list as seen in Table 18. This risk identification can be extended if a complete risk analysis is required. This research only pursued a qualitative risk analysis. A traditional risk quantification methodology was not used due to the lack of access to enough knowledgeable experts in the field and since the risk ranking will vary for each project. The identified risks are presented, and how they could have influenced the case study is discussed to supplement the calculated results and labour related information. The importance of the individual risks will vary between projects, but the classification shown in Table 18 is applicable to the investigated project, as identified by the researcher.

Table 18: Risk register

Rank	Risk	Description	Effect	Identified through
Class 1	Lack of expertise on site	Lack of expertise for supervision allows faulty material to pass inspections and be used in construction	Poor supervision opens the potential for the application of underperforming material and/or batch plant issues	Interviews
	Formwork failure	Formwork failure under hydrostatic pressures associated with fresh state SCC	Formwork failure can lead to total material loss, injury and rework expense	Interviews
	Total material loss	The loss of all the concrete when formwork leakage or formwork failure occurs	Major spillage due to formwork leakage or failure requires cleanup operation and can lead to injury and extra cost	Interviews
	Formwork leakage	Material leakage through formwork openings due to poor sealing or openings formed as the load of the fresh concrete is applied to the temporary structure	Material leakage leads to material loss, resulting in element distortion, cleanup activities, schedule delays, extra cost and rework	Interviews and case study analysis
	Resistance from project team due to lack of knowledge	Lack of knowledge and resistance to change can provide challenges for SCC implementation on site	Improper implementation and underrealisation of the advantages of SCC usage	Interviews and literature
	Rate of pour limits reduce time savings	Time savings and cost savings are forfeited due to the adherence to pour rate limits, as prescribed by the SANS codes	Pour rate limit adherence dissipates potential time saving and financial gain	Interviews and literature

Rank	Risk	Description	Effect	Identified through
	Inability to construct gradient finishes	High flowability of SCC can provide challenges with constructing gradient finishes if care is not taken with the mix design and manufacturing	Difficulty in constructing the structure as specified will lead to additional screeding work	Literature and case study investigation
Class 2	Shrinkage cracking	Severe shrinkage cracking on the structural surface, due to poor curing practices and the moisture sensitivity of SCC	Cracks should be repaired at high cost	Interviews and literature
	Inferior material properties	Poor quality hardened concrete due to lack of manufacturing knowledge or utilization knowledge of SCC	Underperformance of structural elements can require reconstruction or lead to collapse	Literature and case study investigation
	Segregation of fresh concrete	Poor segregation resistance due to poor SCC manufacturing knowledge	Segregation of SCC and underperforming material properties cause the structure to underperform with regards to specifications	Interviews, literature and case study investigation
	Surface voids on finished elements	Excessive surface voids on elements due to the use of a poor quality shutter release agent	Rework required to construct the required concrete finish	Interviews
	Inability of site lab to do specification tests	Poor laboratory knowledge and experimental skill can lead to incorrect test results and misrepresentation of the construction material	Misrepresentation of structural characteristics can lead to structural overload and/or underperformance	Interviews and site investigation
	Inability to successfully manufacture SCC due to moisture variation	Poor quality SCC is produced due to the lack of moisture control and lack of understanding the moisture sensitivity of SCC	Inconsistent fresh SCC properties and an inability to meet design requirements	Literature
	Poor quality SCC received from the supplier	Poor quality and inconsistent quality SCC can disrupt the project schedule and have a detrimental effect on the quality of the finished product	Inconsistent fresh SCC and inability to meet design requirements	Interviews
	Machinery leakage due to wear and tear	Material leakage through machinery openings due to poor sealing or openings formed by general 'wear and tear'	Material loss can incur property damage and injury	Interviews
Class 3	Lack of skilled labour	Lack of skilled labour for SCC production leads to the inability to produce usable concrete	Skills shortages lead to inconsistency in material that can cause other risks to realise	Interviews and case study investigation

Rank	Risk	Description	Effect	Identified through
	Slow strength gains due to high cement replacer content	High cement replacer content can act as a retarder on the rate of concrete strength gain	Retarding effect of high volume cement replacers can lead to structural failures if formwork support times are not adjusted	Literature
Class 3	Over performance of concrete characteristic strength	High cement content and low water/binder ratios can lead to a non-optimal strength of the hardened concrete. (overdesign and uneconomical)	Unnecessary expense	Literature, interviews and case study investigation
	Difficulties in managing the labour force size during construction	Concrete placement labour reductions can lead to idle workers on site if the labour management is not adjusted according to the accelerated placement rates	Underutilized labourers can lead to unnecessary expense	Interviews and case study investigation

The classification shows the relevance of the risks to the specific case study in this research. The classification is based on the interpretation of the researcher. The interpretation is based on the likelihood that a risk will realise and the severity of the impact if the risk realises. The likelihood and impact was evaluated based on the information that was gathered through the interviews and the literature.

Certain risks such as formwork leakage and total material loss can be interdependent, but it is not necessarily the case. Total material loss can also occur if a shutter kicks, or if certain formwork failure types realise.

This risk register can be used, and extended, if the decision is made to implement SCC at a South African construction project. It should then be used to compile a complete risk analysis and risk management plan.

The risks in Table 18 are classified into different types in Appendix E and possible mitigation strategies are identified for each risk.

7.5 Qualitative risk evaluation

A qualitative risk evaluation is a discussion on each identified risk. What the risk is, why it is important and how it can be managed is included in this discussion. The identified risks are categorised into three categories in Table 18 (Class 1, Class 2 and Class 3). These categories serve as a prioritisation guideline for risk management strategies and the evaluation is done according to this categorisation as well.

Class 1

The risks classified under Class 1 in Table 18 are identified as important risks that should receive the most attention for the bridge construction case study.

The lack of expertise would have been the most important risk since it would open up the potential for misuse of SCC. The lack of expertise can be mitigated by acquiring key personnel who do possess the required expertise (the expertise do exist in the South African industry and the successful South African SCC projects are proof thereof). Low quality SCC can be detrimental to the whole structure and even lead to collapse or the realisation of other risks such as formwork failure and leakage. The three formwork related risks (failure, total material loss and leakage) are important and should be managed by employing an expert formwork designer. By including a formwork company from the start of the project, these risks can be shifted to the formwork design company. Formwork failure and leakage can potentially lead to total material loss for a specific element. If this element is, for instance, one of the bridge deck spans the effects can be significant. The spillage of all the material and the clean-up operations can cause project delays, additional expense and even injury or death. Since the slabs are elevated, formwork failure will cause damages as specified and additionally, environmental damage due to the spillage into the river underneath.

The resistance from the project team, due to lack of knowledge could also have been detrimental if it were to realise. No new technology can be implemented with ease if a lack of cooperation from the project team exists. The pouring rate limits can dissipate the potential time saving and the financial gain involved with an accelerated schedule. This will raise the cost difference between NCC and SCC usage and can render SCC financially unviable.

The inability of constructing gradient finishes could have increased the cost of the bridge deck since it is designed to have an inclined top surface to allow water drainage. The cost increase will be the construction of an inclined plane with a screed layer. It is possible to construct an inclined finish with SCC, but it is more expensive compared to NCC.

Class 2

The risks classified under Class 2 have a medium influence on the project. The influence is a combination of the impact if it realises and the probability that it will realise. These risks can all be mitigated by proper preparation and by ensuring best practice guidelines are adhered to (similar to NCC).

With regard to the concrete supplier, the procurement details should stipulate the supplier's responsibility for delivering SCC that meets the specified requirements. SCC suppliers will accept the responsibility of ensuring proper in-situ compaction if SCC is implemented. The machinery leakage can cause material loss and property damage. This will be the case, for example, if a project is in a city and concrete placement is done by crane but the bucket has to be transported over other structures or vehicles, the falling concrete can then damage the property underneath the travel zone of the bucket. It is important to inspect the equipment and to ensure that no significant leakage can occur.

Class 3

The risks classified under Class 3 are all low risks and can be managed or prevented through proper preparation. Otherwise, their impact is low if they realise. The only risk that can have a large impact if it were to realise is the slow strength gains due to high cement replacer content. This risk will however not be relevant if SCC is externally supplied or if the SANS codes for concrete mix designs are adhered to.

It should be noted that a project manager or contractor could implement SCC in different elements according to their personal risk profile. Smaller, ground level elements, which are not on the critical path of the project, can be cast if the user is risk averse. These elements can be used to gain experience with the use of SCC in a low risk application.

7.6 Chapter summary

An investigation into the policies that aim to alleviate unemployment in South Africa was conducted in this chapter. This was done to identify the effect of these policies on the decision to implement SCC at a South African construction site. The NDP and EPWP both showed no significant impact on the decision. The prescriptions regarding labour-intensive construction focus on smaller construction tasks, where labour-intensive construction is cost-effective.

The influence of the policies is most influential for contracting parties, but the challenges brought on by the policies are smaller than perceived. The conclusion is that SCC should not be disregarded due to the perception that labour reductions will have a detrimental effect on tenders. No significant compliance strategy is needed since the restraints are bordering on insignificant for medium and large structural projects.

The risks identified through the research were listed in a risk register and their rankings were performed qualitatively, as perceived by the researcher, for the specific case study. In this case, the most important risks that should be mitigated and managed are the lack of expertise on a site and formwork related risks. The formwork related risks are formwork leakage, formwork failure and total material loss due to formwork failure. The formwork risks are important in this case study due to the high volume of horisontal concrete applications that are elevated over the Modder River. The classification and risk register will change for different projects and the type of elements that are constructed with SCC will influence the classification.

It is important to understand the true impact of the labour related policies and to know that SCC is not a risk free material. If the decision is made to implement SCC at a South African construction project, these two considerations can enhance the experience of SCC usage by eliminating unnecessary complications.

8 CONCLUSIONS

The objective of this research was to construct a cost implication model that can be used to quantify the impact of the decision to implement self-compacting concrete technology on a typical South African construction project. The study included an investigation into the restrictive effect, on SCC implementation, of labour requirements set out by job creation policies such as the EPWP and the NDP. The study was conducted as a techno-economic analysis and an investigation into the different South African labour requirements set out by governmental policies.

The investigation into the technical properties of SCC was done through a literature review. The technical details of SCC are well published and standards and specifications already exist to guide the industry in the implementation of the material. Research publications about the material properties of SCC are abundant and mostly coherent. The existing research shows that the material is suitable to apply to any concrete construction project. The concrete mix contains more fines than NCC and the addition of superplasticiser is the differentiating element between the production of SCC and NCC. The long-term material properties of SCC are comparable or better than that of NCC. The extent of the implementation of SCC in South Africa is lagging behind that of the developed nations, but the local industry has achieved successful applications of SCC on large-scale projects. Advantages and disadvantages of SCC (as discussed in Section 2.5), as with any material, should be understood before it is implemented. The material has improved workability and can lead to improved durability of a structure, but SCC can be more expensive and requires higher skilled personnel in the manufacturing process.

The interviews conducted for this research highlighted the following important points:

- There is only a limited awareness of SCC in the South African construction industry at present
- The cost experiences reported by the interviewees regarding SCC usage were unclear and fragmented, but most reports mentioned an increased cost when SCC is used (This highlighted the importance of this research and identified costing details to include in the model)
- The reported challenges of using SCC were mainly a lack of knowledge, the additional design criteria (for the mix design and the formwork) and increased cost
- SCC cannot currently replace NCC with financial viability in low cost, low strength concrete applications or for elements with inclined finishes
- SCC and superplasticiser manufacturers reported an initial market excitement that subsided when the material unit cost was considered
- SCC sales reached a plateau and suppliers might focus on high strength concrete applications for future SCC sales growth
- The main reasons identified for the lower levels of SCC implementation in South Africa was
    - The overall lowest bid tender award structure of the industry
    - The lack of client knowledge about SCC
    - Increased material unit cost

The model that was created for this research was built to calculate the cost impact of implementing SCC at a South African construction project. A static model was created to capture the value chain associated with concrete placement on a construction site. A Monte Carlo analysis was chosen for the heuristic modelling of uncertainties due to the time-efficiency of data collection and the easily interpretable visual results. The model structure consists of input data, the five CPA's and the sixty possible KPI's that can be extracted from this CPA's. The format of the results is useful and easily interpretable. The results extracted from the model can provide the following information to decision makers:

- The construction cost breakdown into the different CPA's (material cost, formwork cost, placement labour cost, rework cost and other cost implications)
- The KPI change summary shows how SCC implementation affects the cost of each CPA for different element types and for the entire project
- The total cost difference associated with the implementation of SCC
- The time impact of using SCC on different elements and/or the entire project

A case study was used to test the proposed costing model. The chosen case was a bridge near George, spanning the Modder River. The project consisted of 40 concrete casts and 1223 cubic metres of concrete. The model was used to calculate the potential cost impact of implementing SCC and to show the value of the information contained in the calculated results. The variety of element types in the bridge, and the in-situ construction of all the bridge elements made this case suitable for investigation. The major shortcomings of the project as a case study are the absence of beam elements, the lack of complete access to the project details such as overhead expenditure and the lack of certain SCC specific uses such as elements with complex geometry. Note that only one relevant SCC quote, for every characteristic concrete strength, was used as an input to the model.

The results of the case study were discussed with respect to the value of the information contained in the answer, as well as the interpretation of the actual figure value of the answer calculated with the model. From the static results it was concluded that an overall cost increase could be expected.

The cost increase is mainly due to the increase in the cement content of SCC, due to the higher binder content, and stronger formwork requirements. The cost of rework, placement labour and other costs such as penalties and overheads are expected to decrease with the implementation of SCC. The time required for construction was calculated to decrease with 5% if SCC is used. The cost increase of SCC can be interpreted as a crash cost analogy if project accelerations are required, as well as an additional expense that can potentially realise a higher quality finished product due to better compaction. The cost increase in slab and column elements are mainly attributed to the increased unit price of SCC, while that of walls are mainly due to the increase in formwork cost.

The calculated results confirm the cost related expectations of the interviewees. The results can be used (which is supplemented with the interview information) to investigate the overheads that will render SCC advantageous due to the acceleration in the project schedule. The break-even figure the investigated case study for overheads was R26 050 per day. If the overheads of the project were higher than R26 050 per day, SCC implementation would have reduced the total concrete related project cost.

A sensitivity analysis showed that a 10% reduction in the unit price of SCC would halve the total cost difference between SCC and NCC.

The resulting distributions of the output KPI's, as calculated with the Monte Carlo analysis, was evaluated to identify a confidence level in the answers calculated with the static model. There was 90% confidence that the final cost increase would have been between 14.0% and 20.9% (R294 800 and R438 200) if SCC was used in the construction of the investigated bridge. The probability had a bell-curved distribution.

The labour requirements investigation and risk identification was done to satisfy the secondary objective of this research. An investigation into the policies that aim to alleviate unemployment in South Africa was conducted to identify their effect on a decision to implement SCC at a South African construction site. The NDP and EPWP were the focus areas and they both showed no significant impact on the decision. No significant compliance strategy is needed since the restraints on SCC usage borders on insignificant for medium and large structural projects. This finding does not correlate with the perceived challenges identified by the interviewees, since the challenges were found to border on insignificant.

The most important risks regarding SCC usage at the investigated project, which should be mitigated and managed, are the lack of expertise on a site and the formwork related risks. The formwork related risks are formwork leakage, formwork failure and total material loss. These risks are important due to the large portion of the total concrete volume that is used in the construction of horisontal applications that are elevated over a river. The risk rankings and risk register will change for different projects and different element types that are constructed with SCC.

Other conclusions about SCC usage that were made during this research include:

- The time-quality-cost trade-off associated with SCC can make the material useful for time constrained projects
- The cost difference between NCC and SCC can be significantly influenced by logistical construction process alterations
- If the duration of concrete placement is a project schedule bottleneck, SCC can alleviate the constraint
- The bottleneck alleviation is similar to enhancing a project schedule by means of Theory of Constraints management and the increased quality can be utilised in Six-sigma management principles for a construction environment
- The advantages and cost implications of using SCC are distributed unevenly between project stakeholders such as clients and contractors
- Clients should be informed about the technical advantages that SCC can have since they have the most incentive and potential to benefit from SCC usage
- Clients can investigate the justification of the increased construction cost from a holistic life cycle cost perspective
- Clients need to be informed by consultants about SCC to ensure that it can be financially viable for a contractor to use SCC and deliver a higher quality finished product

The ratio of the total outer surface (which requires formwork) and the volume of an element can provide an indication of the financial cost implication of using SCC for constructing a certain element. The higher the ratio, the higher the probability of financial gain through SCC implementation. This is due to the increase in the formwork cost contribution and the increase of the required labour intensity per cubic metre of concrete (this also translates into an increased importance of the reduction in the labour cost contribution). The cost increase in labour and formwork is smaller than the cost increase in material when SCC is used (labour cost generally decreases and formwork cost generally remain constant). The total effect is a diminishing importance of material cost increase. This is especially applicable on precast elements and it can be seen in industry where SCC is widely applied in the precast industry. For example, the cost contribution of material cost for a square column with constant height is approximately 50% if the side length is 175mm. This material cost contribution increases to 75% if the side length of the square column is 500mm, rendering the increase in material unit price more significant for larger elements and reducing the financial viability of using SCC.

The low usage of SCC in South Africa, compared to certain developed countries can be attributed to the cost increase that SCC usage incurs for a South African construction project. The relatively cheap labour and the absence of other restrictions (such as noise limits and strict equipment restrictions for urban areas) is a structural difference between the South African industry and those countries with higher SCC utilisation. The structural differences, combined with the lowest tender awards structure in South Africa, deprive the industry of incentives to harness more time-efficient and higher workability materials at an increased cost.

The cost difference between NCC and SCC can be minimised by means of cement extenders and logistical changes in the construction process. This can lead to increased SCC usage in the South African construction industry.

The methodology explained in this dissertation can be used to identify the areas where cost management and cost reduction efforts can be focussed for the greatest advantage, and the minimum risk, on a specific project.

9 RECOMMENDATIONS

The techno-economic analysis of SCC versus NCC and the results and conclusions discussed in this dissertation led to the following recommendations about the construction operations, when using SCC, and further study that should be done about the use of SCC in South Africa.

9.1 Operational recommendations

If the decision is made to implement SCC at a South African construction site, the following operational recommendations should be considered.

9.1.1 Proposed calculation method implementation

The proposed calculation method, as developed in this research, should be used to quantify and interpret the cost influence of implementing SCC. A project dashboard with all the graphical results and the KPI summary can be used to summarise the cost impact. The type of information contained on this dashboard can be adjusted according to the role of the project participant. The heuristic modelling, especially the Monte Carlo analysis, should be tailored to cover only the information that has inherent uncertainty at a specific project.

By using the static model to quantify the cost impact of implementing SCC and the heuristic part of the model to translate the uncertainty, one can construct the dashboard to convey all the required information to base a decision on. This output information can be tailored to suit each participant of a project. The client can see the additional construction cost and time saving associated with SCC usage. The contractor can develop a cost and labour management strategy to ensure competitiveness. Consultants can quantify the cost of increasing constructability and/or enhancing the structural durability of the finished product.

9.1.2 Project team operations recommendations

It is recommended to inform the clients of the potential benefits that can be realised if SCC is implemented for a construction project. It is necessary that the client is aware of the quality-time-cost trade-off since the potential benefits of the shortened project schedule and the increased concrete quality is beneficial to the client.

To minimise the cost increase, the incorporation of cement extenders should be considered. Cement extenders have already been shown to work well with SCC mixes. A SCC expert should be included in the project team during the project inception phase. This will increase the probability of realising the most benefits that SCC can provide. A formwork specialist company, or person, should be consulted continuously through the design and construction phase. These recommendations are made to mitigate the major SCC usage risks related to material and formwork by shifting the risk of inferior material quality and formwork failure off-site to a supplier.

It is possible to reduce the cost of using SCC further by constructing only certain structural elements with SCC. The most beneficial elements can be identified through the proposed calculation method and the most expensive elements can be eliminated (such as slabs of which the major cost contributor is material cost).

An assessment of the project logistics can also provide a project planner with new possibilities if SCC is used. These possibilities can include new concrete placement task relationships that are made possible by faster placement times and the possibility of building higher single cast columns.

9.2 Recommendations for further study

This research highlighted several areas that can be further investigated to enhance the knowledge and potential benefits that SCC technology can bring to a South African construction project. These are further cost implication studies, SCC opportunity investigations and investigations into specific cases of successful SCC implementation in South Africa.

9.2.1 Further cost implication studies

The management of the cost difference between SCC and NCC is one of the major concerns for any project team that has to decide between the concrete materials. The following areas of study can enhance the understanding of the cost impact and lead to reductions in expenses.

- Investigate the cost and structural impact of using the maximum cement extenders in the manufacturing of SCC
- Execute a study into the life cycle cost impact of SCC from a client's perspective, since they are the stakeholder that might benefit the most from SCC implementation
- A detailed investigation into the cost influence of SCC on the construction of smaller elements can provide valuable insights to project teams and the precast industry
- A viability study on the cost influence of combining SCC and hybrid-concrete construction to fast track a project and/or provide financial benefits
- A detailed quantification of the savings that a schedule acceleration can provide due to a reduction in running costs and overhead expenditure of a project
- Investigate and quantify the second order cost influence of an accelerated project for a client and contractor. It can provide a faster turnaround time for capital and decrease the time between project inception and revenue start. It can also provide a contractor with the ability to do more projects in a specified time frame, thus increasing his revenue
- The cost breakdown between NCC and SCC for a commercial structure with a high quality concrete finish specification, considering especially rework quantification

9.2.2 Opportunity investigation of SCC in the South African market

The plateau of the SCC market in South Africa can be changed if a better understanding can be achieved in the following areas:

- The viability of including the proposed calculation method into Building Information Models (BIM) and to test whether the efficiency and accuracy of the cost comparison between SCC and NCC can be improved by incorporating the calculation method in existing BIM software
- The quantification of the identified risks might show potential opportunities for reducing the complexity of SCC implementation
- An investigation into the environmental impact of SCC usage and the possibility of assigning a Greenstar rating to the material due to the low energy use during concrete placement. This can provide incentive to the industry to consider SCC on a regular basis
- The compilation of managerial and logistical changes that become available, and their effect on time and cost, due to the use of SCC

9.2.3 Additional SCC related studies

Other studies that can add value to the knowledge area of SCC implementation in South Africa are:

- The comparison of additional case studies, of various geometries, to compare the cost breakdowns of the element types in different applications. This can highlight certain trends associated with specific element characteristics such as element size and geometry
- The quantification of the success rate of SCC implementation in South Africa of projects of different sizes can be used to identify the present problems that are associated with the technology in the South African industry
- The model created in this research can be applied to various projects of different geometries to investigate correlations between the geometric characteristics of a project and the relationship between cost and time savings. Such a study can evaluate the expected overhead expenditures that will economically justify the use of SCC for various project geometries.

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APPENDIX A – INTERVIEW SUMMARY

This appendix provides details about the interviews. The participants and the investigated knowledge areas are introduced and a summary of all the comments made are listed for each knowledge area.

A.1 Interviewees

Eleven interviews were conducted with industry representatives during the course of this research, the following persons participated in the interviews:

a)	Anthony Venier (Chryso)	-AV:	Material supplier
b)	Jan van Rensburg (Department of Public Works – Western Cape)	-JR:	Client/Owner
c)	Hennis van Zyl (Lafarge Agilia)	-HZ:	SCC supplier
d)	Herbert Groenewaldt (Lafarge Agilia)	-HG:	SCC supplier
e)	Christiaan de Villiers (UWP)	-CV:	Consultant
f)	Francois Vermeulen (Stefanutti Stocks)	-FV:	Contractor
g)	Riaan Brits (PERI)	-RB:	Formwork supplier
h)	Johan Hartman (Element Consulting)	-JH:	Consultant
i)	Anonymous quantity surveyor (Murray & Robberts)	-MR:	Contractor party
j)	Quintin Smith (SNA Civil and Structural Engineers)	-QS:	Consultant
k)	Jacques Niemand (Baseline Civil Contractors)	-JN:	Contractor

Additional data has also been accumulated from non-official interviewees, such as sub-contractors on site and academic personnel. This information will be quoted with the abbreviation (AA). The order in which this information is reported on, is the same as the order in Chapter 3.

A.2 Knowledge area information

A.2.1 Cost impacts on materials, formwork and labour

Material

- SCC can be more expensive since the binder content can be 400kg/m³ and more, as well as the requirement of adding superplasticiser to the concrete mix (AV, FV)
- The addition of cement replacers, such as fly-ash and slag, might dramatically lower the cost of SCC in comparison to NCC, especially in the northern parts of SA, where fly-ash is readily available (HZ)
- The higher material cost is also due to the higher skills required for producing SCC, technicians are always present at the plant when SCC is produced and lab representatives (from the SCC producer) are present on site when the concrete is placed (HZ)
- The plant equipment cost for mixing SCC is about the same as for NCC (HZ)
- The cost impact of using SCC for column construction might be less notable due the low concrete volume used to construct columns, with regard to the total volume, but with walls in commercial buildings it will be noticeable (RB)

Formwork

- The formwork cost for high single cast columns, such as a 12m single cast column, will not be cheaper than casting 4 days at 3m intervals, this is due to the difficulty in erecting column boxes of this size and the increased equipment expense involved in erecting such formwork. The expense of the additional requirements will outweigh the benefits (RB)

- The formwork cost will rise if SCC is used on projects with certain characteristics such as higher columns and walls, typically at projects such as a mall with 4m high ceilings (AA).
- If a project specifically need of-shutter concrete (Class F1 finish) the size of the formwork cost contribution will differ from that of normal concrete finishing specifications. The formwork price can double and rework becomes a major problem, SCC might perhaps be economical in this application (AA)
- For horisontal applications of SCC, the formwork cost is comparable to that of NCC applications. The risk involved and the probability of material loss is much higher however.
- Custom built formwork that can accommodate hydrostatic pressures will always be more expensive than standard formwork. How much more expensive will depend on the design (RB)

Labour

- Labour reductions is a certainty with SCC implementation, two labourers can place 1000m³ of concrete per day. This can lead to at least a 50% reduction in the labour involved with concrete works (HZ)
- Labour savings can only realise if the management approach and labour levelling (on-site labour utilisation management) is done correctly (FV)
- Labour savings will not be significant in terms of the whole project due to the cheapness of labour in the South African economy (RB)

A.2.2 Other cost impacts

- SCC can lead to time savings, this can reduce the project cost by reducing overheads, insurance etc. (FV, JH, RB)
- Savings on rework can also be a reason for the implementation of SCC, especially in heavily reinforced elements (AA, HZ)
- SCC rework expense is much lower than that of NCC and SCC doesn't have compaction problems (RB)
- If formwork failure occurs with SCC placement it can be more costly than for NCC formwork failure (AV)
- Additional technicians might be needed for producing SCC and to seal the equipment before usage (to prevent leakage and material loss) (AV)
- Using SCC can eliminate the need for screeding slabs, this can save roughly R60/m² (HZ)
- The financial viability of SCC might be increased by using more fly-ash or slag in the SCC concrete mix. It will also reduce the carbon footprint associated with concrete usage (FV)
- In the northern part of South Africa, the price of producing SCC is closer to that of NCC than in the Western Cape. This is due to the high availability of fly ash (which is about half the price of slag), as well as the cheaper aggregate that is a by-product of various mining activities (HG)

A.2.3 Experiences regarding total cost, time, quality and ease of use

Total cost experience

- If used correctly, SCC might lead to a formwork saving due to a quicker turnaround time on shutters (HZ)

Total time experience

- In the precast yard, the use of SCC can lead to significant time savings, especially with the production of precast columns (AV)
- Bulk elements, such as raft foundations might realise notable time savings when using SCC (CV)

Quality experience

- For ground level floors (where formwork leakage is eliminated), lift shafts, piling and off-shutter architectural concrete SCC works well. It provides good results for heavily reinforced sections, casting elements with difficult access, columns and in the pre-cast yard(RB, HZ)
- SCC can lead to higher quality end products in specific applications (RB)
- SCC might have a larger market potential if it can be given a Greenstar rating to create a structure that is classified as more environmentally friendly (JR)
- The risk of poor concrete quality, due to bad compaction on site, can be moved to an external concrete supplier if SCC is used (HZ, FV, HG)
- SCC has a better resistance to free falling than NCC, this simplifies placement on site (HZ)
- SCC can meet durability specifications easier, such as incorporated by SANRAL for their bridge construction projects (CV)
- With the construction of large water reservoirs, SCC can make it possible to eliminate joints, consequently also water stops (JH)

Ease of use experience

- The mix consistency of the suppliers are sometimes poor in the South African industry (MR)
- In the heavy precast industry, SCC provides better workability and working conditions. It reduces the noise pollution by eliminating the noise of external shutters and it does not have compaction problems with high stone content concrete mixes (HZ, AV)
- SCC reliefs the problems of NCC in terms of lower rework, easier removal of air voids during placement and lowering the labour required for these two tasks (AV)
- SCC can accommodate other admixtures and it can be designed to stay workable for up to 6 hours (AV)
- Contractors might use SCC incorrectly by casting it to fast due to its flowability. This can lead to formwork failures due to the development of hydrostatic pressures (FV)
- Formwork failures, due to hydrostatic pressures, can be eliminated by involving an external formwork company from the start. They can design the system to accommodate these pressures and thus relieve the constraint of a slow pouring rate limit (HG)

A.2.4 The impact of SCC on construction processes

Elements

- Higher single cast columns are possible, and easier to cast. This is especially significant in high ceiling structures where columns exceed 3 metres for a single storey (JH)
- Larger single cast slabs, especially if it is ground floor slabs, and longer single cast wall elements becomes possible when using SCC (AV, HZ)
- With the construction of piles, the reinforcement cage can be inserted before concrete placement and there is no need for shoring (HZ)

Risk

- Higher single cast columns can lead to problems with entrapped air that leads to air voids on the outer surface of an element (AV), this can be alleviated by ensuring the correct use of high quality shutter oil (HZ)
- The risk of poor compaction is shifted to the SCC supplier (implied by the name self-compacting), if they sell a SCC product they are selling different characteristics, thus taking on the responsibility involved with it (HZ, AV, HG)
- The risk of formwork failure due to bad design can be shifted off-site to the formwork company, if they are involved from the start and they know they are designing for SCC (HZ)
- High quality finished elements can be built on site with low skilled workers (HZ)
- The sealing of the formwork can create challenges on site, if the formwork leaks it can possibly lead to total material loss (FV)
- Proper curing is needed to prevent shrinkage cracks from forming (SCC is more susceptible than NCC due to the higher fines content) (FV)
- The risk of water addition by the site personnel due to low workability is eliminated by using SCC (HG)

Other implications

- The carbon footprint of SCC is larger due to the increased cement content, but it has other environmental impact considerations that differ from NCC, such as the lower energy usage during placement. In South Africa, the environmental law does not dictate any specific carbon emissions documenting yet, this might change in the near future (FV)
- The more volume one can cast per time unit, the better it is economically (JN)

A.2.5 Challenges and additional design criteria when implementing SCC

Challenges

- If SCC is used and the formwork leaks, it can lead to total material loss (AV, HG, MR). The leakage occurs if the formwork is not designed to accommodate hydrostatic pressures (HZ). The challenge is to mitigate this risk and ensure proper design and construction of formwork.
- SCC has a high sensitivity to moisture content and the moisture has to be controlled much stricter than for NCC (AV). Otherwise it can lead to plastic shrinkage cracks (FV, HZ)
- How superplasticiser work is often misunderstood, this leads to the misconception that the flowability of SCC is due to an increased moisture content (JR)
- A lack of knowledge often leads to the application of poor quality shutter release agents or using old or dirty shutters, this leads to low quality finishes that detrimentally affect the reputation of SCC as a construction material (HZ, AA)

Additional design criteria

- Formwork leakage should be prevented by designing for low formwork displacement when concrete is placed. Large formwork displacements during concrete placement enlarges the openings at the joints between the formwork panels (AA)

- SCC usually has a high strength (40 MPa entry level) and it can lead to over designed concrete. Especially if the required strength is 35 MPa, or lower, and the SCC realises a 50 MPa characteristic strength (HG)
- Formwork should be able to resist hydrostatic pressures, this often requires custom formwork designs as the standard economy formwork systems in the market will fail under such a load if the element depth is large (RB)
- The pouring rate should be controlled if standard strength formwork is used, this rate is dependent on a collection of variables which include volume, ambient temperature, concrete temperature and admixture information, the applicable design codes can be consulted in the formwork design process (RB)

A.2.6 Decision criteria for implementing SCC

Contractors

- SCC is implemented in the construction of elements with complex geometries, densely reinforced sections, in areas with difficult access or for large, time constricted pours (CV, FV, HZ, AA)
- SCC will be implemented if it gives any overall cost advantage (FV)

Consultants

- The implementation of SCC is not a concern for consultants, since a structural consultant does not need to be involved in the concrete choice, only a strength performance parameter is specified (CV)
- The design of water retaining structures or bridges might necessitate a consultant to specify other concrete characteristics than only characteristic strength. Increased constructability and other considerations can influence the concrete specified by a consultant. The constructability of these structures can be improved if the concrete is flowable and very workable (CV)
- SCC might also be specified if the construction of high single cast columns are required (JH)

Clients

- SCC might be specified if off-shutter concrete is a specified requirement due to aesthetics (HG)
- If the client knew more about SCC it might be specified for better structural integrity or for a faster project schedule (JR, HG)
- If the usage of SCC is connected to environmental incentive such as the Green Star rating the client can consider SCC as a material specification (JR)

A.2.7 Where can NCC not be replaced by SCC

- Low cost, low strength concrete applications. SCC does not have a low strength version in the South African market and the high cement content makes SCC financially unviable for these low strength applications (HZ, HG)
- Where an element has an inclined finish on the top, it is not impossible to achieve this incline with SCC, but it is more troublesome than with NCC (HG)
- If there is a skill shortage in any of the production or construction phases (AA)

A.2.8 Labour requirements and their effect on SCC usage

Industry comments

- The obligation of creating work lowers the rate of SCC uptake in the market (AV)
- The use of SCC can create new possibilities for shifting your labour around on site (AV)
- New, higher-skilled labour opportunities can open up when SCC is used. SCC suppliers have two technicians present when every truck of SCC is loaded (AV)
- Labour saving technologies get opposed by contractors (HG)
- Contractors have other prescriptions to satisfy such as the percentage of the workforce that should be local, labour unrest can be a consequence of using labour reduction technologies (HG)
- The labour expense savings alone, will not convince a contractor to use SCC (HG)

Governmental tender procedures

- Labour intensive projects can be specified through a tender, but it very seldom happens (JR)
- State tenders are approached differently between provinces and between different government departments (JR)
- Tenders of the Department of Public Works in the Western Cape are done according to Annexure F of the CIDB conditions of tender (JR)
- Most open tenders in the Western Cape are done according to the second or the fourth method as set out by the CIDB, any method that is non-compliant with the CIDB is thus illegal to use (JR)
- Implementing SCC (or another labour reducing technology) at a government financed site in the Western Cape, will not give a contractor any labour requirement problems (JR)
- There are currently no legal prescriptions for the implementation of the EPWP, the tender system of the Western Cape Government has just been revamped and the EPWP representatives were asked for inputs onto the new system. No prescriptions were received so no prescriptions were included in the new Conditions of Tender regarding the EPWP (JR)
- The implementation of the Infrastructure Delivery Management System is considered on a national scale, this system aims to improve service delivery and to get rid of adversarial contracts. (JR)

Other considerations

- Labour requirements such as local labour requirements is sometimes specified as a percentage of the total workforce, and not on the number of men employed (AA)

A.2.9 The SCC market over the last decade and the expected future

Development and current status

- Major precast customers use a material similar to SCC , it is very different from what the ready-mix customers use in the sense that precast customers prefer a smaller open time on the fresh concrete state (AV)
- The application of SCC in South Africa includes precast applications such as masts for wind turbines and other repetitive elements. Certain companies use their own batch plants while others prefer to order SCC as ready-mix concrete (AV)
- When SCC entered the South African market, the industry accepted it with an initial excitement, this excitement subsided due to the high material unit price (AV)

- Companies see SCC as a value-added product, but the suppliers of SCC are still disappointed with the growth in the South African market (AV)
- At this time, many users still prefer pumping concrete over SCC (AV)
- There is a shift in the SCC market towards the use for off-shutter concrete, mostly driven by architects (HZ)
- In Europe, the higher growth might be due to the higher labour cost and/or to certain policies which favour SCC (such as noise pollution limits) (JR)
- SCC sales contributes around 10% of the total concrete sales for Lafarge internationally while the South African market reached a plateau at about 1% (HZ, HG)

Future

- Lafarge Agilia (South Africa) wants to focus on the high strength concrete market in the future, that is concrete with a strength of 45MPa or higher (HG)
- The growth expectation is low due to the high amount of new concrete technologies that have recently entered the market and the market might be temporarily overwhelmed (HZ)

A.2.10 What reasons have been given for not implementing SCC

Consultants

- The need for implementing SCC has not yet become apparent (JH)
- The usage of SCC has a low impact on the work of consultants, it is mainly used for off-shutter concrete and complex geometries (CV)
- The knowledge about SCC is limited and consultants prefer to specify concrete by the characteristic strength, it is a deliberate decision to specify the minimum number of performance parameter (CV)
- There is no incentive for consultants to specify SCC to shorten the project schedule since consultants work on hourly rates (CV)
- A consultant will not oppose the decision if a contractor wants to use SCC (CV, JH)
- The industry might be conservative and choose to hold on to old specifications to which they are well accustomed (JH)

Contractors

- Using more labour is not a big problem, since South African labour is relatively cheap compared to developed countries (HZ)
- The lack of knowledge about SCC leads to the perception that the flowability of SCC is due to a higher moisture content (HZ)
- Bad experiences with SCC usage, that originates from a lack of knowledge and inconsistent SCC received from suppliers can prevent a contractor from using the material (AA)

Clients

- Due to a lack of knowledge and awareness about the product (JR)

APPENDIX B – INPUT DATA STRUCTURE

The input data, as described in Chapter 4, was divided into four categories. These categories are:

- Project specific inputs
- Concrete mix design inputs (for SCC and NCC)
- Element detail inputs (slabs, beams, columns and walls)
- Concrete placement schedule inputs

The project specific inputs define the high-level project information. The information required to populate the model is shown in Table 19.

The second category contains the detail about the concrete mixes used for construction. This includes the mix composition, characteristic strengths and the cost of producing the concrete on-site and the cost of using an external supplier. The model can accommodate up to six NCC mixes and six equivalent strength SCC mixes.

The third category is split into the four general structural elements namely beams, slabs, columns and walls. Each element class may contain up to ten individual elements. This means that up to ten slab types, beam types etc. can be defined from the project drawings and entered into the model.

The last category contains the logistical information. The concrete mix type, element type and supply choice for every concrete cast is defined in this category. Whether or not the specific element's construction is on the critical path and if a crane or pump is used during placement can also be entered in this category. The critical path and equipment usage information enables the model to assess the cost impact differently if a time saving on a specific concrete cast can lead to overhead savings, time saving or placement equipment savings (these savings occur for elements on the critical path of the project schedule).

Table 19 to Table 22 show the model spreadsheet and thus the data that is required for each of the categories. Note that although only one example is given of each category, the model can accommodate up to six concrete mix strengths, ten individual element types for every element class and up to a hundred concrete casts. The specific values that were used will be excluded due to the sensitive nature of certain productivity and procurement values (due to the preference of the source).

Table 19: Project specific input

PROJECT SPECIFIC INFO		Units
Project Name:		
Project start date:		
Project duration (total days):		days
Total project value:		Rand
CONCRETE RELATED COST		
Total volume used [m³]:		m³
Vibrator cost per day:		R/d
Concrete placement overhead cost per day:		R/d
TIME RELATED COST		
Daily running cost:		R/d
% of casts done after original project due date		%
Penalty cost per day:		R/d
Total number of casts to be done		casts
Crane cost per day:		R/d
CAPITAL RELATED COSTING INFO		
Funding method (Capital/Debt):		
MARR on capital:		%
Interest rate on debt:		%
Inflation mean:		%

Table 20: Concrete mix design input

	MIX DETAILS - DECK SLABS PUMP MIX					
SELF-SUPPLIED	Mix 1	Strength -	40 / (19 & 13.2)			
	Constituent	Weight[kg]	RD	Volume [m³]	Cost [ZAR]	
	Water				0	
	Aggregate				0	
	Cement				0	
	Fly-ash				0	
	Slag				0	
	Sand				0	
	Admixture				0	
					0	[R/m³]
R	Name	Cost [R/m³]				
M						

Ensure that mix i for SCC correspond with mix i for NCC ito strength

CONSTITUENT DETAILS				
Constituent	Type	Cost [R]	Costing unit	Cost [R/kg]
Water				
Aggregate				
Cement				
Fly-ash				
Slag				
Sand				
Admixture				

Table 21: Element input data

Slab number:	1		
Description:	Bridge deck spans (1-6)		
SLAB SPECIFIC COSTING INFORMATION:			
Item	Description	Amount	Unit
Screed cost	Saving on screed with use of SCC		R/m²
NCC Labour rate	Cost of 1 manhour of placing labour		R/h
SCC Labour rate	Cost of 1 manhour of placing labour		R/h
NCC Placement rate	Time required to place one element with NCC		hours/element
SCC Placement rate	Time required to place one element with SCC		hours/element
Element volume	Total concrete volume per element		m³/element
Vibrators for NCC	Amount of vibrators required per element, for the duration of the cast		
Formwork required	Total area of formwork to be used		m²
Slab surface area	Surface area that requires screed when NCC is used		m²
Formwork Sealing	Additional Sealing for the use of SCC		R/m²
SCC Formwork rate	Cost of hiring or owning the formwork for SCC		R/m²/day
NCC Formwork rate	Cost of hiring or owning the formwork for NCC		R/m²/day
Formwork Idle time	Time that formwork supports the structure before being stripped		days
SCC Formwork erection cost	Cost of labour, scaffolding, crane etc.		R
NCC Formwork erection cost	Cost of labour, scaffolding, crane etc.		R
SCC Formwork dismantling cost	Cost of labour, scaffolding, crane etc.		R
NCC Formwork dismantling cost	Cost of labour, scaffolding, crane etc.		R
NCC Rework rate	Usual observed rework done as a % of total concrete cost per element		%
SCC Rework rate	Usual observed rework done as a % of total concrete cost per element		%
NCC Rework cost	Usual observed rework requirements, expressed in terms of volume		R/m³
SCC Rework cost	Usual observed rework requirements, expressed in terms of volume		R/m³

Table 22: Concrete placement input data

Cast nr	Date of placement	Volume [m³]	Mix type	Concrete supply (int/ext)	Element	Critical path	Crane used
1							
2							
3							
4							

APPENDIX C – CASE STUDY DRAWINGS INFORMATION

The project described in Chapter 5, the bridge construction near George in the Western Cape, is detailed in this Appendix. Certain structural drawings are provided, as well as any other information that might be needed in evaluating the project and populating the model. Strategic rates and values will not be discussed, due to the sensitive nature of this information.

The following drawings can be used to extract the required information to populate the model.

1. Site plan
2. General arrangement
3. Foundation layout and details
4. Pier concrete details
5. Retaining wall layout and details
6. Deck concrete details

C.1 Case study structural breakdown

The following elements were included in the model as summarized below in Table 23. The different elements can be identified in the drawings. Elements with similar geometry were modelled under a single element definition (All six bridge deck spans was modelled as Slab1 in the costing model since their concrete construction cost attributes are almost identical).

Table 23: Element breakdown of bridge case study

Element nr	Slabs	Columns	Walls	Concrete mixes
1	Bridge deck spans (1-6)	Pier 1	Eastern abutment wall	Deck slab pump mix 40/(19&13.2)
2	Approach slabs (1&2)	Pier 2	Western abutment wall	Piling columns 40/(19&13.2)
3	Eastern abutment foundation	Pier 3	Retaining wall (1&7)	Abutments and ear walls 40/19
4	Western abutment foundation	Pier 4	Retaining wall (2&8)	Approach slabs and retaining walls 30/19
5	Retaining wall foundation (1&7)	Pier 5	Retaining wall (3&9)	
6	Retaining wall foundation (2&8)	Pier 6	Retaining wall (4)	
7	Retaining wall foundation (3&9)		Retaining wall (5)	
8	Retaining wall foundation (4)		Retaining wall (6)	
9	Retaining wall foundation (5)		Ear Wall (1&2)	
10	Retaining wall foundation (6)		Ear Wall (3&4)	

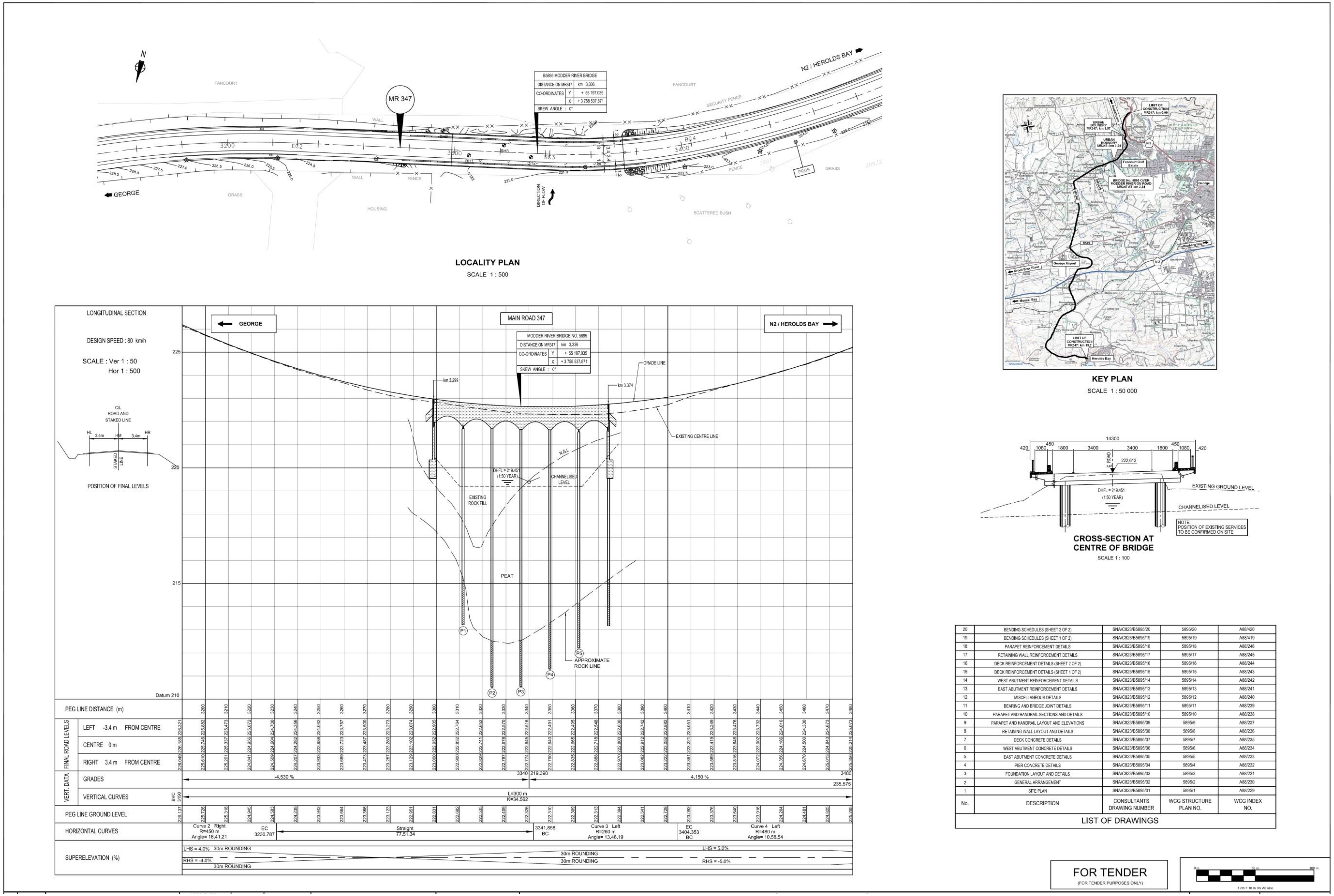


Figure 31: Site Plan

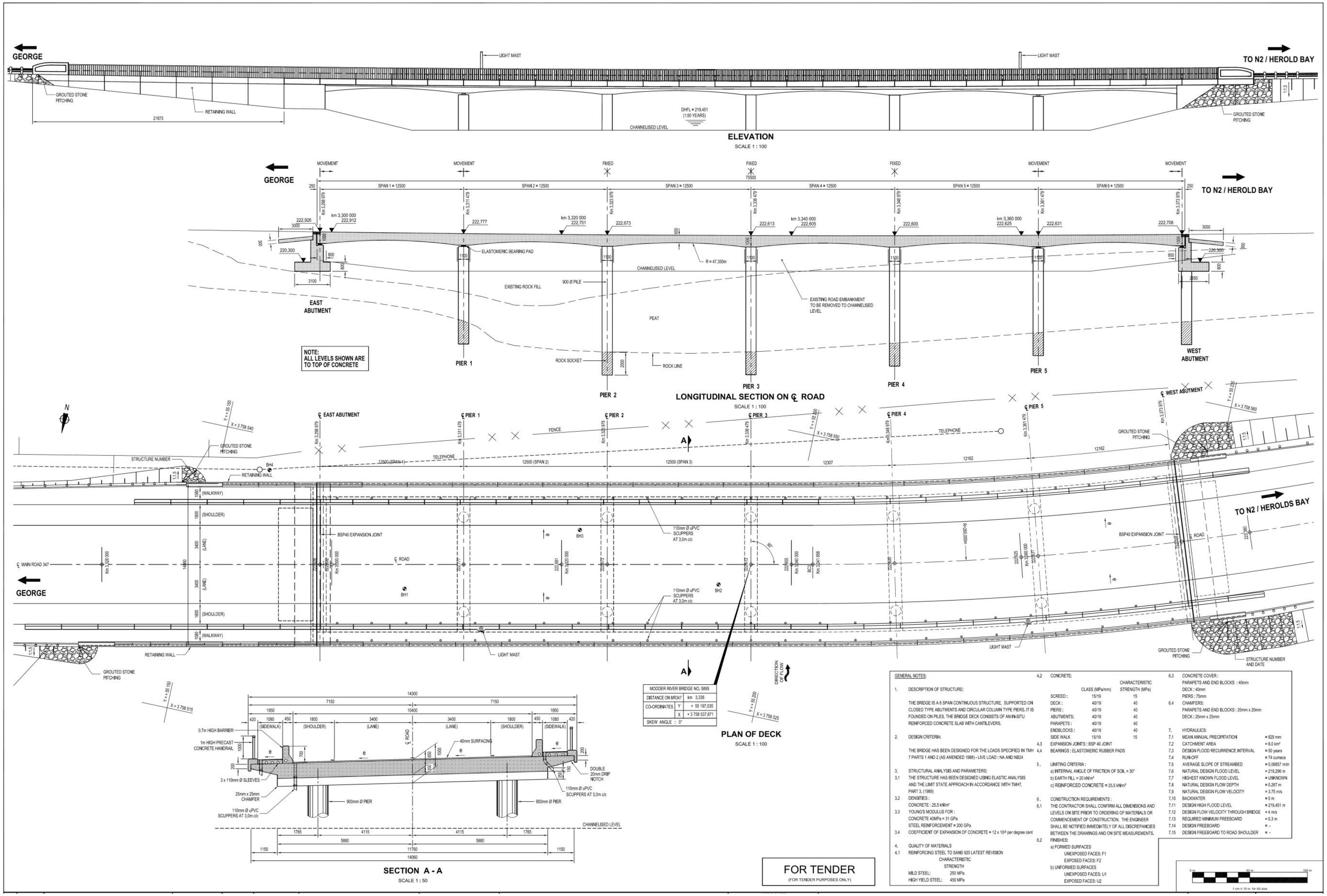
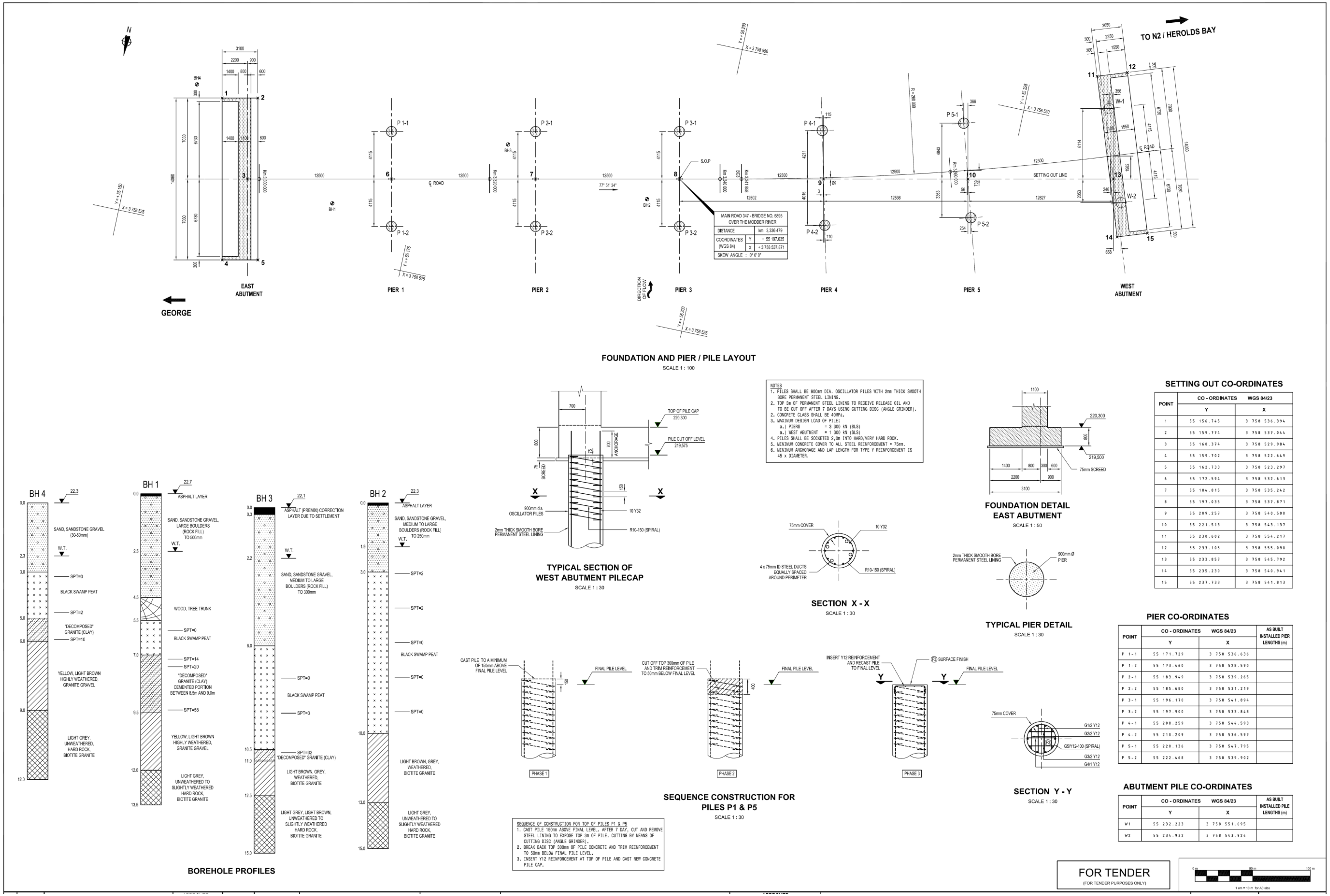


Figure 32: General arrangement



POINT	CO - ORDINATES WGS 84/23 Y	X
1	55 156.745	3 758 536.394
2	55 159.774	3 758 537.044
3	55 160.374	3 758 529.984
4	55 159.702	3 758 522.649
5	55 162.733	3 758 523.297
6	55 172.594	3 758 532.613
7	55 184.815	3 758 535.242
8	55 197.035	3 758 537.871
9	55 209.257	3 758 540.500
10	55 221.513	3 758 543.137
11	55 230.602	3 758 554.217
12	55 233.105	3 758 555.090
13	55 233.857	3 758 545.792
14	55 235.230	3 758 540.941
15	55 237.733	3 758 541.813

POINT	CO - ORDINATES WGS 84/23 Y	X	AS BUILT INSTALLED PIER LENGTHS (m)
P 1-1	55 171.729	3 758 536.636	
P 1-2	55 173.460	3 758 528.590	
P 2-1	55 183.949	3 758 539.265	
P 2-2	55 185.680	3 758 531.219	
P 3-1	55 196.170	3 758 541.894	
P 3-2	55 197.900	3 758 533.848	
P 4-1	55 208.259	3 758 544.593	
P 4-2	55 210.209	3 758 536.597	
P 5-1	55 220.136	3 758 547.795	
P 5-2	55 222.468	3 758 539.902	

POINT	CO - ORDINATES WGS 84/23 Y	X	AS BUILT INSTALLED PILE LENGTHS (m)
W1	55 232.223	3 758 551.695	
W2	55 234.932	3 758 543.924	

Figure 33: Foundation layout details

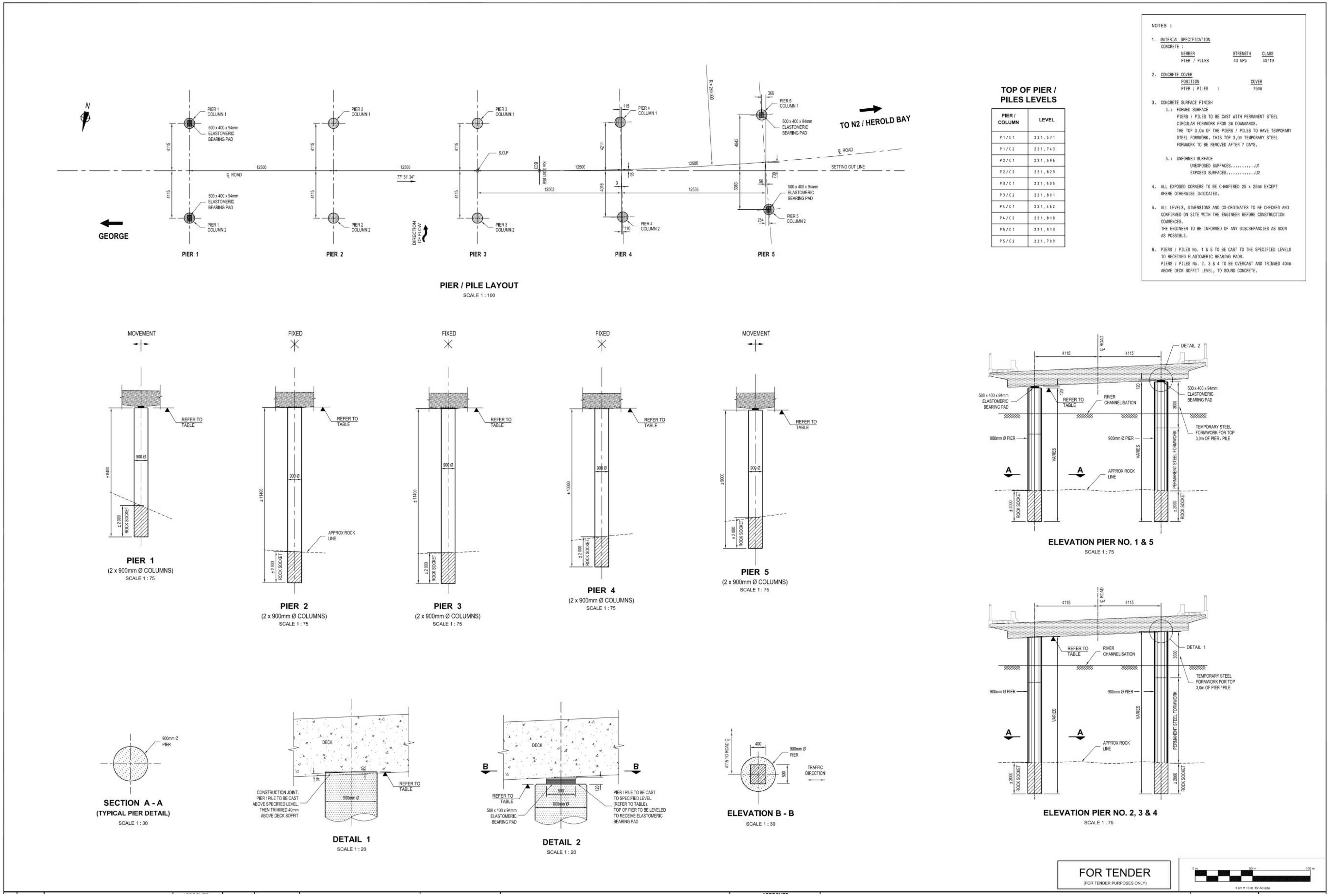


Figure 34: Pier concrete details

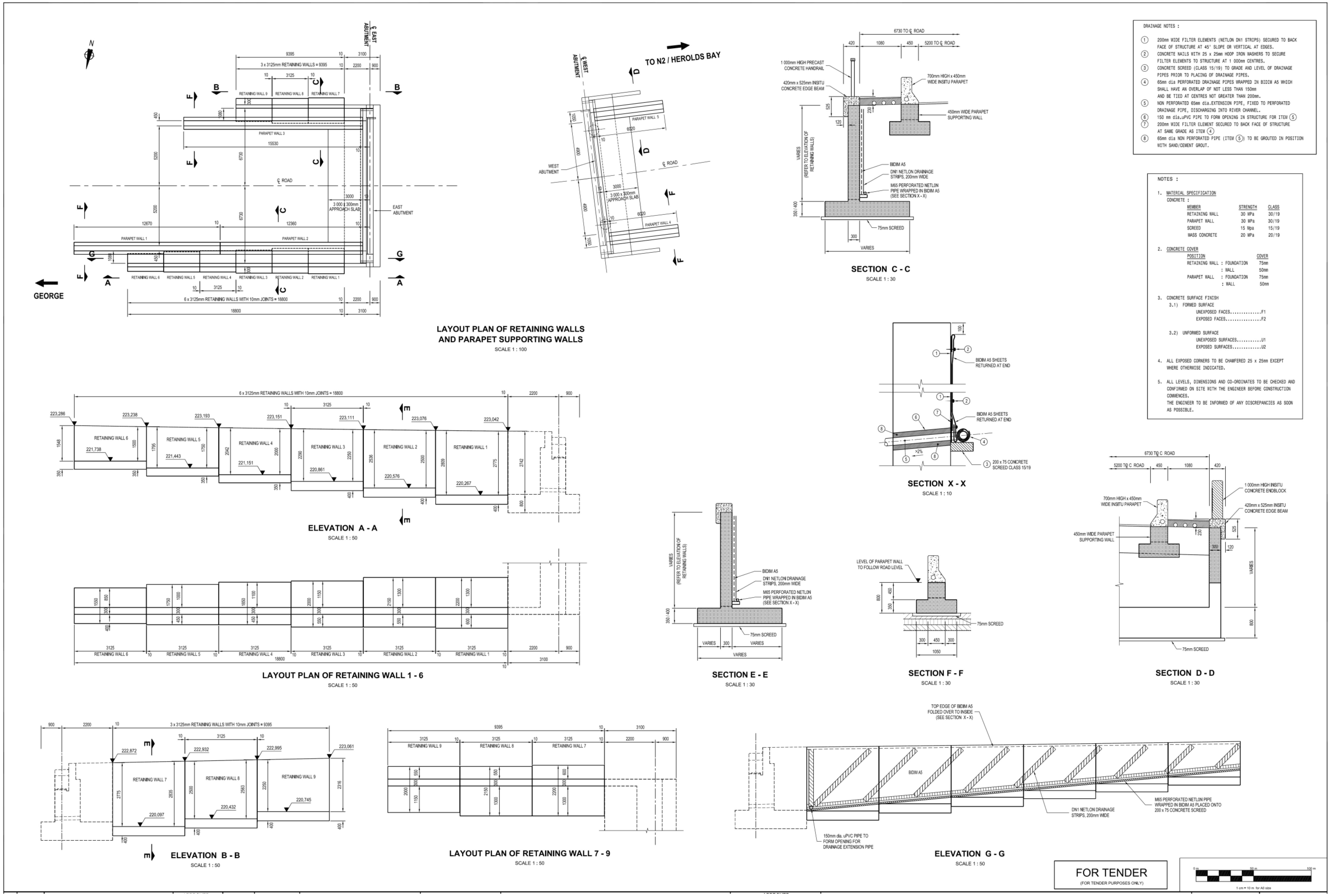


Figure 35: Retaining wall layout and details

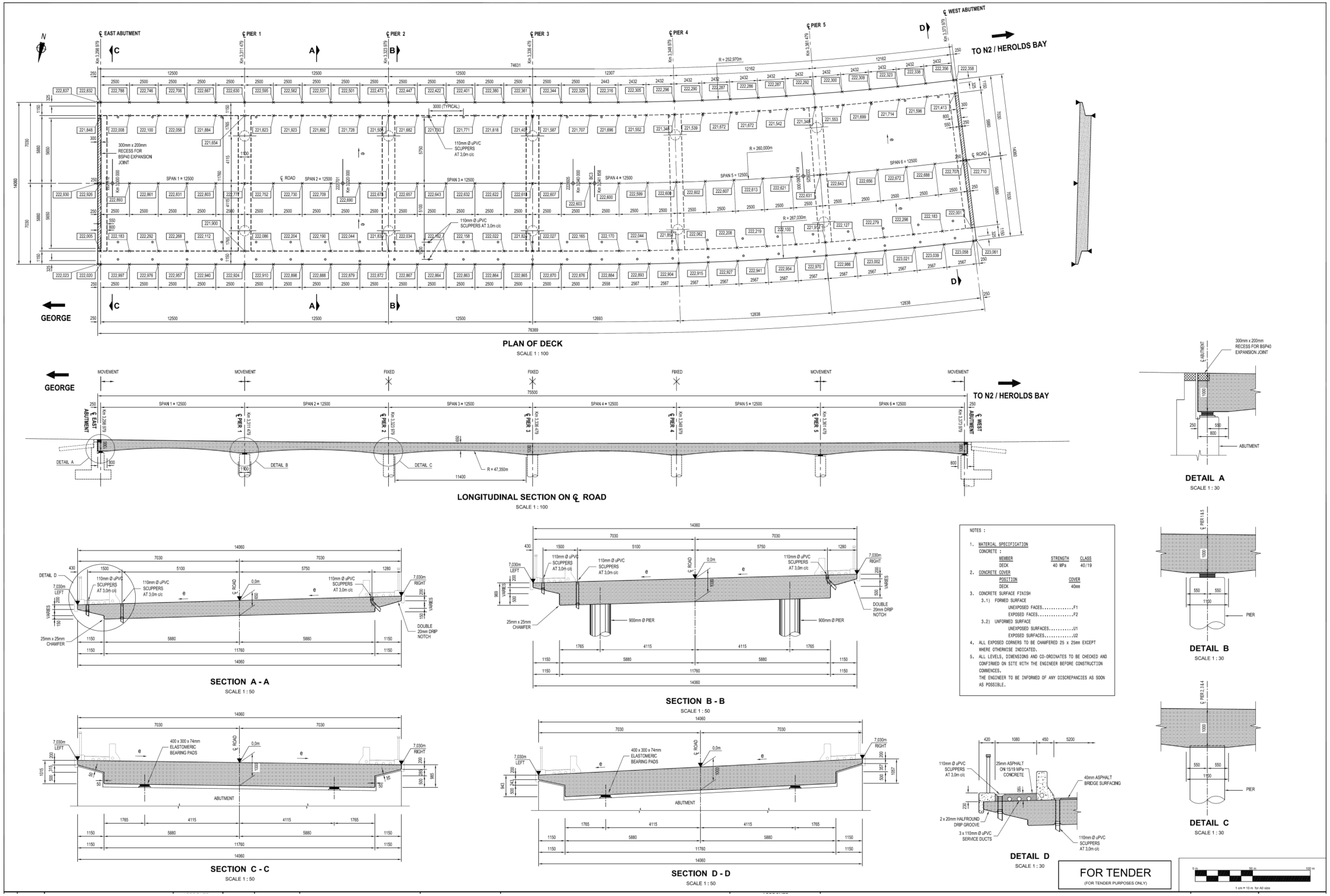


Figure 36: Deck concrete details

APPENDIX D – RESULTS RELATED INFORMATION

D.1 Relationship between element size and material or formwork cost contribution

As stated in the report, larger elements have a lower outer surface to volume ratio than smaller elements. This means that the size of the formwork cost contribution towards the total cost will show an inversely dependent relationship with element size.

This inversely dependent relationship means that the effects of an increased material price will diminish as element size reduces. The influence of varying element size, on the cost contribution of material and formwork cost is shown in this section for slabs, columns and walls.

The following dimension notation scheme was used:

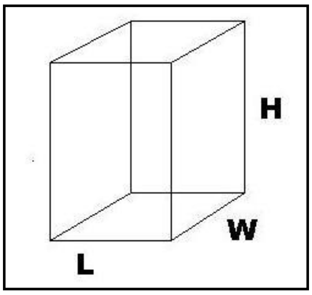
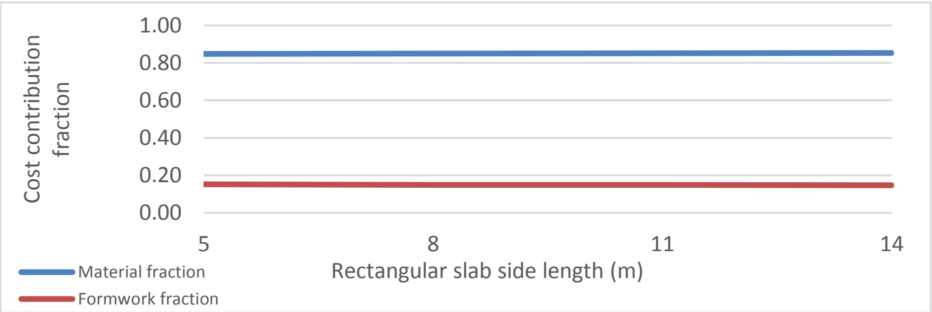


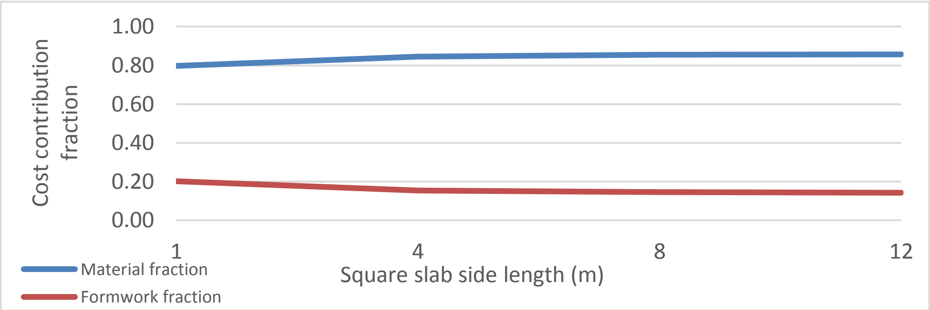
Figure 37: Notation scheme for element size

D.1.1 Slabs

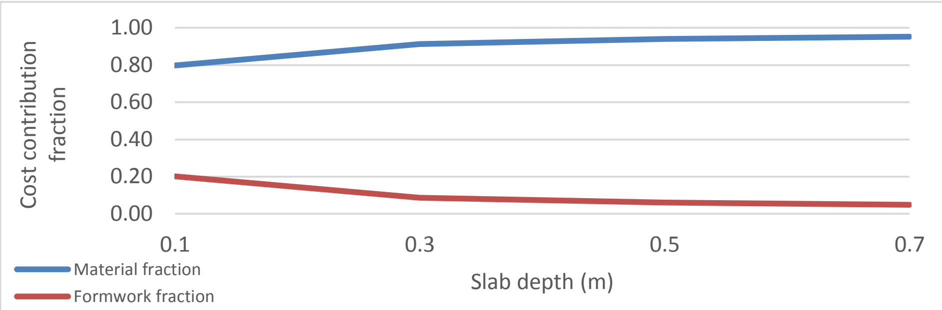
L [m]	W [m]	H [m]
5	4	0.15
8	4	0.15
11	4	0.15
14	4	0.15



L [m]	W [m]	H [m]
1	1	0.15
4	4	0.15
8	8	0.15
12	12	0.15

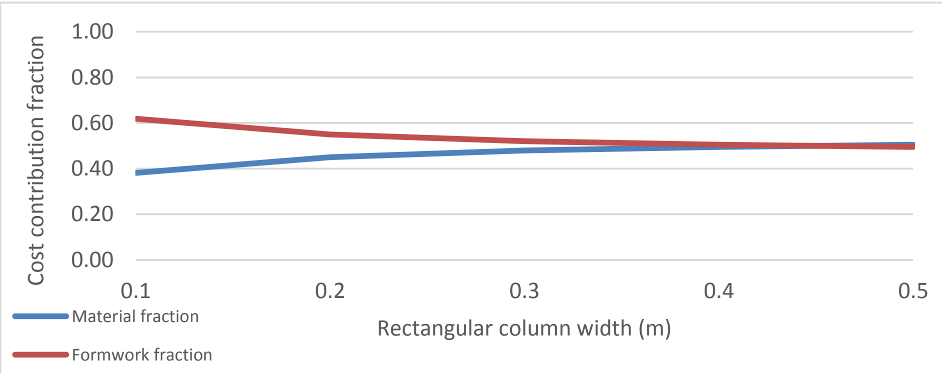


L [m]	W [m]	H [m]
10	4	0.1
10	4	0.3
10	4	0.5
10	4	0.7

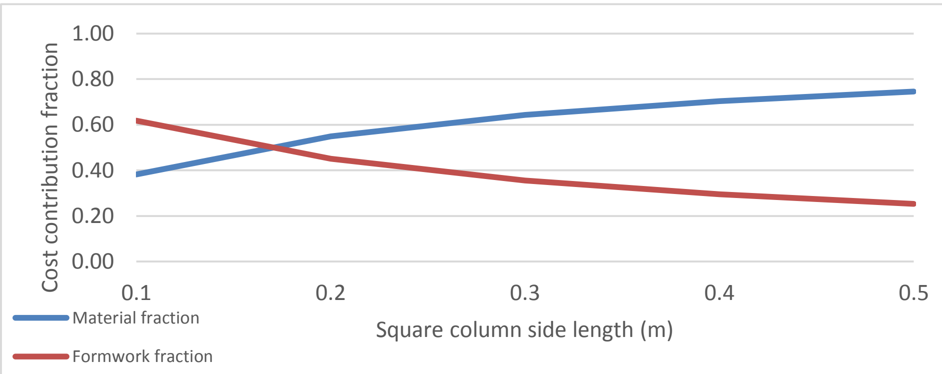


D.1.2 Columns

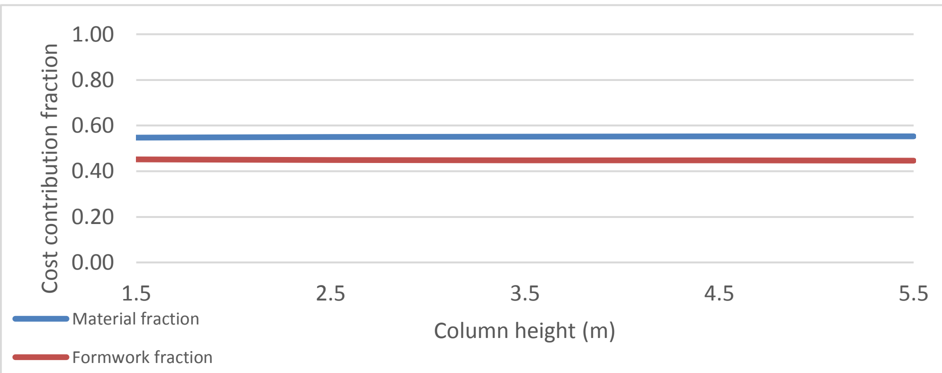
L [m]	W [m]	H [m]
0.1	0.1	2.0
0.2	0.1	2.0
0.3	0.1	2.0
0.4	0.1	2.0
0.5	0.1	2.0



L [m]	W [m]	H [m]
0.1	0.1	2.0
0.2	0.2	2.0
0.3	0.3	2.0
0.4	0.4	2.0
0.5	0.5	2.0

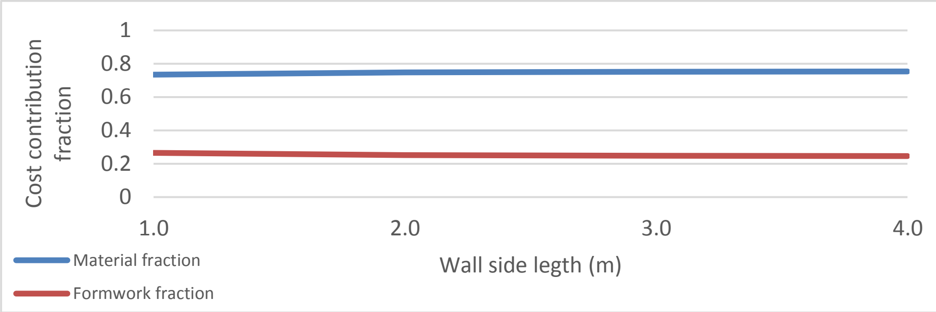


L [m]	W [m]	H [m]
0.2	0.2	1.5
0.2	0.2	2.5
0.2	0.2	3.5
0.2	0.2	4.5
0.2	0.2	5.5

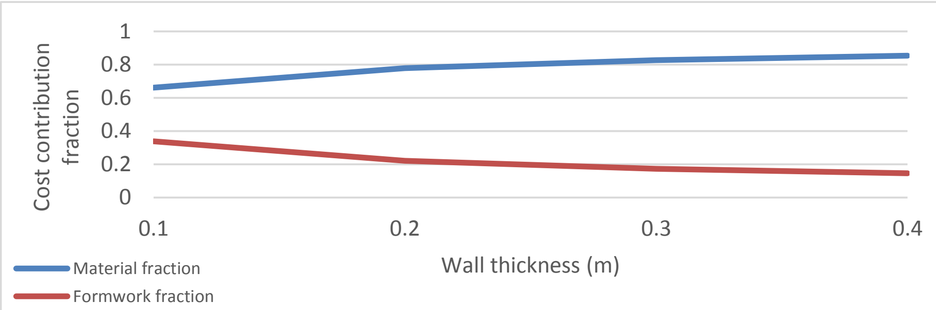


D.1.3 Walls

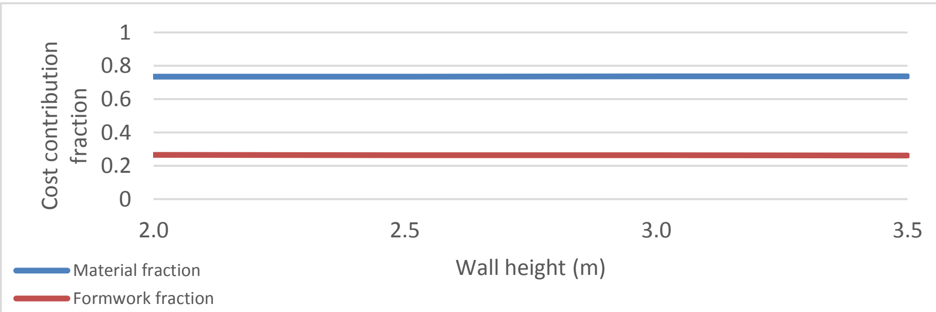
L [m]	W [m]	H [m]
1.0	0.2	2.0
2.0	0.2	2.0
3.0	0.2	2.0
4.0	0.2	2.0



L [m]	W [m]	H [m]
1.0	0.1	2.0
1.0	0.2	2.0
1.0	0.3	2.0
1.0	0.4	2.0



L [m]	W [m]	H [m]
1.0	0.2	2.0
1.0	0.2	2.5
1.0	0.2	3.0
1.0	0.2	3.5



D.2 Outer surface to volume ratios of different element types

The following outer surface to volume ratios were calculated for the different elements by using the same notation and element sizes as in the previous section. This ratio provides an indication of the size of different cost contributions. It is an easy ratio to calculate and it can provide information that can be used in strategizing cost management. A low ratio means the material cost will be a significant contributor to the total cost and a high ratio means other cost contributors will become important as well (such as formwork cost). If the ratio is high, an expense reduction in costs such as labour and formwork has the potential to lower the cost difference between NCC and SCC significantly. The outer surface area is defined as all the surfaces that will be supported by formwork during construction.

D.2.1 Slabs

L and W changes					
L [m]	W [m]	H [m]	Volume [m³]	Outer surface [m²]	Outer surface/Volume [m²/m³]
1	1	0.15	0.15	1.60	10.67
4	4	0.15	2.40	18.40	7.67
8	8	0.15	9.60	68.80	7.17
12	12	0.15	21.60	151.20	7.00

D.2.2 Columns

L and W changes					
L [m]	W [m]	H [m]	Volume [m³]	Outer surface [m²]	Outer surface/Volume [m²/m³]
0.1	0.1	2.0	0.02	0.81	40.50
0.2	0.2	2.0	0.08	1.64	20.50
0.3	0.3	2.0	0.18	2.49	13.83
0.4	0.4	2.0	0.32	3.36	10.50
0.5	0.5	2.0	0.50	4.25	8.50

D.2.3 Walls

L changes					
L [m]	W [m]	H [m]	Volume [m³]	Outer surface [m²]	Outer surface/Volume [m²/m³]
1.0	0.2	2.0	0.3	4.75	15.83
2.0	0.2	2.0	0.6	8.9	14.83
3.0	0.2	2.0	0.9	13.05	14.50
4.0	0.2	2.0	1.2	17.2	14.33

D.3 Influential input parameters and sensitivity analysis results

The influential input parameters that were identified through the sensitivity analysis are listed in this section for every element class. Table 24 and Table 25 show the KPI's and the different influential input parameters, as identified by the sensitivity analysis.

The resulting distributions of the output KPI's are also included in this appendix. The resulting KPI distributions were calculated with the Monte Carlo analysis. These distributions are shown in Table 26. Note that only those KPI's that are dependent on one or more of the varying influential input parameters have a distribution as their output parameter. The general geometry of the output distribution indicates the dependency of the output on the varying inputs. This relationship is only visible because relatively few inputs had their own distributions assigned. A mathematical approach would be required to investigate the correlation if more variable inputs was included in the model (thus if more uncertainty was included in the model).

The resulting distributions for the 'other costs' of slabs and the overall project are worth elaborating on. The overall maximum that is situated on the downwards slope of the distribution is due to the addition of savings on *overheads* and *penalties*. The modelled relationship between these expenses and the assumed *percentage of casts done in the penalty period* can induce major spikes and dips in the financial implication of the 'other costs' (overheads and penalties are classified as 'other costs'). The assigned distribution of the assumed *percentage of casts done in the penalty period* will be carried over to the number of days for which penalties can be avoided. The spike is due to the few scenarios (as calculated by the Monte Carlo Analysis) in which the final deck slab is cast in the penalty period, if this cast can be completed earlier it is possible to accelerate the project and prevent major penalties.

The cost impact is small in comparison to the total cost (the mean is R38 907) and the explanation of the irregularity was not investigated mathematically. The explanation is however supported by a sensitivity analysis that was performed on the resulting distribution for slab elements (slab elements are the source of the spike in the overall 'other costs implication' KPI) and the assumed percentage casts that are executed in the penalty period. The results showed that if the assumed percentage is lowered from 5% to 3.4% the other costs implication KPI will lower by approximately 23%.

Table 24: Influential input parameters for slab and column elements

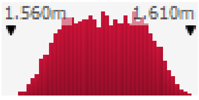
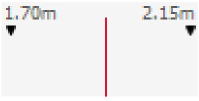
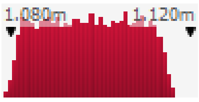
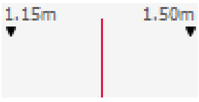
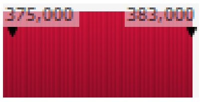
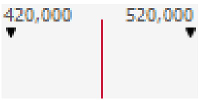
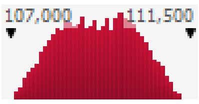
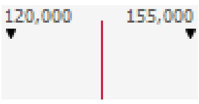
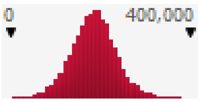
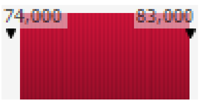
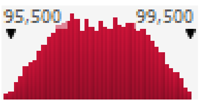
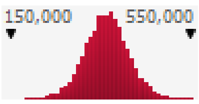
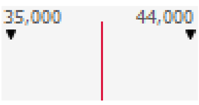
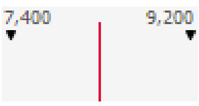
SLABS PARAMETERS										
VARIABLE	1	2	3	4	5	6	7	8	9	10
CP Time saving	FormErectTime_NCC_Slab1	FormErectTime_SCC_Slab1	PlaceRate_NCC_Slab1	PlaceRate_SCC_Slab1	FormDismantleTime_NCC_Slab1	FormDismantleTime_SCC_Slab1	PlaceRate_NCC_Slab2	FormErectTime_NCC_Slab2	FormErectTime_SCC_Slab2	PlaceRate_NCC_Slab5
Total Cost	Mix1_SCC_extCost	Mix1_NCC_extCost	FormErectTime_NCC_Slab1	FormErectTime_SCC_Slab1	TotalCasts	MIx3_SCC_extCost	Mix3_NCC_extCost	MIx4_SCC_extCost	Erecter/Number of men (H21)	Erecter/Number of men (L21)
SCC Material Cost	Mix1_SCC_extCost	Volume (Cast33)	Volume(Cast34)	CastVolume(13Aug)	Volume(Cast37)	CastVolume(11Sep)	Volume(Cast38)	Mix3_SCC_extCost		
NCC Material Cost	Mix1_NCC_extCost	Volume (Cast33)	Volume(Cast34)	CastVolume(13Aug)	CastVolume(11Sep)	Volume(Cast37)	Volume(Cast38)	Mix3_NCC_extCost		
SCC Placement labour cost	PlaceRate_SCC_Slab1	Placer/Number of men (L7)	Supervisor/Number of men (L9)	Foreman/Number of men (L8)	PlaceRate_NCC_Slab2	PlaceRate_NCC_Slab5	PlaceRate_NCC_Slab6	PlaceRate_NCC_Slab7		
NCC Placement labour cost	PlaceRate_NCC_Slab1	Unskilled/Number of men (H7)	Skilled/Number of men (H9)	Semi-Skilled/Number of men (H8)	PlaceRate_NCC_Slab2	PlaceRate_NCC_Slab5	PlaceRate_NCC_Slab6	PlaceRate_NCC_Slab7		
SCC Formwork cost	FormErectTime_SCC_Slab1	FormArea_Slab1	Erecter/Number of men (L21)	Foreman/Number of men (L22)	Supervisor/Number of men (L23)	FormIdleTime_Slab1	FormDismantleTime_SCC_Slab1			
NCC Formwork cost	FormErectTime_NCC_Slab1	FormArea_Slab1	Erecter/Number of men (H21)	Foreman/Number of men (H22)	Supervisor/Number of men (H23)	FormIdleTime_Slab1	FormDismantleTime_NCC_Slab1			
Rework cost	Mix1_NCC_extCost	Volume_Slab1	Mix3_NCC_extCost							
Additional cost impact	TotalCasts	PercCastInPenaltyTime	Cast nr (A41)	Cast nr (A38)	Cast nr (A39)	Cast nr (A40)	Cast nr (A42)	Cast nr (A43)	FormErectTime_NCC_Slab1	FormErectTime_SCC_Slab1

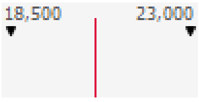
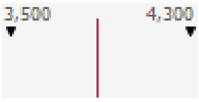
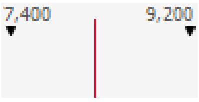
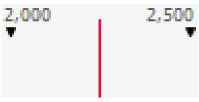
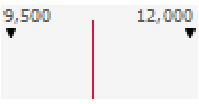
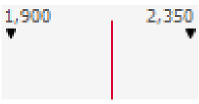
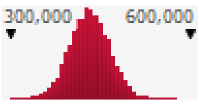
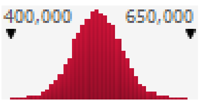
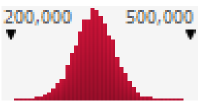
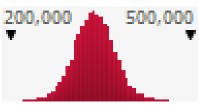
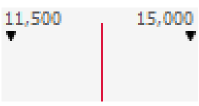
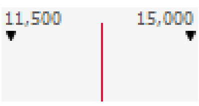
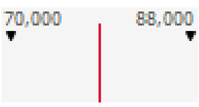
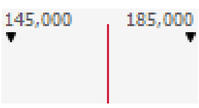
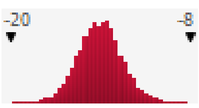
COLUMNS PARAMETERS										
VARIABLE	1	2	3	4	5	6	7	8	9	10
CP Time saving	PlaceRate_NCC_Column2	PlaceRate_NCC_Column3	PlaceRate_NCC_Column4	PlaceRate_NCC_Column5	PlaceRate_NCC_Column6	PlaceRate_NCC_Column1				
Total Cost	Mix2_SCC_extCost	Mix2_NCC_extCost								
SCC Material Cost	Mix2_SCC_extCost									
NCC Material Cost	Mix2_NCC_extCost									
SCC Placement labour cost	PlaceRate_NCC_Column2	PlaceRate_NCC_Column1	Supervisor/Number of men (L120)	Supervisor/Number of men (L157)	Supervisor/Number of men (L9)	Supervisor/Number of men (L46)	Supervisor/Number of men (L83)	Supervisor/Number of men (L194)		
NCC Placement labour cost	PlaceRate_NCC_Column1	PlaceRate_NCC_Column2	PlaceRate_NCC_Column3	PlaceRate_NCC_Column4	PlaceRate_NCC_Column5	PlaceRate_NCC_Column6	Placer/Number of men (H155)	Placer/Number of men (H7)	Placer/Number of men (H44)	Placer/Number of men (H81)
SCC Formwork cost	FormErectTime_SCC_Column1	FormDismantleTime_SCC_Column1	FormErectTime_SCC_Column2	FormDismantleTime_SCC_Column2	FormErectTime_SCC_Column3	FormDismantleTime_SCC_Column3	FormErectTime_SCC_Column4	FormDismantleTime_SCC_Column4	FormErectTime_SCC_Column5	FormDismantleTime_SCC_Column5
NCC Formwork cost	FormErectTime_NCC_Column1	FormDismantleTime_NCC_Column1	FormErectTime_NCC_Column2	FormDismantleTime_NCC_Column2	FormErectTime_NCC_Column3	FormDismantleTime_NCC_Column3	FormErectTime_NCC_Column4	FormDismantleTime_NCC_Column4	FormErectTime_NCC_Column5	FormDismantleTime_NCC_Column5
Rework cost	Mix2_NCC_extCost	ReworkRate_NCC_Column2	ReworkRate_NCC_Column3	ReworkRate_NCC_Column4	ReworkRate_NCC_Column5	ReworkRate_NCC_Column1	ReworkRate_NCC_Column6			
Additional cost impact	PlaceRate_NCC_Column6	VibratorQuant_Column6	PlaceRate_NCC_Column1	VibratorQuant_Column1	PlaceRate_NCC_Column2	VibratorQuant_Column2	PlaceRate_NCC_Column3	VibratorQuant_Column3	PlaceRate_NCC_Column4	VibratorQuant_Column4

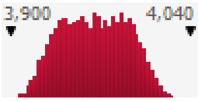
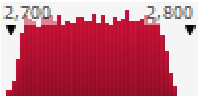
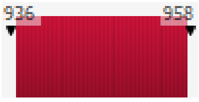
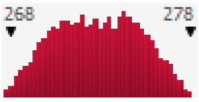
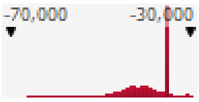
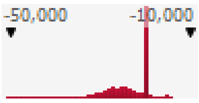
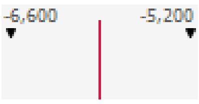
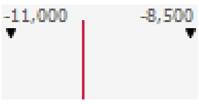
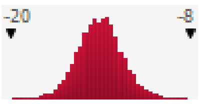
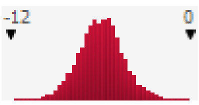
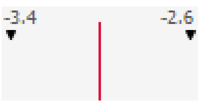
Table 25: Influential input parameters of wall elements

WALLS PARAMETERS										
VARIABLE	1	2	3	4	5	6	7	8	9	10
CP Time saving	PlaceRate_NCC_Wall1	PlaceRate_NCC_Wall2	PlaceRate_NCC_Wall3	PlaceRate_NCC_Wall4	PlaceRate_NCC_Wall5	PlaceRate_NCC_Wall10	FormErectTime_NCC_Wall10	FormErectTime_SCC_Wall10	FormErectTime_NCC_Wall3	FormErectTime_SCC_Wall3
Total Cost	Mix3_SCC_extCost	Mix3_NCC_extCost	Mix4_SCC_extCost	Mix4_NCC_extCost	FormArea_Wall1	FormArea_Wall2	FormArea_Wall10	FormErectTime_SCC_Wall1	Volume (Cast30)	CastVolume8
SCC Material Cost	Mix3_SCC_extCost	Volume (Cast30)	CastVolume8	Mix4_SCC_extCost						
NCC Material Cost	Mix3_NCC_extCost	Volume (Cast30)	CastVolume8	Mix4_NCC_extCost						
SCC Placement labour cost	PlaceRate_NCC_Wall1	PlaceRate_NCC_Wall2	PlaceRate_NCC_Wall3	PlaceRate_NCC_Wall4	PlaceRate_NCC_Wall5	PlaceRate_NCC_Wall9	PlaceRate_NCC_Wall10	Foreman/Number of men (L8)	Foreman/Number of men (L45)	Foreman/Number of men (L82)
NCC Placement labour cost	PlaceRate_NCC_Wall1	PlaceRate_NCC_Wall3	PlaceRate_NCC_Wall4	PlaceRate_NCC_Wall5	PlaceRate_NCC_Wall2	PlaceRate_NCC_Wall9	PlaceRate_NCC_Wall10	Placer/Number of men (H44)	Placer/Number of men (H7)	Placer/Number of men (H81)
SCC Formwork cost	FormArea_Wall1	FormArea_Wall2	FormArea_Wall10	FormArea_Wall9	FormErectTime_SCC_Wall1	FormErectTime_SCC_Wall10	FormErectTime_SCC_Wall2	FormErectTime_SCC_Wall9	FormIdleTime_Wall1	FormErectTime_SCC_Wall3
NCC Formwork cost	FormErectTime_NCC_Wall10	FormArea_Wall1	FormErectTime_NCC_Wall9	FormErectTime_NCC_Wall3	FormErectTime_NCC_Wall4	FormErectTime_NCC_Wall5	FormArea_Wall2	FormErectTime_NCC_Wall1	FormErectTime_NCC_Wall2	FormArea_Wall10
Rework cost	Mix3_NCC_extCost	Volume _Wall2	ReworkRate_NCC_Wall2	Volume_Wall1	ReworkRate_NCC_Wall1	Mix4_NCC_extCost	Volume_Wall10	ReworkRate_NCC_Wall10	Volume_Wall3	ReworkRate_NCC_Wall3
Additional cost impact	PlaceRate_NCC_Wall1	VibratorQuant_Wall1	PlaceRate_NCC_Wall4	VibratorQuant_Wall4	PlaceRate_NCC_Wall2	VibratorQuant_Wall2	PlaceRate_NCC_Wall3	VibratorQuant_Wall3	PlaceRate_NCC_Wall5	VibratorQuant_Wall5

Table 26: KPI Monte Carlo results

Name	Graph	Min	Mean	Max	5%	95%	Errors
Overall NCC Material cost		1564110	1586263	1609153	1571455	1601068	0
Overall SCC Material Cost		1938843	1938843	1938843	1938843	1938843	0
Slabs NCC Material cost		1080476	1098133	1115643	1084175	1112116	0
Slabs SCC Material Cost		1330338	1330338	1330338	1330338	1330338	0
Columns NCC Material cost		375013.80	378922.90	382832.30	375404.40	382441.30	0
Columns SCC Material Cost		470576.80	470576.80	470576.80	470576.80	470576.80	0
Walls NCC Material Cost		107285.4	109206.2	111154.9	107819.4	110598.9	0
Walls SCC Material Cost		137928.8	137928.8	137928.8	137928.8	137928.8	0
Slabs / Total cost difference		20676.84	189641.5	370860.4	117661	261001.8	0
Columns / Total cost difference		74868.6	78787.7	82706.59	75260.4	82314.59	0
Walls / Total cost difference		95551.67	97505.23	99430.89	96108.97	98895.09	0
Overall / Total cost difference		197617.9	365934.4	546240.9	294096.3	437531.6	0
Overall NCC Placement labour cost		39599.38	39599.38	39599.38	39599.38	39599.38	0
Overall SCC Placement labour cost		8297.915	8297.915	8297.915	8297.915	8297.915	0

Slabs NCC Placement labour cost		20670.1	20670.1	20670.1	20670.1	20670.1	0
Slabs SCC Placement labour cost		3895.23 5	3895.23 5	3895.235	3895.23 5	3895.23 5	0
Columns NCC Placement labour cost		8263.20	8263.20	8263.20	8263.20	8263.20	0
Columns SCC Placement labour cost		2248.08	2248.08	2248.08	2248.08	2248.08	0
Walls NCC Placement labour cost		10666.0 8	10666.0 8	10666.08	10666.0 8	10666.0 8	0
Walls SCC Placement labour cost		2154.6	2154.6	2154.6	2154.6	2154.6	0
Overall NCC Formwork cost		311486. 8	435670. 9	572320.8	387382	484594. 6	0
Overall SCC Formwork cost		410213. 4	523200. 6	638753.4	474397. 5	571831	0
Slabs NCC Formwork cost		219129. 9	343314	479963.8	295025	392237. 7	0
Slabs SCC Formwork cost		230326. 8	343314	458866.8	294510. 9	391944. 4	0
Columns NCC Formwork cost		13301.1 3	13301.1 3	13301.13	13301.1 3	13301.1 3	0
Columns SCC Formwork cost		13301.1 3	13301.1 3	13301.13	13301.1 3	13301.1 3	0
Walls NCC Formwork cost		79055.8	79055.8	79055.8	79055.8	79055.8	0
Walls SCC Formwork cost		166585. 5	166585. 5	166585.5	166585. 5	166585. 5	0
1 / TOTAL CP TIME SAVING [d]		- 19.3129 6	-13.9375	-8.450515	- 16.1137 3	-11.778	0

Overall NCC Rework cost		3911.629	3967.024	4024.272	3930.007	4004.044	0
Slabs NCC Rework cost		2702.618	2746.791	2790.601	2711.914	2781.755	0
Columns NCC Rework cost		937.53	947.31	957.08	938.51	956.10	0
Walls NCC Rework cost		268.1263	272.9263	277.7959	269.461	276.4065	0
Overall / Other costs implication		-65037.36	-38907.44	-30425.8	-46203.23	-35865.39	0
Slabs / Other costs implication		-49171.01	-23041.08	-14559.45	-30336.87	-19999.03	0
Columns / Other costs implication		-5903.76	-5903.76	-5903.76	-5903.76	-5903.76	0
Walls / Other costs implication		-9962.595	-9962.595	-9962.595	-9962.595	-9962.595	0
Overall time		-19.31296	-13.9375	-8.450515	-16.11373	-11.778	0
Time saving on slabs		-11.25046	-5.875	-0.3880146	-8.051226	-3.715505	0
Time saving on columns		-3.00	-3.00	-3.00	-3.00	-3.00	0
Time saving on walls		-5.0625	-5.0625	-5.0625	-5.0625	-5.0625	0

APPENDIX E – RISK CLASSIFICATION AND MITIGATION

The following table shows the risk register discussed in Chapter 7. The classification of risks into different types and a possible mitigation action has been proposed for each risk. This is not the only possible mitigation strategy, but it is the strategy considered for the investigated case study.

Table 27: Risk classification and mitigation

Rank	Risk	Type	Possible mitigation action
Class 1	Lack of expertise on site	Strategic risk, Project risk, Technical risk, Reputation risk	Run supervision skills development programs prior to the construction phase of the project
	Formwork Failure	Project risk, Environmental risk, Reputation risk, Safety risk	Subcontract temporary works to a specialist company to transfer the risk
	Total material loss	Project risk, Environmental risk, Reputation risk, Safety risk	Mitigate through prevention of formwork leakage and/or subcontracting formwork to a specialist
	Formwork Leakage	Project risk, Environmental risk, Reputation risk, Safety risk	Seal the formwork prior to concrete casting and set deflection limits for temporary works to prevent gaps from forming between panels
	Resistance from project team due to lack of knowledge	Strategic risk, Project risk, Personal risk	Mitigate by means of personnel choice and proper information transfer prior to site establishment
	Rate of pour limits reduce time savings	Strategic risk, Project risk	Design formwork for full hydrostatic pressure and include a safety factor
	Inability to construct gradient finishes	Project risk, Technical risk, Reputation risk, Personal risk	Mitigate through test mixes prior to full scale application
Class 2	Shrinkage cracking	Technical risk, Reputation risk	Additional supervision for curing practices and use high quality curing compounds
	Inferior Material Properties	Technical risk, Safety risk	Supply SCC externally to transfer the risk to the manufacturer
	Segregation of fresh concrete	Technical risk, Reputation risk	Supply SCC externally to transfer the risk to the manufacturer
	Surface voids on finished elements	Project risk, Technical risk, Environmental risk, Reputation risk, Safety risk	Ensure clean formwork and use high quality shutter release agents
	Inability of site lab to do specification tests	Technical risk. Project risk	Reduce the risk by importing knowledge through additional personnel and skills development

Rank	Risk	Type	Possible mitigation action
Class 2	Inability to get the mix done due to moisture variation	Technical risk, Project risk, Personal risk	Supervise the moisture control on site and do moisture tests on the aggregates and fines daily before producing any mixes
	Poor quality SCC received from supplier	Technical risk, Reputation risk, Safety risk	Ensure the risk transfer is known to the supplier and execute in-situ testing during construction
	Machinery leakage due to poor sealing	Project risk, Environmental risk, Reputation risk, Safety risk	Mitigate through regular inspections and maintenance
Class 3	Lack of skilled labour	Strategic risk, Project risk, Technical risk	Run skills development programs prior to the construction phase of the project
	Slow strength gains due to high cement replacer content	Technical Risk, Project risk	Mitigate through extensive laboratory testing of trial mixes prior to the construction phase of the project
	Over performance of concrete characteristic strength	Technical risk, Project risk	Adjust the design geometry for higher strength concrete or make use of cement extenders
	Difficulties in managing the labour force size during construction	Strategic risk, Reputation risk, Personal risk	Mitigate through experience and by taking cognisance of labour leveling challenges during the scheduling of the project