

On-site application of self-compacting concrete (SCC)

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ON-SITE USE OF SELF-COMPACTING CONCRETE (SCC)

By
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of the degree Doctor of Engineering (EngD), at Loughborough University

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ABSTRACT

Self-Compacting Concrete (SCC) is a material which under its own self-weight flows to form and fill any shape, attains full compaction, without external energy input, to create a dense homogenous mass (based on Holton, 2003; The Concrete Society and BRE, 2005; Damtoft et al, 2008). It is, in respect to the history of concrete, a relatively new development, with its first UK application occurring in the late 1990s. Since then a significant amount of research has sought to understand its physical and structural properties, but there is a lack of a knowledge base on its practical application and performance in construction projects. Where it does exist, such research lacks robust and transparent data, particularly relating to the claimed attributes of the material (such as better surface finish, faster construction and lower overall costs).

Using a combination of qualitative and quantitative research methods, this research investigates the construction practices employed when pouring SCC and presents new data on its practical applications. Interviews with a range of building contractors, ranging from multinationals to small UK businesses (SMEs), show that current perceptions of SCC limit its use to specific applications because practitioners see SCC as ‘just another type of concrete’. A critical examination of these attitudes led to the identification of three distinct scenarios for the use of SCC:

1. Reactive selection: in which a particular attribute of SCC provokes its use to solve a particular problem, often as a last minute substitution for conventional concrete – the most common scenario.
2. Strategic change: in which the material is chosen on the basis of a balanced assessment of all its benefits and on the understanding that such benefits can only be attained if the contractor appreciates that there may be implications for the construction process – a rarely experienced scenario.
3. Specification: in which there is complete acceptance of SCC as a method, not just as a material; a significant amount of early project involvement with knowledge holders, such as contractors and material suppliers, optimises the construction process.

A rigorous work measurement study of live construction projects has made it possible to quantify the as-built costs of SCC for selected UK residential slab and multi-storey flat slab applications and compare this with the equivalent conventional concrete slab construction.

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The results indicate that SCC can reduce construction times of structural topping layers of residential slabs by up to 73%, and has shown that SCC can also match, if not reduce, total as-built concrete placement costs in multi-storey applications. This new data will enable contractors, designers and specifiers to better understand the practical implications of using SCC for on-site applications, thereby leading to more potential instances of its early and planned specification, hence resulting in more of its full benefits being realised.

KEY WORDS

Concrete; construction materials; self-compacting concrete; work measurement.

PREFACE

This thesis presents the culmination of four years of research undertaken to fulfil the requirements of the qualification of Doctor of Engineering. The Engineering Doctorate (EngD) programme, undertaken at the Centre for Innovative and Collaborative Construction Engineering based at Loughborough University, is the industry based equivalent of the PhD. The essence of the EngD is to solve to one or more real world industrial challenges with the focus on providing effective and viable solutions which can be taken forward and applied by industry and specifically the industrial sponsor.

Within the EngD programme the industrial sponsor, Lafarge Aggregates Ltd., play a significant role in the initial development of the research programme and provide the basis of requirements of industrial outputs.

The EngD is examined based upon a thesis, which describes the research and its subsequent findings, along with at least 3, but no more than 5, refereed papers. Research within this thesis is supported by 4 refereed papers (3 conference and 1 journal) together with a further journal paper that is currently under review.

GLOSSARY OF TERMS USED

ACT	Average Construction Time
BRE	Building Research Establishment
Brite-EuRam	Basic Research in Industrial Technology and European Research in Advanced Materials
CEMBUREAU	European Cement Association
CIJC	Construction Industry Joint Council
CONSTRUCT	Concrete Structures Group
Conventional concrete	Concrete which is required to be compacted by mechanical means
EFCA	European Federation of Concrete Admixtures Associations
ENFARC	European Federation of National Associations Representing producers and applicators of specialist building products for Concrete
EngD	Engineering Doctorate
ERMCO	European Ready Mixed Concrete Organization
GB	Ground Bearing
LNG	Liquefied Natural Gas
NHBC	National House Building Council
RS	Residential House Slab
SCC	Self-Compacting Concrete (or Self-Consolidating Concrete (North America))
SME	Small to Medium Enterprise, defined as an organisation which has less than 250 employees.
SS	Suspended Slab

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- Paper 1 –** To SCC or not to SCC? UK contractors' views
Rich, D, Glass, J., Williams, D, Gibb, A.G.F. and Goodier, C.I., "To SCC or not to SCC? UK Contractors Views", *Proceedings of SCC2010, Montreal, Canada, 26 - 29 September 2010*, 2, Kamal H. Khayat and Dimitri Feys, SCC 2010 6th Int. RILEM Symposium on Self-Compacting Concrete - 4th North American Conf. on the Design and Use of SCC., Montreal, Quebec, Canada, 26th September 2010, 647-654
- Paper 2 –** UK contractors' views on SCC in construction
Rich, D, Glass, J., Gibb, A.G.F. and Goodier, C.I., *UK Contractors' views on self-compacting concrete in construction*. Proceeding of the ICE – Construction Materials, Volume 165, Issue 4 August 2012, pages 201-210
- Paper 3 –** Developing an ideal scenario for SCC: New findings from the UK
Rich, D., Glass, J., Williams, D. and Gibb, A.G.F., "Developing an ideal scenario for SCC: new findings from the UK", *The 11th Annual International fib Symposium, CONCRETE: 21st Century Superhero*, Denton, S. and Clark, G., The Concrete Society, The 11th Annual International fib Symposium, CONCRETE: 21st Century Superhero, London, 22nd June 2009, 22-24
- Paper 4 –** SCC on site: Understanding the implications for construction operations
Rich, D., Glass, J., Williams, D. and Gibb, A.G.F., "SCC on site: understanding the implications for construction operations", *The 11th Annual International fib Symposium, CONCRETE: 21st Century Superhero*, Denton, S. and Clark, G., The Concrete Society, The 11th Annual International fib Symposium, CONCRETE: 21st Century Superhero, London, 22nd June 2009

- Paper 5** – Self-consolidating/compacting concrete: construction time and cost data from UK residential projects
ICE – Construction Materials, currently under review.

1. INTRODUCTION

This chapter acts as an opening to the research that has been undertaken during the Engineering Doctorate (EngD) programme; it sets out the background to the research, the structure of the thesis, its aim and objectives and the justification for its undertaking. The Industrial Sponsor (Lafarge UK) is discussed, their background and their rationale for involvement in the programme.

1.1 BACKGROUND TO RESEARCH

The UK construction industry has a historical reputation of conservatism and being unaccommodating of change and innovation, driving the emergence of critical reports, such as those by Latham (1994), Egan (1998) and Wolstenholme (2009), amongst others. That said, recent years have witnessed more organisations focusing on the development of new and innovative methods of construction, in a bid to improve productivity and performance. Although innovation is present within the concrete manufacturing industry, it is not consistent across all producers, with those that do, typically having a range of highly innovative materials and products, with others following behind. Innovation in concrete is not typically the result of a step change from existing design; the majority of innovations are derived from enhancing or suppressing existing, known properties. Such materials range from those that have rapid strength gain properties, the ability to bear loads two hours after placement, pervious or insulating concretes. More significant leaps have also taken place, including the development of materials with ultra high strengths in both compression and tension, which can be used to create concrete structures of a very thin section and without steel (e.g. Ductal (Armourcoat, 2013)).

Self-compacting concrete (SCC) (called self-consolidating concrete in North America) is, in the history of concrete, a relatively recent innovation. Although labelled by some as the ‘most important innovation within concrete technology for the last 50 years’ (Damtoft et al, 2008), its impact and application on site is still limited (see Table 1.4). SCC is defined as a material which under its own self-weight flows to

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form and fill any shape, attains full compaction, and without external energy input, creates a dense homogenous mass (based on Holton, 2003; The Concrete Society and BRE, 2005; Damtoft et al, 2008). Originating in Japan, knowledge of the material has spread globally since its first application in the late 1980's, in the construction of the Akashi Kaiko Bridge (Concrete Society and BRE, 2005). Development and application has now been carried out in many countries with use steadily increasing. Within the UK at Lafarge, SCC accounted for 6.1 % of ready-mixed concrete produced in 2011 up from 4.3 % in 2007 (Lafarge, 2012). The proportion supplied by other readymix suppliers is likely to be less than this as Lafarge has spent considerable time and effort in its commercialisation. Although this appears low, the variety of applications where the material has been used has broadened, from general builders in the construction of small domestic extensions to large multi-national organisations utilising the material in structural frames and external facades for architectural purposes, in both ready-mixed and precast forms.

Physical and structural performance has formed the nucleus of previous SCC research; whilst important in helping material development, the study of its implementation and application in construction has been neglected. Utilisation has increased steadily, but there has been little or no quantification of the bearing that this innovative material can have on on-site construction processes. Many researchers have suggested or identified improvements or advantages that could be brought to the construction process through the application of SCC; however these claims have generally been without any clear, robust or verifiable evidence or justification.

The need for research into the improvements or advantages SCC can bring to construction has not diminished; however, the papers presented at the 6th International RILEM symposium on Self-Compacting Concrete (Khayat and Feys, 2010) held in 2010 show that most of the research on SCC is still focused on its physical properties and structural performance. The research presented in this thesis concentrates on SCC's role as a construction innovation, current construction practice and the development of construction methods all within the on-site environment. Through the process of fulfilling and addressing research gaps, the focus has been directed towards those organisations and individuals who undertake – and are responsible for – the practical aspects of construction. It is this approach that will enable the effect of SCC

to be ascertained, in respect to changes that need to occur within supporting structures of organisations prior to and during construction. The overarching focus will therefore be the role and effect of SCC as a construction innovation in onsite construction procedures and processes. Its use in the factory-based pre-cast concrete sector is already well documented (Concrete Society and BRE, 2005; Goodier, 2003; Henderson, 2000), so will not form part of this research, however parallels and comparisons will need to be drawn.

1.2 THESIS PLAN

This thesis documents the work undertaken to achieve the qualification of Doctor of Engineering and is structured as follows:

Chapter 1

This chapter serves to introduce the research project, establishing the background to its undertaking and the review of core literature to determine existing levels of knowledge. The primary research aim is also discussed along with its supporting objectives, culminating in the identification of the sponsoring company's role and interest in the research.

Chapter 2

A number of distinct research methods have been applied within this research to address the aim and objectives set out in Chapter 1. This chapter documents those methods, providing an understanding of their application and a justification for their use.

Chapter 3

The majority of results revealed throughout the duration of the project have been disseminated through several papers (listed on page xvi), but it is the objective of this chapter to bring these findings together to reveal a concise synopsis of the project's major findings. Throughout this chapter the findings have been interrogated to provide a wider understanding in relation to the overarching research aim.

Chapter 4

This chapter forms a review of the project, aligning the findings and their interpretations with the initial aim and objectives, to determine its success in satisfying these. Recommendations for Lafarge, the wider industry and academia have been identified, including recommended future research directions and areas.

Appendices

The appendices contain all the papers published from the work thus far, along with other supporting documentation, referred to throughout this thesis.

1.3 THE DEVELOPMENT AND APPLICATION OF SCC

1.3.1 INTRODUCTION

SCC has been defined in many ways by many authors, however the definition set out in Section 1.1 will be the agreed definition used throughout the thesis. This section explains the development of SCC, from its inception to its expansion throughout the global construction industry. It will focus on the UK development of the material, existing perceptions of the material, the barriers and issues related to its uses, how it is believed to improve the construction process, before identifying gaps in existing research and literature. Paper 4 in Appendix D, “*SCC on Site: Understanding the Implications for Construction Operations*” (Rich et al, 2009) details this background in greater depth.

1.3.2 INITIAL DEVELOPMENT

During the early 1980’s Japan’s construction industry was searching for a solution to aid the delivery of durable concrete structures, which is inextricably linked to quality in the construction process (Okamura and Ouchi, 2003). It is accepted that compaction is crucial in achieving durable concrete (Goodier, 2003; Concrete Society and BRE, 2005), however numbers of competent skilled operatives to carry out the

compaction process were also seen to be in decline (Holton, 2004). Coupled to this issue it had also been documented that a significant proportion of concrete placed during insitu applications is “never fully compacted” (Concrete Society and BRE, 2005), subsequently resulting in strength, durability and aesthetic shortcomings.

The solution in Japan, at that time, was to create a concrete that was significantly less dependent on labour skill by removing the need for compaction (Holton, 2004; The Concrete Society and BRE, 2005), the result of which was an SCC[†].

Japanese prototypes were first completed in 1988 using materials readily available to conventional concrete producers and derived from existing concretes, designed for operations where compaction was impractical, such as underwater applications and piling (Bartos and Grauers, 1999). These initial prototypes were deemed to be satisfactory when compared to the performance properties required of conventional concretes (Okamura and Ouchi, 2003). However, since that time, the body of knowledge on SCC has matured and its defining properties are well understood and linked to its fluid state, including:

- **Flowing ability:** The flowing action of the SCC under its own weight to completely fill the form into which it has been placed, without leaving voids.
- **Passing ability:** The material’s ability to pass embedded elements and through areas of congested reinforcement without blocking or detrimental effects on homogeneity. Passing ability is dependent on correct aggregate size selection.
- **Resistance to segregation:** The materials ability to keep its coarse aggregates in suspension, avoiding settlement which is traditionally expected with a fluid product. Suspension of coarse aggregates within the concrete paste is fundamental to achieving a homogenous product (Gaimster and Gibbs, 2001; Goodier, 2003; RILEM Technical Committee, 2006).

[†] Note that the US term for SCC is self-consolidating concrete.

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The preceding core fundamental properties of SCC can only be achieved through a delicate proportioning of constituents, and as such there is no single universal mix design approach. Rather, there are three generic approaches commonly applied to achieve these properties: powder, viscosity-modifying admixture (VMA) or combined (De Schutter et al, 2008; EFNARC, 2006).

- **Powder:** The aim of this approach to achieve self-compactability and workability through the paste content of the mix, as well as the principles of rheology and particle packing (De Schutter et al, 2008). Particle packing involves the microscale level of concrete looking at the volumetric proportioning and interaction of particles within the mix. The concrete is proportioned involving the two entities, aggregates and paste. Aggregates are granular materials, which lack fluidity and are subject to varying degrees of particle interlock, depending upon the aggregate type and its grading. The paste consists of fines, cement and additional fillers (such as limestone fines, ground granulated blast furnace slag and pulverised fuel ash), which acts as a 'lubricating' coat that enables deformation, whilst adequately supporting the aggregates in a state of suspension (De Schutter et al, 2008; Kyhayat, 1999). As the volume of paste in the mix increases, the inter-particle spacing of aggregates also increases. This increases the material's deformability by reducing the potential for particle (aggregate) interaction.
- **Viscosity Modifying Admixture:** VMAs work on the principle of retaining cohesion and stability within a concrete mix by the addition of a specific admixture. In SCCs they are used in conjunction with a high water/cement ratio and high water/powder ratio (De Schutter, 2008). VMAs operate by changing the concrete's structure at a microscopic level, increasing viscosity, yet inhibiting flow, with the combined effect of improving stability and reducing potential for segregation (Lachemi et al, 2004; Khayat, 1998).
- **Combination:** This utilises elements from both powder SCC's and VMA SCC's; particle packing, VMA's and where necessary the addition of superplasticisers. While in the powder approach the aim is to utilise the

increase paste volumes to facilitate flow and workability, superplasticiser can be added in circumstances where this is not viable (EFNARC, 2006). The VMA is used to ensure robustness of the mix (De Schutter, 2008; Lachemi, 2003, Khayat, 1999).

Whilst these are three approaches to the creation of a viable SCC there are significantly more variations when individual mix designs are considered. Variation is encountered due to the sensitive nature of SCC mixes (Goodier, 2003), where slight changes in constituents can have dramatic effects on both fresh and hardened performance (Concrete Society and BRE, 2005). Due to commercial sensitivity, it is not possible to provide the specific mix designs and constituents of the SCCs produced and supplied by Lafarge, however a significant number of academic papers catalogue and identify specific mixes and mix variations dependent on locations and materials (e.g. Bogas et al, 2012; Dinakar et al, 2013; Herbudiman and Saptaji, 2013). Work by Domone (2006) is particularly relevant as it compares and critiques 51 SCC mix designs via the critical analysis of case studies.

The characteristic differences between a conventional concrete and an SCC mix design is illustrated by Gaimster and Gibbs (2001) (Figure 1.1).

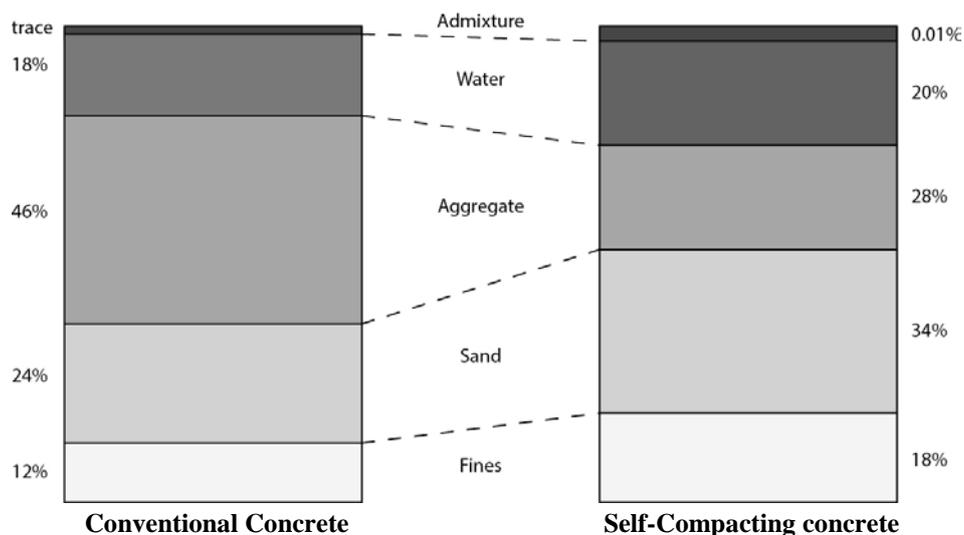


Figure 1.1 Differences between typical mix design constituents in a conventional concrete and SCC (adapted from Gaimster and Gibbs (2001))

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Figure 1.1 shows the changes in typical material proportions between conventional concrete and SCC, the latter containing an increase in fines (typically cement and other fine powders such as limestone fillers and/or cement replacements) and sand contents, a larger percentage of admixtures and water and a significantly lower fraction of coarse aggregates. An SCC is therefore typically less coarse in texture when in its fresh state and appears to be much more ‘liquid’. It is the paste content, particularly the fines, that aids the self-compacting action (see the preceding types of SCC), with a fundamental constituent being the cement. Analysis of SCC mix designs against British Standards for conventional concrete design demonstrates the significant increase in cement content required to create a viable SCC. BS 8500 (BSI, 2006) for a C40/50 strength class concrete states the minimum cement content required to be 340 kg/m³. For SCC, the lowest cement content presented by Domone (2006) was 470 kg/m³ (to achieve a 28 day strength of 50-60 MPa). Of all the 68 cases investigated, the lowest fines content was 385 kg/m³ (incorporating Portland cement and pulverised fuel ash (PFA), achieving a compressive strength of 41 MPa (see Appendix F for further mix details).

The distinct change in material properties between conventional concretes and SCC also demands a change in approach to design, production and application. As a relatively ‘new’ material, with respect to the history of concrete (Damtoft et al, 2008), resistance and hesitation existed in the understanding of how approaches were required to develop. It was in response to this that The Concrete Society and BRE’s Technical Report (TR) 62 (2005) was created to help bridge the knowledge gap between conventional and SCC utilisation. In 2002, prior to TR 62, the document ‘Specification and Guidelines for Self-Compacting Concrete’ (EFNARC, 2002) had been created as a stop-gap before the fuller integration of SCC into British and European standards, which were also revisited in 2005 (SCC European Research Group, 2005). TR 62 (The Concrete Society and BRE, 2005) and the European Guidelines (SCC European Research Group, 2005) identified specific changes to be followed when using SCC. A key issue was the fundamental differences that existed between material properties which drove the additional testing requirements (Gibbs, 2004; Day et al, 2005). The methods for testing along with the properties that are defined by these tests are identified in Table 1.1.

Table 1.1 SCC fresh property tests to ensure suitability (Day et al, 2005, SCC European Research Group, 2005, Gibbs, 2004, Bartos and Grauers, 1999)

Characteristic Property of SCC	Test
Flowing ability	Slump Flow
Passing ability	L – Box
	J – Ring
Resistance to segregation	Sieve Stability
Viscosity	V – Funnel

Table 1.1 lists the range of tests that are required to ensure the fresh performance of an SCC - a significantly more demanding test regime compared with conventional concrete, which typically relies upon the slump test to BS 12350-2:2009 (British Standards Institute, 2009).

Since the publication of TR 62 (The Concrete Society and BRE, 2005) and the European Guidelines (SCC European Research Group, 2005), further work has been undertaken and SCC is now represented within the European and British Standards, EN 206 – 9:2010 (BSI, 2010).

Following on from questions surrounding the testing of SCC, a second area which requires consideration is formwork pressure due to contradictions in literature (when SCC is used in vertical applications). Early work in this area identified that the level of pressure encountered was dependent on a number of factors: rheology, thixotropy, method and rate of placement (The Concrete Society and BRE, 2005; SCC European Research Group, 2005). In response to this it was advised that full hydrostatic head should be assumed for formwork design purposes (The Concrete Society and BRE, 2005; SCC European Research Group, 2005). However, research has shown Lange (2007) that full hydrostatic head may not necessarily be encountered (Lange, 2007; Vanhove and Djelal, 2002) and that the need to design formwork systems to support such pressures may not be necessary. Notwithstanding this, more research is required to determine an increased understanding of its influencing factors, to determine which characteristics are applicable in which circumstances. Recent research demonstrates that changes in constituent materials (such as type and content of powders and aggregates) or placement methods (such as fill and placement rates and methods) can

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have varying effects on formwork pressure (Kim et al, 2012; McCarthy et al, 2012; Billberg, 2006).

1.3.3 GLOBAL GROWTH OF SCC

Europe, in particular Scandinavia and Sweden, was the first region outside Japan to begin development of SCCs (Holton, 2004). Consequently development spread throughout the rest of Europe, initially with other Scandinavian countries, France and the UK all becoming key developers, with a number of other major European countries undertaking some level of research (Holton, 2004). It is difficult to determine who is currently the world leader in the development and use of SCC - Damtoft et al (2008) suggests Denmark: in 2008, 25% of Denmark's ready-mix concrete and nearly all of its pre-cast concrete was SCC. This is a considerably higher proportion than in the UK market, where SCC accounted for approximately 6% of Lafarge's 2011 output (Lafarge, 2012).

Historically, the development of SCC began within academia in Japan with the first reference to a modern SCC in 1992 (Ozawa, 1992). Development transfer from academia to the research departments of large construction companies followed (Goodier, 2003). Industrial development of SCC led to the commencement of major construction projects utilising and employing SCC, moving the material from design to reality (Goodier, 2003). Early projects which adopted SCC included the construction of the Akashi Kaiko Bridge anchor blocks (The Concrete Society and BRE, 2005) and part of a large LNG (Liquid Natural Gas) tank owned by the Osaka Gas Company (Kitamura, 1999).

Initial research and development in Europe was driven by the creation of several task groups, such as the RILEM Technical Committee, who were set up to review current SCC technology. Swedish trials led to the creation of the Brite-EuRam project group, tasked with establishing a vibration-free production system in order to reduce the cost of insitu concrete construction (Goodier, 2003). European development continued with research being led by the University of Paisley, including several European trade

groups[‡], to address the lack of test methods and standards (Holton, 2004; Goodier, 2003). The result was the specification and guideline document, “*The Guidelines for Self-Compacting Concrete*” (2005). The guidelines covered details from engineering properties and constituent materials to the specification and placement of SCC. Following this work began on developing a supplement for European Standard EN 206 (2000) to address the additional concerns regarding the conformance of SCC with existing standards. The standard was subsequently published in 2010 as “*EN 206 Part 9: Additional Rules for Self-compacting Concrete*” (2010).

1.3.4 SCC IN THE UK

Within the UK, at the time when SCC was first introduced, the construction industry was exhibiting symptoms similar to Japan at the time of initial development of SCC. Egan’s Rethinking Construction report (1998) stated that there was a shortage of trainees within the industry, which could lead to future skills shortages, which coincided with later work that highlighted issues of substandard concrete due to poor workmanship (Goodier et al, 2002).

As in Japan, progress in the UK towards application began with academic research at the University of Paisley and University College London, and then by major construction material suppliers (Goodier, 2003). One of the first major practical applications of SCC was in 2000 on the Millennium Point project in Birmingham to construct columns encompassing complex and congested reinforcement (Henderson, 2000). The publication of ‘*Technical Report No. 62: Self-compacting concrete, a review*’ by the Concrete Society and BRE (2005), was seen as major step towards broader industry acceptance, when combined with the previously published ‘*Guidelines for Self-compacting Concrete*’. Since its introduction into the mainstream construction market, the use and application of SCC has slowly increased. SCC is currently used in a number of markets throughout the UK; in particular the housing

[‡] bibm - Bureau International du Béton Manufacturé, CEMBUREAU – The European Cement Association, EFCA – European Federation of Concrete Admixtures Associations, ENFARC – European Federation of National Associations Representing producers and applicators of specialist building products for Concrete, ERMCO - European Ready Mixed Concrete Organization.

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sector, ground works, concrete frames, major civil engineering projects and pre-cast concrete manufacture. The volume of SCC produced has also shown a steady increase over the past few years with the trend is expected to continue (figures and market information provided by Lafarge Aggregates Ltd.).

Table 1.2 Volume of SCC produced by Lafarge as a percentage of total concrete volume (source Lafarge Aggregates Ltd.)

Year	Percentage of total concrete volume produced
2011	6.1
2010	5.6
2009	4.1
2008	4.3
2007	4.3

Table 1.2 illustrates a trend in increasing manufactured volumes of SCC by Lafarge UK. Whilst these figures only represent the volume supplied by one producer, it should be noted that all of the UK's major concrete manufacturers have created their own branded SCC products, including Cemflow (Aggregate Industries, n.d.), Evolution (Cemex, n.d.), Duraflow (Hanson, n.d.), Topflow (Tarmac, n.d.) and Agilia (Lafarge, n.d.). If the increase in the volume of SCC produced by Lafarge is taken to be representative of the experience of all UK concrete producers (due to the lack of available market wide figures) along with the investment and availability of SCC from major suppliers, it suggests that there is a significant interest in the potential that SCC can offer. It should also be noted that this rise has occurred during a significant downturn in output in the UK construction industry. If the figures provided by Lafarge (2012) are considered in the context of the total volume of all types of concrete produced across the industry (Figure 1.2) (whilst a significant assumption), the scale of this increase appears more dramatic as the ready-mix industry has undergone a particularly significant contraction.

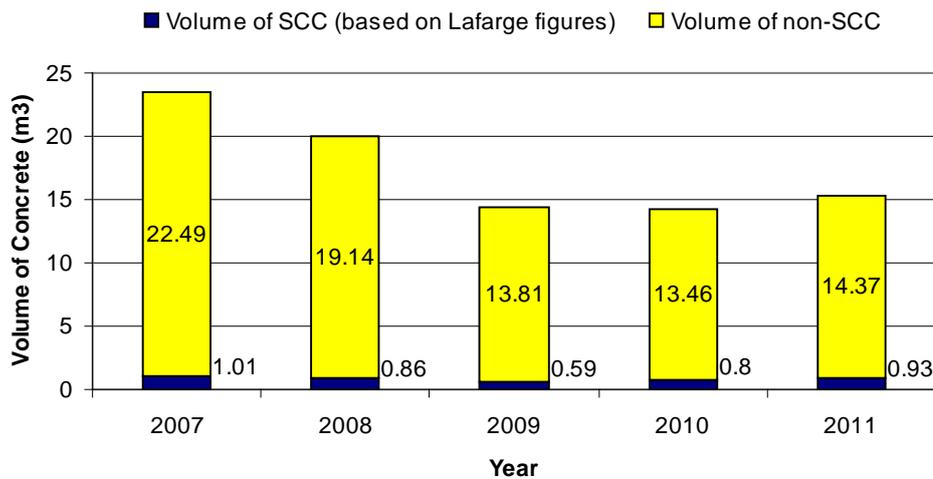


Figure 1.2 Total volume of concrete produced across the concrete industry (Mineral Products Association, 2013) with corresponding volumes of SCC in relation to Lafarge percentages (Table 2.2)

With the volume of SCC produced in 2011 nearing its previous high of 2007, a total volume decrease of nearly 35% demonstrates an increase in market share from 4.3% to 6.1%.

1.3.5 TYPICAL APPLICATIONS AND INDUSTRY PERSPECTIVES OF SCC

Previously, SCC was seen as specialist material, only suitable for one off occasions, which has yet to be fully accepted (Holton, 2003; Clear, 2006). However this generalised view is beginning to change, as evidenced through work by a Danish consortium working towards making SCC the most widely used concrete (Damtoft et al, 2008).

The Concrete Society and BRE's (2005) Technical Report No. 62 presents examples demonstrating the use of SCC in a range of 'routine' construction applications; it has also been used on a number of high profile projects in the UK such as The Collection, Lincoln (Figure 1.3) and The Hepworth Gallery, Wakefield (Figure 3.2).



Figure 1.3 The Collection, Lincoln (photo by Ian Carrington).

Application of SCC in these projects was typically based upon specific characteristics - its ability to aid the creation of complex and detailed facades at The Collection (Grimes, 2005), at The Hepworth as an architectural and structural tool and in Leeds on the Echo 2 residential project as a replacement for conventional concrete (Williams, 2008). While these projects extended the use of SCC from a specialist material to one that is more widely accepted, it has nevertheless tended to be selected as a replacement for conventional concrete (when it cannot fulfil a particular role), rather than on its own merits. There is evidence that specific attributes of SCC, such as its ability to fill complex forms and flow through congested reinforcement, make it a helpful problem-solver on-site, but this single attribute approach does not fully reflect its proclaimed potential.

Views are beginning to alter on SCC and its position as a specialist material. It can be identified that this stance has developed as a result of a lack of knowledge and the fact that SCC tends to be more expensive in terms of cost per sales by volume of material (m^3) (compared to conventional concrete) has not helped; it is often referred to as being 'too expensive' (The Concrete Society and BRE, 2005). The UK economic downturn further hindered this as conventional concrete costs, unlike SCC prices, decreased. There is already an awareness that SCC should not be considered on first-cost alone because of the potential advantages it can bring to construction (Holton, 2003; Concrete Society and BRE, 2005). This approach clearly describes SCC as a

method of construction rather than as a pure material and the author acknowledges that Holton (2003), Concrete Society and BRE (2005) (along with Okamura and Ouchi, 2003) were the first to bring this notion to light. However as stated in Section 1.3.6, there remains a lack of rigorous and documented evidence to underpin and reinforce their original proposition. The concept of method over material is thus revisited extensively within this thesis throughout Section 4.4, and in Paper 1 (Appendix A) to deliver original research evidence to analyse, extend and substantiate this concept.

SCC use in the UK has seen a steady increase, whilst pre-cast use has remained relatively constant, on-site insitu use, with respect to Lafarge volume figures, has grown. SCC supply in 2007 was 4.3 % of total volume and rose to 6.1 % in 2011, whilst total volume has reduced by approximately 700,000 m³ (Lafarge, 2012).

The use of SCC within Lafarge has increased, not just in major projects, but also in projects which make use of its architectural properties for aesthetic applications (Grimes, 2005; Williams, 2008) and in cases where it has been used to solve problems (Holton, 2003). This is evidence of the widening of uses from specialist applications where fine finishes are required to those which have traditionally been completed using conventional concretes. SCC has been readily used for the construction of flooring systems, whether ground bearing slabs, suspended slabs as part of composite systems and as topping layers. SCC has also seen use in foundations, walls, retaining walls, columns and most applications where non-specialist conventional concretes are used (Lafarge, 2012).

SCC uptake in the Pre-cast Industry

Although this project is primarily focused on the application of SCC in in-situ applications, the precast industry presents a successful case study for the implementation of SCC. SCC is currently widely used within the precast sector with some of the larger UK precasters using SCC in approximately 60% of their products (Cussigh, 2007; Holton, 2004), whilst some precasters exclusively use SCC (Holton, 2003).

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The driving factors behind the adoption of SCC in the precast industry stem from the proposed improvements listed in publications on the use of the material in in-situ on-site applications (Concrete Society and BRE, 2005; Goodier, 2003 and Henderson, 2000). Similar benefits have been espoused to be viable in precast; Skarendahl (2003) believes the application in precast is due to the culture of closely-controlled materials management in the precast manufacturing environment, which is in direct contrast to the in-situ on-site environment (featuring multiple firms and fragmentation of roles and activities). Fragmentation on this level can result in a lack of continuity throughout an organisation and a lack of knowledge and experience transfer to similar projects (Construction Task Force, 1998). Precast offers the continuation of teams, based in a consistent environment, thereby resulting in an improved implementation process and the development of experience when faced with change (Skarendahl, 2003). Walraven (2003) believes there to be energy savings, improved life span of formwork, reducing maintenance costs and finally a reduction in labour absence. That said, there are no established reasons why SCC should not be viable in in-situ on-site construction, offering similar improvements, but research to explore the practicalities of using SCC on site seems lacking in the literature.

Sustainability credentials of SCC

Sustainability represents one of the most prevalent concerns and topics for discussion within the construction materials industry and the construction industry as a whole. The most significant issue that is raised when discussing construction materials and their sustainability credentials or impacts, is that of CO₂ emissions, primarily linked to the production of cement, a key constituent of all concrete (Frost, 2006; Lay and Gaimster, 2006; Nixon et al, 2004). Sustainability however, is not only concerned with material aspects, but is described as have three influencing pillars of social, economic and environmental effects (Damtoft et al, 2008). Construction and construction material manufacture influences all of these three aspects at varying levels, through production, construction and operation (Damtoft et al, 2008). Defining specific material sustainability credentials cannot therefore be fairly or suitably addressed through the focus on one specific aspect of that material's life span.

With respect to embodied energy and emissions from cement production, steps have been taken within the concrete industry to achieve significant reductions alongside the development and implementation of cement replacement materials to reduce demand (Sustainable Concrete Forum, 2012). Since the establishment of the 1990 baseline for the reduction in emissions Frost (2006) reports that the cement industry has reduced CO₂ emissions by 21.2% and energy consumption by 24%. More recent figure published by the Mineral Product Association (2013) has stated that CO₂ has been reduced by 55% from 1990 base levels.

It should be noted that while cement is responsible for the most significant production of CO₂ in concrete, it is only one of many constituents. However, the main issue with SCC is that it requires an increased cement content (Gaimster and Gibbs, 2001) when compared to conventional concrete, as well as the use of admixtures (see Figure 1.1 and Section 1.3.2), for most mix designs (De Schutter et al, 2008). The variance in cement and cement replacement content ranges from 385 to 635 kg/m³, with the highest portland cement content reported being 607 kg/m³ (see Appendix F) without any replacements (Domone, 2006).

When exploring the wider sustainability credentials of concrete as a material, more considerate approaches to aggregate sourcing coupled with the wider use of recycled or secondary aggregates have been employed (Sustainable Concrete Forum, 2012). However, the ability to use replacement materials with conventional concrete, to reduce their environmental footprint (Bouzoubaa and Lachemi, 2001; Kou and Poon, 2009), may not be as successful with SCCs due to their sensitivity. The incorporation of cement replacements, recycled or secondary aggregates may be more difficult in SCC compared to conventional concretes (Bouzoubaa and Lachemi, 2001). Understanding the sustainability impacts due to the manufacture of SCC when compared to conventional concrete is beneficial as it provides a foundation for the understanding of the 'costs' associated with the increased cement contents and difficulties of using replacement materials. The sensitivity to cement replacements and increased cement content of SCCs will result in an increase of embodied CO₂ compared with conventional concretes (for its cradle to gate life).

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Damtoft et al (2008) however, stated that it is necessary when considering the sustainability credentials of SCC to examine the broader influence of its use, in reference to the three pillars of sustainability. By considering a broader approach, perhaps through a full life-cycle assessment (LCA), it would be possible to create a more balanced appraisal of SCC's environmental footprint. A full LCA (British Standards Institution, 2006) would present the opportunity to consider and explore the potential improvements that have been listed in literature which present opportunities to make significant changes, such as shorter construction programmes, costs savings or the exposure to risks (see Table 1.3). Simply comparing on the basis of a single environmental impact category would not present the full holistic picture of SCC with regards to sustainability.

The ability to carry out a fair assessment of the sustainability of SCC compared to conventional concrete requires a holistic assessment that considers the effects of all impacts both positive and negative that SCC brings to a construction project. The scale of an assessment of this form would be significant; however it would require the clarification and robust determination of what the improvements and issues of on-site SCC use are. The lack of this evidence (described in the following section) creates a barrier to the completion of full and comprehensive assessment and is therefore outside of the scope of this research. Outputs from this research are considered to be an incremental step towards the sponsoring company or wider industry in completing a full LCA analysis.

1.3.6 THE BENEFITS OF AND BARRIERS AGAINST USING SCC

SCC offers a number of benefits that are linked to its properties, i.e. flowing ability, passing ability and segregation resistance (Skarendahl and Billberg, 2006), which are outlined here and described in more detail in 1, in Appendix A – “*SCC on site: Understanding the implications for construction operations*” (Rich et al, 2009).

In terms of physical and structural advantages, it is possible to achieve more complex and innovative structures with SCC than previously possible with conventional concrete, due to its ability to flow, fill formwork and compact without external energy

input (Goodier, 2003; Grimes, 2005). Improved quality, in respect to homogeneity, can result in improved durability and resistance to degradation (Skarendahl and Billberg, 2006; Gaimster and Gibbs, 2001; Henderson, 2000;), it is also possible to improve surface appearance with a reduction in defects such as blowholes and honeycombing (Goodier, 2003; Gaimster and Foord, 2000).

As a consequence of the utilisation of SCC there are a number of advantages for the on-site team. The first is the ability to reduce and remove plant traditionally associated with concrete construction and subsequent effects. Compaction requires the use of vibrating tools, which can cause hand arm vibration syndrome (HAV) due to prolonged exposure (Walraven, 2003). SCC does not require vibration; its associated plant, such as compressors, hoses and pokers, can also be excluded from site, providing secondary benefits of the removal of site hazards (Skarendahl, 2003) and reducing manual handling (Damtoft et al, 2008). Further benefits such as reducing operative numbers, skill levels and improving final quality have also been cited (Holton, 2003; The Concrete Society and BRE, 2005).

Any economic advantages with SCC are essentially linked to changes to construction processes; the ability to reduce the number and skill level of operatives achieved through the removal of the compaction process (Damtoft et al, 2008; Goodier, 2003; Bernabeu, 2000). In tandem, this presents an opportunity to also make savings in plant and equipment, where quality has been improved remedials will also be reduced (Grimes, 2005; Gaimster and Foord, 2000).

However, despite the reported benefits associated with SCC, there has been relatively little research carried out to establish the extent of these benefits or establish their credibility. Table 1.3 outlines the work that has been completed, but it is far from robust; there is a lack of detail in these sources about the derivation of the data and many simply cite values from elsewhere without providing any detail.

While there are extensive advantages linked to the use of SCC there are also a number of issues and barriers which may hinder its successful application and use. SCC requires a change from conventional concrete approaches in terms of on-site methodologies and in terms of manufacturing and quality assurance. SCC is more

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sensitive to variations in constituents and mix design (Goodier, 2003) creating more stringent demands for producers. Producers are required to demonstrate increased vigilance in the monitoring of processing and material storage (Concrete Society and BRE, 2005). It is also extremely rare for a single mix design to be used in a multitude of locations, requiring producers to create local mix designs. Therefore any publicly-available mix designs (Section 1.3.2) should be considered only broadly indicative of current practice and should only be used for guidance (Skarendahl, 2003). It is not just mix design that is affected but also the delivery and manufacturing processes themselves when compared to conventional concrete. The fluid nature of SCC requires that delivery load volumes are reduced to avoid the loss of material during transportation from readymix concrete plants to construction sites, 5m³ carried in a 6m³ capacity truck (Lafarge Agilia™ Product Development Manager[§]). The process of manufacturing also adds additional demands; conventional concrete can be ‘dry’ batched where the consistent materials are loaded directly into the delivery truck and mixed on route to site. In circumstances where the SCC mix design is particularly sensitive it is required to be ‘wet’ batched where the concrete, in its delivered form, is created prior to discharge into the truck for delivery, thus placing additional demands on the material supplier (Lafarge Agilia™ Product Development Manager[§]).

Placement is an area where a number of advantages have been declared, however there are challenges here which can have detrimental effects on the quality of the concrete. Key to good quality SCC, according to Holton (2003), is minimising the entrapped air, which otherwise would lead to poor surface finish and can detrimentally affect concrete strength. The most suitable method of placement for SCC has been identified as via low-level inlets allowing concrete to rise ‘as a homogenous mass’ (Holton, 2003) removing the issue of ‘freefall’, which is a cause of air entrapment and segregation. Skips, a traditional method of placing concrete, can cause issues of segregation due to skip movement and vibrations and the leakage of fines (Holton, 2003). Due to the nature of SCC, i.e. its ‘flowability’ (Gaimster and Gibbs, 2001), forming of vertical upstands are inherently difficult, alongside achieving finishes on unformed surfaces (Goodier et al, 2002) as a result of the reduced surface bleed of SCC (Holton, 2003).

[§] Information provided through internal company discussions

Determination of the suitability of SCC for a particular application, as with all concrete, is fundamental to the final quality of a concrete element. The characteristics of SCC, 'Flowability', 'Resistance to Segregation' and 'Passing Ability' (Gaimster and Gibbs, 2001), make it unsuitable for traditional acceptance test methods (Bartos and Grauers, 1999), in fact several tests are needed to check the suitability of an SCC (Day et al, 2005). In response, a number of tests for defining the primary characteristics of SCC are identified in key documents (Concrete Society and BRE, 2005; European Guidelines for SCC, 2005) (see also Table 1.1).

The differences between conventional and SCC mix design (Section 1.3.2) create a number of potential problems when SCC is used in place of conventional concrete. Mechanisms which govern the performance of SCC are not completely different to conventional concrete, primarily hydration (Concrete Society and BRE, 2005), however the higher fines content and the viscosity of SCC creates a denser microstructure, which can have both positive and negative effects (The SCC European Project Group, 2005, Concrete Society and BRE, 2005, Gaimster and Gibbs, 2001). With respect to durability, in particular carbonation, no distinct difference in performance has been recorded (Concrete Society and BRE, 2005), however permeability has been found to be reduced (Zhu and Bartos, 2003), offering less opportunity for deleterious actions to occur, such as sulphate attack and carbonation (European Guidelines for SCC, 2005). The denser microstructure present in SCC is identified to have dual effects on shrinkage; initially it is expected that drying shrinkage would be increased due to a lack of aggregate restraint (Concrete Society and BRE, 2005) inhibiting moisture movement, but it has been shown that the dense microstructure reduces bleed and moisture movement, reducing the effects of drying shrinkage (Gaimster and Gibbs, 2001). Autogenous shrinkage is another form of shrinkage that causes concern for both SCC and conventional concretes, it is driven by the internal consumption of water during hydration (The SCC European Project Group, 2005). This form of shrinkage is more prevalent in concrete mixes where w/c ratios are low, causing mix water to be consumed prior to the completion of hydration. Lange et al (2008) reported that autogenous shrinkage for SCC became a problem at w/c ratios below 0.38. The extensive case studies of mix designs (68 in total) explored by Domone (2006) provide an average w/c ratio of 0.35, suggesting

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therefore that shrinkage could be a problem in many cases. Lange et al (2008) also state that when compared to conventional concretes SCCs tend to have a higher paste content (confirmed in section 1.3.2), hence in fact higher total shrinkage can be expected (including drying and plastic shrinkage). A lack of internal bleeding – whilst beneficial in creating a more stable concrete when compared to conventional concretes (at similar water/cement ratios due to reduced volume change) – minimises the effect of plastic settlement, as a consequence it can however have detrimental impacts on plastic shrinkage (Coppola et al 2004). Plastic shrinkage is driven by surface water evaporating and not being replaced (Day et al, 2005), the inhibiting of and low internal and external bleeding associated with SCC has the potential to exacerbate this issue (RILEM Technical Committee 174 (2000) and Gaimster and Gibbs, 2001). It has been demonstrated by Turcry and Loukili (2003) that SCC plastic shrinkage rates can be twice that experienced with conventional concrete. The issues that surround the movement of moisture within SCC clearly identifies that curing, whilst important with all concrete, is fundamentally more important for SCC than with conventional concrete (European Guidelines for SCC, 2005). It is the process of curing that helps to maintain the ideal conditions for concrete and minimises surface moisture losses through early age drying (RILEM Technical Committee 174, 2000), a driver for shrinkage issues, and it should therefore commence as soon as practicable after placing and finishing (Gaimster and Gibbs, 2001). The importance of curing was demonstrated by Qureshi et al (2007) who compared different curing solutions and their effect on compressive strength. It was shown that when compared to ideal conditions (laboratory condition controlled water baths) that samples cured utilising a site-applied curing compound showed a reduction in strength of 7% and those left to cure under site conditions an 11% reduction when compared to the laboratory samples.

Cement, the core component of SCC powder content, whilst contributing to sustainability concerns (Section 1.3.5), also presents potential problems with regards to quality and durability. It is cement which drives hydration and the generation of internal heat within concrete as it cures, resulting in thermal stresses; thermal cracking can occur in concretes where these stresses exceed the strength of the concrete (Neville, 1996). The higher cement contents required in SCCs (Section 1.3.2) can increase the heat of hydration and subsequently thermal stresses, increasing the risk of

thermal cracking (Poppe and De Schutter, 2001). Hydration temperatures are cited to be reduced through the use of cement replacements; however the susceptibility of SCC to changes in constituent materials can present difficulties in achieving this (Section 1.3.5). In addition, the use of limestone fillers as a replacement for Portland cement can lead to an increase in the heat of hydration and an additional peak in the hydration process (Figure 1.4), increasing concerns of thermal cracking (De Schutter, 2011).

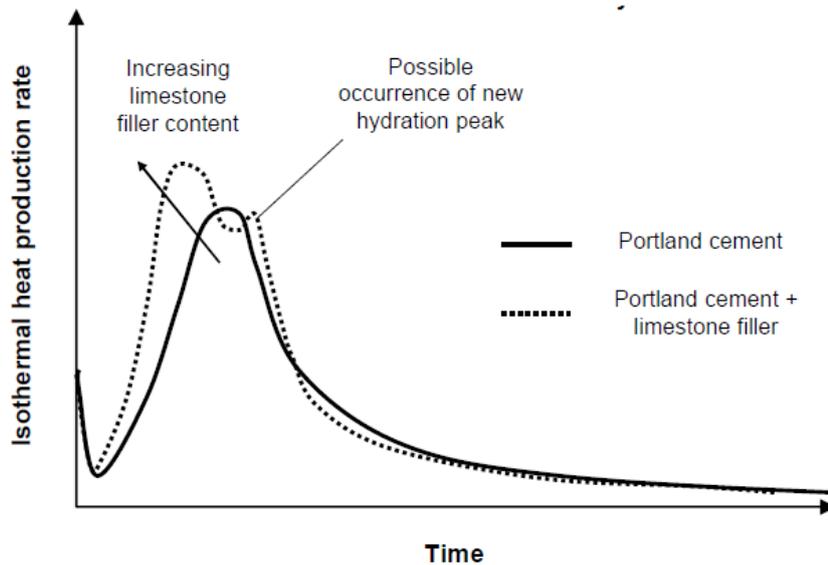


Figure 1.4 Effect of Limestone filler on Hydration (De Schutter, 2011)

Should any cracking (of any type) occur, then this can present opportunities for deleterious actions to take place, in contrast to reports which state that SCC can be more resistant (Concrete Society and BRE, 2005 and Zhu and Bartos, 2003).

Tables 1.3 and 1.4 summarise the advantages and disadvantages of SCC respectively. Comparing the two tables shows that the arguments for and against the selection of SCC over conventional concrete is finely balanced.

Table 1.3 Summary of the advantages of SCC, as reported in literature

Benefit	Improvement	Detail
Reduction of Costs	15% reduction	Early decision to use material in Swedish construction (Nilsson, 1998).
	21.4% reduction	French comparison undertaken by Lafarge, SCC vs. conventional (Concrete Society and BRE, 2005).
	5 – 15% reduction	SCC's at design stage derived from "experience" within Europe (Holton, 2003).
	5 – 15% reduction	Comparison of SCC vs. conventional bridge construction (Billberg, 1999).
	10% reduction	Estimated cost savings based on full scale testing (Bernabeu, 2000)
Reduction in Construction Time	2.5 months	French comparison undertaken by Lafarge, SCC vs. conventional (Concrete Society and BRE, 2005).
	20% reduction, 2.5 year build to 2 year	Live construction of Akashi-Kaikyo Bridge in Japan (Okamura and Ouchi, 2003).
	22 months reduced to 18 months	SCC on construction of LNG tank for Osaka Gas Company (Kitamura et al, 1999).
Improved Tensile Strength	10 – 30% increase	Reported results for SCC compared to conventional (Concrete Society and BRE, 2005).
Labour Reduction	150 reduced to 50 operatives	SCC on construction of LNG tank for Osaka Gas Company (Kitamura et al, 1999).
Energy Saving	20 – 30% reduction in greenhouse gases.	SNRA report, result of reduced resources in construction (Nilsson, 1998).
Productivity Improvements	60% improvement over conventional concrete.	Observation of Swedish works on 19 bridges and house slabs (Persson, 1999).

Table 1.4 Summary of key disadvantages related to SCC use, as reported in literature

Barrier / Issue	Detail
Sensitivity of mix design	SCC is more sensitive to variations in constituent materials when compared to conventional concretes (Goodier, 2003). Subsequently producers are typically required to produce location specific mixes and tighter control over constituent variations (Concrete Society and BRE, 2005; Skarendahl, 2003).
Open life	It has been cited that changes to workability may occur after only 30 minutes of batching a SCC, which can have detrimental effects on placing and finishing (Concrete Society and BRE, 2005).
Placement methodologies	The use of SCC requires significant changes to placement methodologies and decisions to be made in more detail than when dealing with conventional concretes (Holton, 2003, Concrete Society and BRE, 2005; Skarendahl, 2003).
Formwork pressure	There is a large amount of contradictory literature regarding the question of formwork pressure; some stating that formwork pressures experienced are higher than with conventional concrete, others not (Billberg, 2006; Self-Compacting Concrete European Research Group, 2005)
Conformance testing	Acceptance testing remains a requirement prior to the placement of any concrete to ensure fitness for purpose. Unlike conventional concrete there is no single test to assess suitability of SCC which can result in a lengthy testing and accepting process (Day et al, 2005; Gaimster and Gibbs, 2001).
Material cost	SCC first cost or material costs are significantly higher than expected with conventional concretes (Goodier et al, 2002; Holton, 2003; Concrete Society and BRE 2005)
Lack of exemplar projects	Primary experiences of the use of SCC are related to its application as a specialist material and its application in problem solving applications (Clear, 2006).

It is clear that the perceptions and views of SCC are contrasting, which as aforementioned creates a difficulty, in determining its fitness for purpose in a given situation. Tables 1.3 and 1.4 collate and recognise the major proclaimed improvements and issues that exist with the application of SCC and arguments in one

appear to counter points made in the other; as such, it can be very difficult to draw definitive conclusions. The unavailability of some reports and publications which state the improvements that can be realised also brings into question the validity of these statements. One such report has been produced by the sponsoring company and cited by The Concrete Society and BRE (2005), which stated a 2½ month improvement in construction time and an accurate 21.4% reduction in costs on a French comparison project. It is clear that due to the lack of public availability of said reports the validity of these improvements and as such the potential of SCC to offer any advantages, over and above that linked to researched areas of physical performance, is questionable. Headline improvements with Table 1.3 are also project specific; without robust details of the projects where they were achieved or the methodology used in assessing them, the viability for similar savings to be feasible and achievable is once again questionable. It is clear that it is only possible to rebut the published disadvantages if any potential advantages can be robustly qualified; this identifies a clear and significant research gap.

1.3.7 GAPS IN CURRENT KNOWLEDGE ON SCC

The majority of SCC research to date has focused on mechanical and rheological performance properties, rather than on-site applications. This trend can be said to be continuing (e.g. the most recent SCC conference, SCC 2010; the joint 6th International RILEM Symposium on SCC and 4th North American Conference on the Design and Use of SCC (Kamal et al, 2010), in which the majority of papers were focused on technical rather than applied aspects). Subjects which have remained prevalent at major academic and industry conferences have been mix design (Huss and Reinhardt, 2010), workability (Lowke et al, 2010), rheology (Hassan et al, 2010), fresh and hardened properties (Vikan et al, 2010), hydration and microstructure (Heikal et al, 2013) with little reference to case studies and applications. As a result there is a need to assess the on-site implications of SCC use. Through literature it has been shown that research gaps exist in understanding how SCC is introduced to projects, the roles of project teams and team members; how problems with SCC use and variations between SCC and conventional concrete methods are addressed; and, whether SCC presents a viable alternative to conventional concrete, and can improvements or

benefits be realised and what are its whole life sustainability credentials. All these aspects require support through the provision of well grounded, robust and accessible data.

This research project is therefore focused on the on-site effect of SCC. Within the aforementioned research gaps, the adoption of SCC onto projects alongside the processes and challenges that accompany this, the balance between issues and benefits and the measurable effect of SCC use has formed the main focus. A number of additional research aspects have also been explored as a consequence of the complex nature of construction projects and construction research. These research gaps have been tackled through a number of work elements driven by interlinked and supporting objectives.

1.4 AIM AND OBJECTIVES

As with any major research programme there is an overarching question which drives the work. However, the size and complexity of a research question for a programme such as an EngD requires division into several discrete objectives. It is the findings from these objectives that, when combined, will satisfy the research aim.

1.4.1 AIM

It has been established that the majority of research into SCC has been directed towards the physical and structural performance properties of the material, with little clarity provided on the on-site effects of SCC use. The overarching aim of the research was therefore *to determine the effect of SCC on on-site construction processes when used in place of conventional concrete*. Research has, therefore, concentrated on the direct application of SCC on construction projects to understand its effects and the role of SCC in the on-site construction process. This has been undertaken through both quantitative and qualitative methods to provide robust data on SCCs effects and context surrounding its use in these circumstances.

1.4.2 OBJECTIVES

Four distinct objectives were required to facilitate the fulfilment of the research aim and also to provide a structure for the research processes. Whilst each objective facilitates the satisfaction of the research aim, subsequent tasks can also be aligned to the objectives to further describe the steps involved.

- 1) **To understand the site team's perspective in determining the adoption of new or innovative construction methods and materials such as SCC, by;**
Determining the current perceptions of SCC held by on-site construction teams and; understanding the process and ability of on-site teams to influence and effect material or method change in projects.
- 2) **To explore how SCC affects on-site construction, by;**
Undertaking a desk study to validate the potential effect of the SCC method on on-site construction; identifying the requirements and challenges of implementing SCC in on-site construction and; determining the effect of SCC on on-site construction.
- 3) **To quantify the effect of using SCC as a replacement for conventional concrete on-site, by;**
Measuring the on-site processes associated with the SCC method when used as a replacement for conventional concrete.
- 4) **To identify the current position of SCC as an innovation in the UK construction industry, by;**
Drawing together preceding research streams to create an overview of findings and identifying areas of shortfall highlighted through the comparison of findings.

1.4.3 JUSTIFICATION OF OBJECTIVES

It has been described through the results of the literature review that industry and academia, prior to the commencement of this research, had not focused on measuring and determining the practical benefits of SCC. Although there remains a need to continually further understand the mechanical and rheological performance aspects of SCC, there is a requirement to examine and qualify the application of SCC in mainstream construction. Initially, the limits of scope and scale were determined to ensure that any work undertaken was worthwhile and of value to the wider industry, academia and the Industrial Sponsor.

Objective 1 – to understand the site team’s perspective in determining the adoption of new or innovative construction methods and materials such as SCC

Through the literature it is made clear that SCC has the potential to offer significant improvements to construction when used on a project scale, however it is approached as a material that is typically only suited to one off use. SCCs wide use in precast does not reflect reported on-site use, even when similar improvements have been associated with both applications. It is this disparity between perceived and realised use that needs to be addressed with an understanding formed on the processes that surround the implementation of new or innovative methods and materials.

Objective 2 – to explore how SCC affects on-site construction

There are a range of potential improvements and problems highlighted that surround SCCs use on construction projects. It has also been stated that current concrete construction approaches are geared to the use of conventional concretes and that SCC should be considered as a method of construction. This conflict between existing approaches and future requirements for the use of SCC in on-site construction has not previously been examined. There is a need to explore how SCC affects on-site construction, with regards to the SCC method, realisation of improvements and the tackling of problems.

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Objective 3 – to quantify the effect of using SCC as a replacement for conventional concrete on-site

Whilst the need to understand the processes surrounding SCC adoption and the clarification of its on-site effects exists, there remains a significant shortfall in robust quantified data which details the precise effect of SCC. Literature lists a range of quantified improvements linked to the use of SCC in place of conventional concrete. However, these lack detail regarding their foundation/basis and so present issues of validity. There therefore remains a need to quantify the effect of using SCC as a replacement for conventional concrete on-site.

Objective 4 – to identify the current position of SCC as an innovation in the UK construction industry

The preceding objectives will serve to create new robust research findings on SCC, however they will not allow any context to be provided with regards to the overlap of findings, this objective serves to address this shortfall. Without the contextualising of the research results their true value may not be realised in providing an overview and understanding of SCCs current status with on-site construction teams. The understanding of the wider picture will enable the identification of any new concerns and also any desirable future developments needed to improve SCC.

1.5 ABOUT THE INDUSTRIAL SPONSOR

The Industrial Sponsor is a large multi-national construction materials supplier. Lafarge produces cement, aggregates, concrete, asphalt and plasterboard (www.lafarge.co.uk). First established in 1833 at a limestone quarry in France, the company has expanded to now having a presence in 78 countries, initially entering the UK market in 1987 (the company was the subject of a merger in 2012 and is now known as Lafarge-Tarmac).

In the early 2000's, Lafarge's Euro Research Centre in France developed a technically advanced and commercially available SCC (Agilia™). However, in the UK, Lafarge

noticed through experience, a shortfall in knowledge and understanding of its practical application. While the company was confident that improvements could be gained with regards to programme and cost, through engagement with customers, it continued to encounter resistance when offering SCC as a solution to improve contractors' construction activities. The lack of an industry reference point for the practical application of SCC had also increased uncertainty surrounding its use and intensified questions around its benefits. In 2008, Lafarge engaged with the Engineering Doctorate programme at Loughborough University to access specialist research skills and create an independent and rigorous base of knowledge that could address its queries about the applicability of SCC.

1.6 SUMMARY

This introduction has served to set the scene for the rest of the thesis; it has set out and described the organisation and structure of the thesis with respect to each individual chapter. Clear gaps within existing literature have been identified; these have been aligned with a precise aim and objectives to provide robust areas where this research undertaking can add real insight and value to both academia and industry. In particular, it has introduced the need to determine the effect of SCC on on-site construction processes.

On-site use of self-compacting concrete

2. RESEARCH METHODS

2.1 INTRODUCTION

This chapter outlines the overarching research methods used to address the project's aim and objectives, as set out in Chapter 1. An explanation of the methods used and justification for their use has been provided. Further, detailed accounts of the research undertaken are however reported in Chapter 4, within which some of the more specific, technical procedures and analytical techniques are documented for the major work packages. Hence, this chapter provides the contextual methodological background for the research undertaken.

2.2 DEFINING RESEARCH

There have been and are many definitions of what research is, however a suitable and simple definition by Burns (2000) is that it is 'a systematic investigation to find answers to a problem'. It is possible to characterise all research as either qualitative or quantitative, both of which have been deployed in this research.

2.2.1 QUALITATIVE RESEARCH

Subjectivity forms the foundation of qualitative research; it is inherently people-based and is primarily formed of their experiences and driven by their descriptions of these experiences (Naoum, 2006). The participant is the driver of the research direction, as the focus is to understand why an event or action has occurred and to determine the meaning of this to the participant (Fellows and Liu, 2008). Qualitative research does not provide findings which can be measured or calculated, rather its results are subjective not objective, and the nature of the findings can be described as rich and deep (Naoum, 2006).

2.2.2 QUANTITATIVE RESEARCH

In contrast to qualitative research, quantitative studies are objective in nature and can be described as hard and reliable (Naoum, 2006). Qualitative approaches seek to understand why, whereas quantitative approaches are utilised to determine the answers to questions of what, how many or how much (Fellows and Liu, 2008). Quantitative research looks to describe a tangible event or activity through its measurement and creation of numerical data.

2.2.3 EPISTEMOLOGICAL POSITION

In the process of establishing, understanding and assessing research approaches, there is a requirement to clarify the underlying philosophical position of the research, which can aid the selection of appropriate methods or techniques. Determining the epistemological position provides the foundation and rationale for research by describing the manner in which the world is viewed and how this reflects on the theory of knowledge (Fellows and Liu, 2008; Curtis and Curtis, 2011). There are three core epistemological positions: positivism, social realism and social constructivism; however, some authors have developed these positions to identify subsequent positions which fill the voids that are said to exist between the three stances (Creswell, 2009). A simplified description of epistemological position has been adapted from Curtis and Curtis (2011), which in this case describes the calling of when a ball is out of play, in a given sport.

Positivists would hold the view that the ball is called out of play when the ball is out of play and that reality exists which is independent of our own perceptions. It is a scientific approach, which typically lends itself to quantitative research, where the focus is to 'assess the causes that influence outcomes' and focuses on the development of objective findings where it is possible to measure reliability and validity (Creswell, 2009). Social realists would stand by the view that the ball is out of play when it seems to be out of play. It is a development of positivism, where reality is measurable, but exists through the perceptions and actions of the individual. Subjectivity and objectivity exist together where subjective opinions are drawn upon

objective findings to understand the implications of assumptions that have been made surrounding research (Curtis and Curtis, 2011). With social constructivists the ball is out of play when the observer calls it out of play. The social constructivist position is critical of the positivist position and is typically an approach to subjective research. Research of this type is focused on the views of the participant on the subject that is being studied; it is a broad and general approach, rather than specific and targeted. It can be described as a whole world view where the environment and history of the participant is considered in the development of findings, along with the researcher's involvement, the effect of their position and perceptions on the interpretation of findings (Creswell, 2009; Curtis and Curtis 2011).

A positivist stance has been taken throughout this research because the focus has been to provide answers to measurable and quantifiable questions. Where qualitative elements have been included, the subject has been narrowed to consider just the features which affect the specific, technical application of SCC in construction. Consideration of these environmental aspects has been considered when discussing potential research bias (see Section 4.7.7).

2.3 ADOPTED RESEARCH METHODS

When considering the use of both qualitative and quantitative research, a wide range of methods can be used to address specific research questions. Table 2.1 identifies the research objectives, supporting tasks and aligns these with the methods that were employed.

Table 2.1 Research objectives, tasks, methods used and outputs.

Research objectives	Supporting Tasks	Method/s used	Outputs
1 - To understand the site team’s perspective in determining the adoption of new or innovative construction methods and materials such as SCC.	1a. Determine the current perceptions of SCC held by on-site construction teams.	Interviews	Paper 1 – Appendix A Paper 2 – Appendix B
	1b. Understand the process and ability of on-site teams to influence and effect material or method change in projects.		
	1c. Clarify the role of sustainability issues or credentials in influencing the on-site team’s use of methods or materials.		
2 - To explore how SCC affects on-site construction.	2a. Undertake a desk study to validate the potential effect of the SCC method on on-site construction processes.	Case Study	Paper 1 – Appendix A Paper 3 – Appendix C Paper 4 – Appendix D
	2b. Identify the requirements and challenges of implementing SCC in on-site construction.	Observation Interviews	
	2c. Determine the effect of SCC on on-site construction.		
3 - To quantify the effect of using SCC as a replacement for conventional concrete on-site.	Measuring the on-site processes associated with the SCC method, when used as a replacement for conventional concrete.	Case Study Observation Experimental	Paper 5 – Appendix E

<p>4- To identify the current position of SCC as an innovation in the UK construction industry.</p>	<p>Drawing together preceding research streams to create an overview of findings and identifying areas of shortfall highlighted through the comparison of findings.</p>	<p>As above</p>	<p>Aspects drawn out represented in all outputs</p>
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It would not have been possible to fully answer the overarching research aim (Section 1.4.1) through qualitative or quantitative approaches alone; rather, the scale and scope of the research required both approaches. The mix of methods presented above (namely literature review, observation, interviews, case study and experiment) has reduced the effect of the weaknesses that exist inherently within qualitative and quantitative research, for example subjectivity and lack of insight respectively. That said, each method has its own specific characteristics that affect their selection and necessitate specific actions to mitigate any weaknesses. The following sections present an overview of these key methods, prior to a justification of their use for this research.

2.3.1 LITERATURE REVIEW AND ARCHIVAL ANALYSIS

This form of analysis can be used for both qualitative and quantitative research and is the interrogation of existing records or documents, including literature (in its broadest sense). A review of this nature can enable an extensive set of literature to be explored and understood. While not suitable for determining reasoning behind new undertakings, it can provide a basis for the identification of knowledge shortfalls and research gaps (Yin, 1994). Care is required when considering the context of the literature as it will have been created for a specific purpose and a specific audience, which is important when determining its usefulness (Yin, 1994). While literature

review and archival research has not been identified explicitly in Table 2.1, it has played an underpinning and significant role in this research. It has been used to create the foundation on which the project has been based, to ensure that research of value can be undertaken, addressing a true research gap. Figure 2.1 illustrates where archival research findings can be found, providing the basis for the research aim and objectives and also a grounding for all research undertaken.

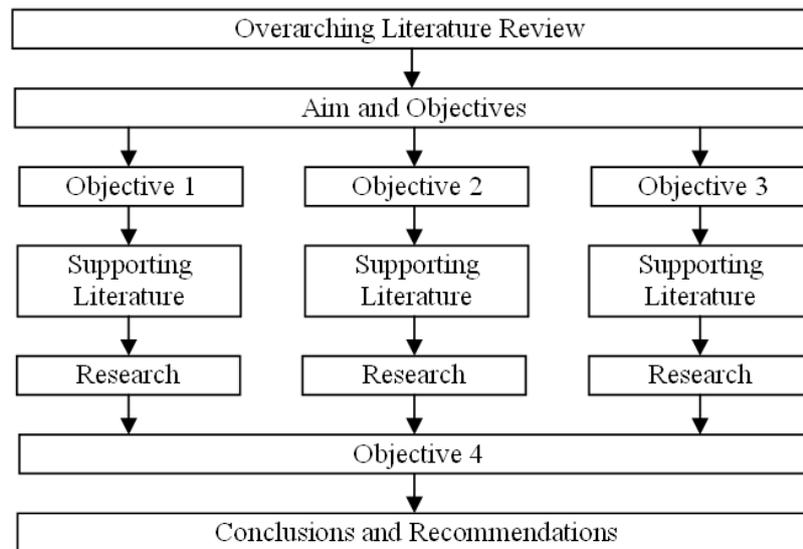


Figure 2.1 Use of literature review/archival research throughout the research

2.3.2 INTERVIEWS

Interviews are a form of survey, which can act as a fast and efficient form of data capture. Based around statistical sampling, surveys are utilised to estimate the characteristics of a large population based upon the results from a representative sample (Bryman, 2004). When implementing a survey special attention is required to be given to the selection of the sample, as this dictates the reliability of research findings (Fellows and Liu, 2008). Interviews however can be described as a ‘verbal interchange’ (Burns, 2000), where the interviewer’s objective is to elicit information from the interviewee on the subject in question, such as their or others behaviour, attitudes, beliefs and values (Bryman, 2004). Interviews can be structured, semi-structured or unstructured; questions are chosen which are correspondingly open-ended or close-ended. Unstructured interviews present the interviewer with the

opportunity to vary question sequence and to delve and explore responses. Structured interviews focus on a linear question route with the creation of more accurate question responses based upon closed questions (Naoum, 2006). Semi-structured interviews fall between the characteristics of structured and unstructured.

2.3.3 OBSERVATION

As suggested by its title, observation is the practice of observing an activity in order to derive and understand information about a specific form of behaviour (Bryman, 2004). Observational techniques are typically employed when it is not clear what aspects need to be researched and when data collected through other methods may not be suitable. Unlike any other method, it provides the opportunity to record activities as they happen rather than relying on the recall and insight of participants (Burns, 2000). Participant observation and direct observation constitute the observational research methods. Participant observation requires the researcher to become immersed in the subject being observed and typically demands a long observation period in order for the researcher to become accepted to ensure that 'observations are of the natural phenomenon' (Trochim, 2006). Direct observation is designed to be unobtrusive and the researcher strives to observe in manner that does not bias or influence findings (Trochim, 2006). The outputs from observational research can be used to formulate case studies, an approach also utilised in this research.

2.3.4 CASE STUDIES

A case study is a method of carrying out an in-depth and intensive analysis of a specific circumstance or problem (Yin, 1994). Case studies develop rich and deep information on the subject which they are focused, which in a time-sensitive programme turn can result in only a limited number of studies being completed (Fellows and Liu, 2008). Researchers typically utilise case studies when they require in-depth support to arguments and findings (Naoum, 2006), alongside the assimilation of a wide range of sources, i.e. documents, interviews etc (Yin, 1994).

2.3.5 EXPERIMENTAL

This method is used primarily to test a theory or a hypothesis; its main application is circumstances where the researcher has the ability to maintain influence over all factors which can affect the results. Experiments are generally employed within the scientific community where it is possible for the researcher to operate within a 'bounded' environment where all variables are known, or can be hypothesised with confidence, (Fellows and Liu, 2008) offering significant internal validity (Bryman, 2004). It is however, also possible to apply this process to external situations, where it is known as quasi-experimental. It is used in circumstances which can not be easily or adequately be replicated under laboratory conditions and, as such, only offer partial control of variables, potentially presenting problems around measurement and accuracy (Fellows and Liu, 2008).

2.4 JUSTIFICATION OF RESEARCH METHODS

The multi-faceted nature of the research subject area necessitated a range of research methods to be adopted, not only to answer the overarching research aim, to determine the effect of SCC on on-site construction processes, but also to answer each specific objective. The selection of research methods is discussed in the following sections, with specific reference to each of the objectives. The limitations of the chosen methods are acknowledged and explained along with the presentation of mitigating strategies used (see section 4.7.2).

2.4.1 OBJECTIVE ONE

To understand the site team's perspective in determining the adoption of new or innovative construction methods and materials such as SCC

Semi-structured interviews were identified as the most suitable method to answer the question proposed by Objective 1 (Section 1.4.2). To satisfy the objective, it was necessary to determine the opinions of teams on site, so interviews were selected as they permit direct communication with appropriate participants. Of the interview

types, semi-structured interviews were chosen as they deploy a standard set of questions, but allow the exploration of participant responses to elicit additional details. The use of a standard set of questions also enabled the comparison of answers between two different participant groups, as described in section 3.2.3. Interviews were deemed to be the most appropriate method because processes within organisations, perceptions and decision-making structures (among individuals) all tend to vary. Hence, these could be identified, explored and clarified sufficiently.

2.4.2 OBJECTIVE TWO

To explore how SCC affects on-site construction

This requires the analysis of the practical construction phase, using a combination of methods. First, a case study approach was used to explore the construction of a multi-storey concrete frame structure, which was part of a residential and commercial development (see section 3.3.1). The case study enabled the interrogation of data to provide not only an in-depth understanding of the effects of selecting SCC on both on-site processes and project finances. Through this method, the research focused on a single case, i.e. a multi-storey frame structure, allowing the exploration of the consequences of SCC adoption. Wider effects of SCC on this project were also examined through direct observation and semi-structured interviews. Within this case, direct observation allowed site work to continue in a natural manner without the author having a significant impact on proceedings. Observation enabled conclusions to be drawn on the optimal method of construction and the practical changes that occurred. After the event, the third major method, interviewing, made it possible to gauge contractors' perceptions and experiences of construction with SCC, cross-examining and referencing observations. Semi-structured interviews were employed to react to and explore the details of participant responses.

2.4.3 OBJECTIVE THREE

To quantify the effect of using SCC as a replacement for conventional concrete on-site

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As with Objective 2, a number of research methods were required to fully satisfy the objective. The objective required the quantification of the effect that SCC has in replacing conventional concrete, which can be determined only through experimental methods. The main data collection activity required the measurement of on-site construction activities (see Section 3.4 and Paper 5, (Appendix E)); the experimental approach allows findings to be presented which are robust and accurately describe the situation. However due to the nature of construction, only certain parameters can be controlled, so quasi-experimental circumstances are typically encountered. Case study and observational methods capture qualitative information, which cannot be obtained through experimental methods. This information, while not directly required for the satisfaction of Objective 3, provides a depth and understanding of the circumstances that influence experimental findings.

2.4.4 OBJECTIVE FOUR

To identify the current position of scc as an innovation in the UK construction industry

Objective 4's purpose was to bring together the research findings from Objectives 1, 2 and 3 in order to provide a wider industry context, to establish SCC's position and to determine if any changes could be recommended as a result of this research. As such the research methods utilised in this section reflect those that have been explained previously.

2.5 SUMMARY

Successful research requires the correct selection of appropriate methods for each individual aim or objective. Through this chapter, the research methods used have been identified. The diversity of the project objectives required a range of methods to be selected which, when combined, enabled detailed answers to be sought and to reinforce findings. The selected methods were a combination of primary data collection methods, i.e. interviews, observation and quasi-experimental techniques,

combined with case studies and archival research, the former relying on a combination of both primary and secondary data.

On-site use of self-compacting concrete

3. RESEARCH UNDERTAKEN

3.1 INTRODUCTION

While SCC has been the subject of extensive research this has been focused primarily on the mechanical and rheological properties of the material, with few authors considering its application in the construction industry (Section 1.3.7). As a result, there is a dearth of research which focuses on resolving the more commercial construction and application aspects (i.e. cost, programme) of the use of SCC, most notably the in-situ, or on-site use (see also section 3.2.2). Although some research does exist, recognised in Table 1.3, it lacks robustness and transparency and it is very difficult to translate the findings to current practice. This leads to the identification of distinct research gaps or shortfalls (section 1.3.7), those that are to be addressed by this research are:

- 1) The lack of understanding about the process through which SCC is adopted and deployed on construction projects; and,
- 2) Its impact on the construction with regards to requirements and challenges that surround its adoption; and,
- 3) The lack of objective, measured data of the direct effect/s that SCC has on construction activities.

The combination of the prior focus on mechanical and rheological properties, the lack of robust research and the identification of significant shortfalls indicates that research should be undertaken on the in-situ, on-site application of SCC.

This chapter presents the three, parallel streams of research that were conducted. First, interviews with members of the on-site construction team (Objective 1); secondly, a case study of the on-site use of SCC (Objective 2), and finally, the quantification of SCC as a replacement for a conventional concrete (Objective 3). Each stream of research commences by revisiting key literature, emphasising the detail of the research gaps and then reports the research used to address these gaps.

Figure 3.1 (a repeat of Figure 2.1) depicts the structure of this chapter, identifying how key results and findings are drawn out from each distinct research activity to answer the research objectives. It shows how Objective 4 is answered through the combination of the previous three streams, so establishing the current UK market position of SCC and identify any required improvements.

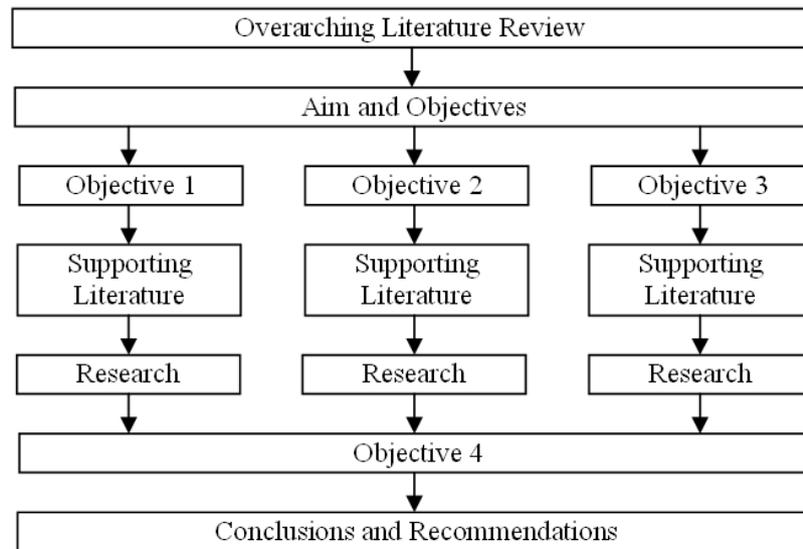


Figure 3.1 Layout of thesis structure illustrating the use of Objectives 1,2 and 3 to derive answers for Objective 4

3.2 UNDERSTANDING SITE TEAMS' PERSPECTIVES ON THE USE OF SCC

3.2.1 INTRODUCTION

This section explains the outcomes of a programme of semi-structured interviews with members of on-site construction teams which focused on understanding the site team's perspective in determining the adoption of new or innovative construction methods and materials such as SCC (Objective 1, Section 1.4.2). It includes details of the participants and the methods used to collect data, followed by analysis and implications for construction with SCC. Further details can be found in Paper 3, "*To SCC or not to SCC? UK contractors' views*" (Rich et al, 2010) (Appendix C), and

Paper 2, “*UK contractors’ views on SCC in construction*” (Rich et al, 2011) (Appendix B).

3.2.2 THE NEED TO UNDERSTAND SCC FROM AN ON-SITE PERSPECTIVE

Construction is said to be geared towards conventional concrete (Okamura and Ouchi, 1999) and, although a number of reports have been published to enable the specification and adoption of SCC in construction projects, namely the European Guidelines for SCC (2002) and the Concrete Society’s Technical Report No.62 (2005) along with supporting reports from the Department of Trade and Industry (Goodier et al, 2002; Holton, 2003), the majority have focused on what can be achieved with SCC, rather than how it is used on site. SCC tends to be described as a specialist material, suitable for one-off use and is yet to be fully accepted by the industry as a viable alternative to conventional concrete (Holton, 2003; Clear, 2006), despite its apparent attributes (Section 1.3.6). Cost is consistently identified as a significant barrier that prevents its use (Goodier et al, 2002; Holton, 2003; Concrete Society and BRE 2005), despite previous calls for SCC not to be considered on a first-cost basis alone (Holton, 2003), i.e. using a value-based approach (The Latham Report, 1994, The Egan Report, 1998; Accelerating Change Report, 2002).

Yet, with broad acceptance of SCC in the precast industry (Section 1.3.4) and similar prescribed advantages (Section 1.3.6), the clear disparity with poor on-site application rates needs to be explored. Precast concrete affords direct and close control of all processes due to single party management. On-site application in contrast is fragmented (Skarendahl, 2003), featuring multiple firms and the fragmentation of roles and activities. This results in a lack of continuity and difficulties in implementing change as there can be a lack of knowledge and experience transfer to and from similar projects (Construction Task Force, 1998). Compared to large construction projects consisting of many stakeholders, precast manufacturers could also be considered to be more agile to adapt to changing market circumstances (Brown and Bessant, 2003), driven by a reduction in bureaucracy resulting from simplified hierarchal structures (Rosenbusch et al., 2011). The precast industry arguably facilitates closer, earlier relationships between activities and decision makers

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(Barrett and Sexton, 2006), yet on-site construction, particularly in-situ concrete construction is often said to be more flexible than precast. Hence, there is a lack of evidence in the literature to account fully for the lack of use of SCC in on-site applications.

Further to this, sustainability is a fundamental topic that is prevalent within the construction materials sector and industry in general; but, it is a complex topic that affects construction from many aspects. From a wider perspective, the three pillars of sustainability should also be fundamentally considered (Damtoft et al, 2007 and Section 1.3.5), but in the context of concrete, sustainability concerns are focused primarily on the topic of carbon (CO₂) emissions. Although these emissions are created principally during the production of cement, which is only one of several constituents of concrete (Section 1.3.2), this burden is significant and cannot be overlooked; any measures that reduce the carbon emissions associated with cementitious products are generally considered beneficial. Indeed, where the adoption of new or innovative methods and materials are concerned focus should not be only on the production impacts but the whole life cycle, use during construction and through operation and also at end of life (Section 1.3.2). Cement replacements, recycled materials and responsibly sourced materials (BRE, 2012), can improve the sustainability credentials of a concrete mix. SCC has a comparatively high cement content, due to its mix design (Section 1.3.2), which can have a disadvantageous impact on its comparative emissions. However, the properties of SCC are very sensitive to changes in its constituent materials, so any attempts to improve its sustainability performance by altering the cement content may not be immediately possible (Section 1.3.6). A broader, site-level approach is arguably needed such that SCC's effect on on-site processes is evaluated in the round (Damtoft et al, 2007).

3.2.3 RESEARCH METHOD, INTERVIEW DESIGN AND PARTICIPANT SELECTION

The previous section makes a clear case for investigating the use of SCC in the on-site context, focusing on selection, application and also the question of sustainability profile.

Within any construction project there are a number of parties that operate within the organisational structure with the ability to influence or dictate the construction project. These influencers can be located anywhere in the project structure, whether the client, architect, engineer, contractor or sub-contractor, to varying degrees. On-site teams, in particular the contractor and sub-contractors, were selected as the most suitable research subjects due to the role they fulfil in the construction process and their interaction with SCC. They play an active role in both the organisation and physical construction aspects of a project and, as such, have extensive knowledge and experience of processes and operations. Importantly within projects they have the power to select the type of concrete used and are therefore able to take advantage of any improvements, but consequently are also subject to any negative effects of changes to procedures. In many cases they themselves are the buyer/purchaser of construction materials and subsequently are expertly placed to talk about why SCC is or is not chosen and its effects. Further details on participants can be found in Appendix J.

Interviews were chosen as they enable a large amount of in-depth information to be gathered from each participant (Bryman, 2004); they provide the opportunity to develop, interrogate and expand on answers provided by participants (Section 2.3). A broad sample of participants was needed to reflect the wide range of applications of SCC reported in the literature, and so two groups were identified, large nationally operating concrete frame sub-contractors and small-to-medium sized contractors, such as house builders. The nationally operating concrete frame sub-contractors were all members of CONSTRUCT^{**}, members of which are '*dedicated to the task of improving the efficiency of building in-situ concrete frames*'. Membership requirements state that member organisations should be focused on concrete frame construction, be forward thinking, construct to high industry standards, be proactive and positive towards innovation and development. The CONSTRUCT members interviewed had been operating in the UK construction industry for 10 to 50 years, with turnovers ranging up to, and in excess of, £115 million. Those interviewed held a range of positions with varying levels of experience such as Managing Director, Commercial Director, Contracts Director, Operations Manager and Project Managers

^{**} CONSTRUCT - <http://www.construct.org.uk/>

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(see Appendix J). The activity of these companies may not be indicative of the construction industry as a whole, however they can be considered representative, because they undertake 93% of total concrete structure sector spend (CONSTRUCT, 2012). A second group of participants was included to broaden the dataset by obtaining a wider range of opinions. These were small-to-medium sized contractors with selection based on three criteria: regular, occasional, and non-users of SCCs. Interviewees in this sample were from house builders, ground workers and general builders, including Company Owners, Project Managers, Site Managers, Foremen, Gangers, Concrete Specialists and Labourers. A total of 72 contractors were approached, with 48 participating in the interview programme, 10 concrete frame contractors (24 approached) and 38 other sub-contractors (48 approached) (see Paper 1, “*To SCC or not to SCC? UK contractors’ views*” (Rich et al, 2010), and Paper 2, “*UK contractors’ views on SCC in construction*” (Rich et al, 2011). The questions were focused on key aspects derived from the literature (Section 1.3.7):

- The construction materials selection process
- Applications and benefits of SCC
- Addressing sustainability objectives

To reflect the inherent differences between subject groups the interview approach and questions were tailored slightly to suit the two groups of interviewees. Appendix H contains the set of questions used with the concrete frame constructors, addressing the identified research areas but from a higher level in a project’s organisational or contractual structure (typically Tier 1 or 2). Appendix I details questions for the SME contractors, are orientated around the on-site activities and focused therefore at Tier 2 or 3 levels.

3.2.4 THE CONSTRUCTION MATERIALS’ SELECTION PROCESS

Interviewees were asked to comment on their role in the decision-making process, selection of construction methods and materials. Main contractors and sub-contractors in general hold the majority of experience and expertise regarding practical

construction issues, yet the interviewees made it clear that sub-contractors often played a minor role. Despite being seen to hold the responsibility of determining the method of construction, they felt limited in practice as they had to comply with pre-defined designs created by other parties. One specialist concrete frame sub-contractor said: *'we can make suggestions on materials'*, but generally can only provide *'a best price and advise'* on construction. When asked to explain how SCC comes to be used in this scenario, it appears that the decision is often driven from site level in response to a specific requirement or technical challenge, at which point it becomes necessary to: *'educate the client or engineer on the material, the role it can have in construction and the reasons for its inclusion'* (concrete frame contractor). This 'reactive selection' was explained by the concrete frame sub-contractors as *'application-led, rather than a conscious decision'*, and was said to be fairly straightforward to justify for primarily technological reasons, as presented in Section 1.3.5.

The notion of SCC as a problem-solver has been reported in the literature (Okamura and Ouchi, 2003; The Concrete Society and BRE 2005; Clear, 2006), but the interviewees concurred that a market that was restricted to such applications would fail to realise the full benefit from the material. It was clear that frequent use of SCC leads to greater understanding and, as a result, the contractors reported that in some instances, SCC is considered much earlier on in the decision-making process as a viable alternative to conventional concrete. Hence, experience and a good understanding of its physical properties lead to a different attitude, i.e. a 'strategic change' such that SCC is considered, even as early as the options study stage. While only two participants had seen SCC in a specification, most of the interviewees also thought that specification of SCC by engineers would be a key method to increase the use of SCC. Grimes (2005) recognises SCC as an 'architectural tool', should it be specified as such and an example of this is The Hepworth in Wakefield (Figure 3.2), where SCC was used to form both the structural frame and architectural façade.



Figure 3.2 The Hepworth, Wakefield (photo courtesy of Lafarge Aggregates Ltd).

Based on the interviews with site teams, it is therefore possible to contribute to the previous knowledge in the literature, by identifying three distinct scenarios to describe how SCC is used (Figure 3.3) which clarifies previous assertions, as discussed below.



Figure 3.3 Three scenarios through which SCC may be deployed on site

The key point is that a progression to the right hand side of Figure 3.3 requires not only greater levels of experience and knowledge, but also a tacit acceptance that SCC should be thought of as embodying a construction method or approach in its own right, not simply as a material to be applied within a given approach. Yet traditional project structures can inhibit this type of structural change. For instance, the time at which participants become involved in projects is typically once a design is agreed, (for specialist concrete frame sub-contractors this is after appointment by the main contractor and for labour-only sub-contractors it can be even later) limiting the scope of their ability to influence and promote change. Interviewees reported that sub-contractors are often only given '*four weeks*' lead time prior to the first site works (concrete frame contractor), at which point the majority of design, specification and construction decisions have been made. To implement changes they would require a

lead time of '2-3 months' (concrete frame constructor), which confirms calls for early engagement in the SCC literature (e.g. Gaimster and Foord, 2000; Clear 2006) and is a concept that has been widely adopted within other industries, manufacturing and IT, to improve overall product performance (Gil et al, 2000).

3.2.5 APPLICATIONS AND BENEFITS OF SCC

When asked about the applications (e.g. floors, walls, columns, trench fill) to which SCC was most suited, the interviewees cited a range of options, but they did not identify any specific instances for which SCC would always be applicable. The larger sub-contractors reported that SCC was used where it was able to '*resolve and remove problems*' i.e. as a reactive, problem-solving tool; a view which is reflected in the literature (Section 1.3.5). However, the small-to-medium sized sub-contractors (i.e. house builders and ground workers) stated that SCC was often being used in the construction of slabs for residential housing projects. This indicates that the small-to-medium contractors are deploying SCC for reasons specific to this market, which they did not make entirely clear, but their unanimity suggests the presence of some implicitly understood benefits, or perhaps, a widely applied method of overcoming any shortcomings.

However, there was some disagreement among the interviewees, particularly about cost, which was generally cited as the major barrier to greater use. Some said '*cost is prohibitive*', '*it is difficult to see where you can actually make savings*' and this remains the '*main problem with the material*' (house builders), whereas others reported that SCC had '*made it possible to reduce both time and manpower*' (general builder) and any increased cost '*can be returned through time saved, reduced labour and removal of power floating*'. It seems that small-medium contractors, unlike the larger concrete frame contractors, were able to balance the advantages and disadvantages of using SCC, in their case, for ground floor slabs.

This simple construction scenario appears to give the SME contractors greater control over their processes on site. Their simplified structure and autonomy provides the opportunity to react and assess new developments, or methods and materials quickly

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(Barrett and Sexton, 2006), such that they can use SCC to help deliver a slab quickly, meeting the minimal strength requirements and achieving a relatively flat surface for subsequent finishes quite easily. Despite this evidence, there was no clear consensus on the major benefits that SCC might bring to on-site operations, but the respondents explained that SCC can reduce '*effort levels in placement*' (general builder), enable '*faster and more accurate*' (general builder) construction and mitigate '*workmanship issues*' (concrete frame contractor), all of which corroborates views expressed previously in the literature (e.g. Okamura and Ouchi, 2003; Concrete Society and BRE, 2005; Goodier, 2003). As a result, while it may appear that views on SCC have not evolved substantially, the consistency of use reported by the small-medium contractors suggests that literature and industry views on the key barriers (e.g. that SCC is 'too expensive') may be outdated and so this gap warrants further investigation.

3.2.6 EMBEDDING SUSTAINABILITY

The need to comply with governmental and industry targets for sustainability (HM Government, 2013) should be a fundamental driver in the consideration of sustainability in the adoption of any new or innovative construction methods. This would be expected to act as a driver for the on-site teams to consider sustainability as a method of implementing change. However, the high carbon emissions associated with all forms of concrete construction and particularly those with high cement contents, such as SCC, may be of concern for end users, so the interviews specifically included questions about the sustainability aspects of SCC.

When asked who should be actively looking to improve sustainability in construction, the majority of major concrete frame contractors thought this should be '*primarily driven by the client*' or the main contractor. One respondent noted that while his company did look at relevant aspects (such as waste management or sustainable timber supply), concrete was overlooked as it tended to be pre-selected by the main contractor. Another concrete frame contractor stated that '*green*' methods were unviable claiming that they could cause the '*company to go bust*', reinforcing perceptions that cost is the primary concern and that holistic approaches are not taken.

There was a clear consensus among the interviewees' on the ways in which materials could contribute to sustainable construction. When asked how they viewed concrete and sustainability, the emphasis was placed on material properties, rather than any aspects of the construction process. Their answers reflected those found in literature, including the use of cement replacements or '*wholesale alternatives*' (concrete frame contractor), recycled materials and end of life recycling (Sections 1.3.5 and 1.3.6). In contrast however, one concrete frame contractor did identify the need to '*have a long term view*' in order to understand sustainability credentials, reflecting a more holistic and all-encompassing approach (Section 1.3.6 and Damtoft et al, 2008). Coverage in the literature is divided about whether SCC is a sustainable or unsustainable construction option (Section 1.3.5 and 1.3.6), a view reflected by the concrete frame contractors. Some stated that SCC is less sustainable due to '*increased cement content*' (reflecting Domone, 2006) and the wider use of '*additional chemicals*', whereas others thought it was more sustainable due to '*a reduction in required finishes*'. A more consistently held view was that not enough evidence exists to determine whether or not it is or is not a sustainable option.

The lack of focus and lack of clarity on sustainability in the responses from these on-site teams makes it difficult to comment on the practical, sustainability credentials of SCC. Certainly, based on this research, it would seem unwise to focus solely on the material properties of SCC, as no consensus can be reached through such a restricted lens. Rather it might be more informative to consider SCC in the context of its application, perhaps via a life-cycle assessment.

3.2.7 SUMMARY

This section has addressed Objective 1, *to understand the site team's perspective in determining the adoption of new or innovative construction methods and materials such as SCC* by determining the current perceptions of SCC held by on-site construction teams and; understanding the process and ability of on-site teams to influence and effect material or method change in projects.

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It is clear, through the interview process, that there is little consensus on the merits or issues of SCC's effects from the on-site teams' perspective; the general findings reported in literature on industry perceptions of SCC do still appear to be broadly reflected in reality.

Clarity has however been provided where project organisational structures are concerned; the current point at which on-site teams become involved in a project hinders their ability to either influence or contribute in a meaningful manner towards project improvement. This situation is primarily relevant to larger concrete frame contractors as the SME sub-contractors seemed to experience somewhat different circumstances. The smaller businesses were able to exert more control and influence over the construction methods they employed on projects, enabling them to be more readily adapt and change to accept new construction methods and materials. This may, in part, be comparable with precast due to the simpler projects on which they are employed (unlike those managed by concrete frame contractors), simpler organisational structures and an ability to exert more control over their activities. Where more complex projects are concerned project team and management structures need to be adapted to facilitate the involvement on the on-site team sooner. This would allow the transfer of knowledge and experience and facilitate the easier adoption of SCC on site.

On sustainability, the on-site teams characterised their involvement and ability as severely limited. They believed that any drive to create a more sustainable project was typically driven from higher in the project organisational chain, i.e. by the client or main contractor. Importantly, the frame contractors felt they had very little scope to influence decisions where construction materials were concerned, particularly with the choice of concrete.

3.3 UNDERSTANDING THE USE OF SCC ON IN-SITU CONCRETE FRAME CONSTRUCTION

3.3.1 INTRODUCTION

Analysis of a live construction project provides the opportunity to explore, observe and collate the changes and effects that SCC could have on on-site construction (Objective 2, Section 1.4.2). Through links with the Industrial Sponsor it was possible to identify a project where this could take place. Areas where SCC affects on-site construction have been identified in literature (Section 1.3.6); the construction of two similar buildings at the same time, one with SCC and one with conventional concrete, presented a valuable opportunity to explore these aspects.

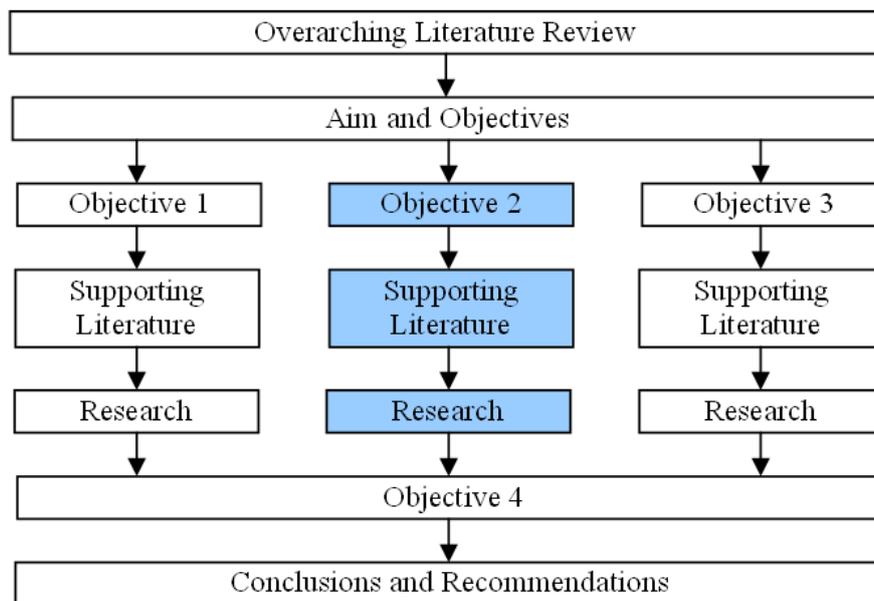


Figure 3.4 Layout of thesis structure identifying aspects covered in Section 3.3

Construction time has been cited as being reduced as a direct result of using SCC (Table 1.4), facilitated by the improvements in productivity (Persson, 1999) and changes to the physical construction method (The Concrete Society and BRE, 2005). Dependence on labour is cited to be reduced through smaller gangs and the deskilling of the concreting process, while maintaining or improving construction quality (Section 1.3.6). The removal of the compaction process has implications for the

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management of the construction site and the site team, plant and equipment can be reduced and/or removed, with the potential to provide energy and overhead cost savings (Walraven, 2003), whilst reducing risk to operatives of HAV exposure and general site hazards (Skarendahl, 2003; Damtoft et al, 2008). If these purported 'improvements' are valid they should be demonstrated and observable not only through site practice, but also in overarching project and whole life costs (provided any other salient technical or practical pitfalls are avoided of course).

The literature describes the 'advantages' of SCC (Table 1.3), but there is also a body of literature that identifies several aspects which hinder its practical application. Fundamental to SCC's use on-site is its impact on formwork pressures in vertical applications – while the effects are still not entirely clear (The Self-Compacting Concrete European Project Group, 2005; Lange, 2007), additional steps are required compared to conventional concrete placement. Placement processes also need to be refined to reflect the differences that exist between SCC and conventional concrete properties (Section 1.3.2), which can also have an effect on formwork pressures. Conventional concrete can be placed easily via skip in vertical applications. This method however, if employed with SCC, can be detrimental to the material properties (Section 1.3.6). The method deemed as most suitable for SCC is via low-level inlets allowing concrete to rise 'as a homogenous mass' (Holton, 2003). In horizontal applications (i.e. with a large area not cured by the formwork itself) the importance of curing in assuring final quality is increased when compared to conventional concrete; this is due to differences in SCC's constituent materials (The Self-Compacting Concrete European Project Group, 2005 and Gaimster and Gibbs, 2001). Demands are also increased on placement speed, due to the open life of the fresh material, which can be subject to relatively rapid change (depending on prevailing conditions, as with all concretes), it has been cited that SCC can present issues after as little as 30 minutes, affecting placement and achievement of final finish (The Concrete Society and BRE, 2005). Open life describes the period of time before the hydration of concrete causes significant change in the characteristics of a concrete, for example in terms of placement, stiffening up which inhibits ease of movement.

These aspects describe and imply SCC to be more a *method* of construction rather than a construction *material*, so there is a need to explore, measure and quantify

whether such factors discussed in literature are prevalent in practice (Okamura and Ouchi, 2001). Literature also exists that can be used to analyse construction methods (Davis Langdon, 2006) and has been created to aid planning and estimation of duration and costs of construction projects. This can provide an effective basis for research to come to some interim conclusions about the viability of SCC (as a method) and its adoption by on-site teams.

A desk-based study was therefore completed utilising the industry construction pricing book, '*Spon's Architects' and Builders' Price Book*' (Davis Langdon, 2006) alongside observations and preceding exploratory work carried out by the author (Rich, 2007). This incorporated four distinct aspects of the construction process, namely material cost, labour cost, plant cost and construction time (Placement Rates). All the data, excluding material costs, was taken from Spon's (Davis Langdon, 2006), with the material costs (of application specific SCC's) provided by the Industrial Sponsor, Lafarge (current as of 4th Quarter 2007).

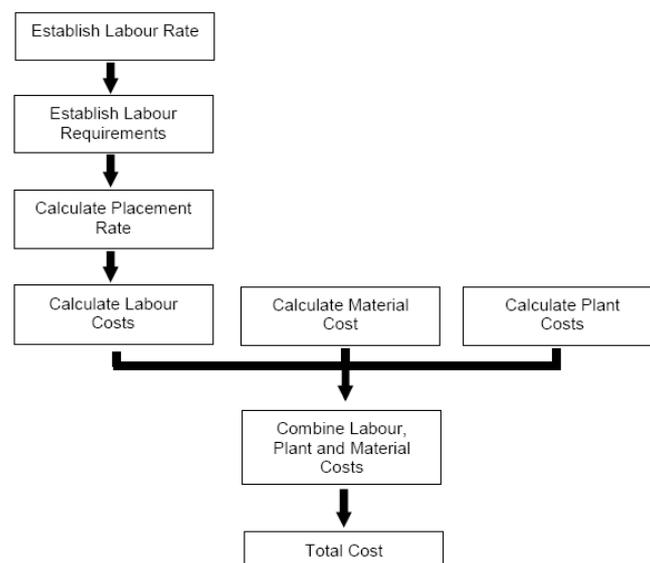


Figure 3.5 Breakdown of cost calculation process for desk study

Figure 3.5 illustrates the desk study process steps; this relatively straightforward exercise was a key component in enabling a direct comparison to be made between SCC and conventional concrete, in the on-site context.

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A range of applications, e.g. walls, slabs and trenches, were considered to allow an understanding of the effects of SCC in its typical uses. Labour costs and plant costs were identified, along with placement rates, for the construction of each element. Adjustments for SCC construction had to be made to gang sizes (as indicated by literature (Goodier, 2003) and author observations) and plant requirements (due to the removal of specific construction activities). The results are summarised in Tables 3.1 and 3.2.

Table 3.1 Comparison of construction costs (per m³) for generic construction applications, as identified in Spon's (Davis Langdon, 2006)

Application	Constructed Cost (£/m ³)				Comparison of m ³ cost (£)
	Conventional	SCC Vertical	SCC Horizontal	SCC Trench	
Wall <150mm	185.08	205.33			+ 20.25
Wall 150 < X < 450mm	164.42	189.03			+ 24.61
Wall > 450 mm	154.82	181.45			+ 26.63
Slab < 150 mm	154.28		172.59		+ 18.31
Slab 150 < X < 450mm	139.91		161.76		+ 21.85
Slab > 450 mm	133.72		157.09		+ 23.37
Trench (Reinforced)	108.89			103.83	- 5.06
Trench (Plain)	101.41			103.41	+ 2.00

Table 3.1 identified only one case where SCC was economically viable: construction of trenches with reinforcement, with the majority of other cases incurring a significant additional cost per m³, as a result of its selection.

Table 3.2 Comparison of cost differential between conventional concrete and SCC, for material cost and as-constructed cost

Application	Material Cost Difference (£/m ³)	As-constructed Cost Difference (£/m ³)	Change in Cost	
			£/m ³	%
Wall <150mm	41.87	20.25	21.62	52.63
Wall 150 < X < 450	41.87	24.61	17.26	41.22
Wall > 450 mm	41.87	26.63	15.24	36.39
Wall <150mm	30.01	8.39	21.62	72.04
Wall 150 < X < 450	30.01	12.75	17.26	57.51
Wall > 450 mm	30.01	14.77	15.24	50.78
Slab < 150 mm	35.94	18.31	17.63	49.05
Slab 150 < X < 450	35.94	21.85	14.09	39.20
Slab > 450 mm	35.94	23.37	12.57	34.97
Trench (Reinforced)	15.77	-5.06	20.83	132.08
Trench (Plain)	21.24	2.00	19.24	90.58
			Average Change (%)	59.59

Although Table 3.1 indicates that SCC is more expensive per m³ than conventional concrete, the additional analysis in Table 3.2 shows that when initial material cost differences are compared to as-constructed costs, the process of using SCC can facilitate a reduction in the overall as-constructed cost.

Essentially, excluding concrete material costs, the process of constructing with SCC is cheaper. This reduction is a result changes to labour and plant (in quantity and time), and can be significant, ranging from a 35-132% potential reduction. Additional research is required however, to understand and quantify this relative improvement. This is supported by literature, which indicates that SCC has the potential to improve aspects such as construction productivity, through the speeding up of the concrete placement process (Okamura and Ouchi, 2003; Concrete Society and BRE, 2005, amongst others). This would still need to overcome specific limitations however, such as open life and conformance testing (Table 1.4). This research has complemented existing literature in identifying a need to further explore how SCC affects both the process and the cost of on-site construction.

The selected building project was the development of a former industrial area near Leeds city centre, consisting of three high-rise, predominantly residential, blocks

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together with two low-rise properties, one commercial, and one residential. The study was based on two of the three concrete frame structures, which were similar in design, one constructed in conventional concrete and the other entirely in SCC, called Echo 1 and 2 respectively (Figure 3.6).



Figure 3.6 Echo 1 (left) and Echo 2 completed structures (photo by author).

Both structures were designed by the same professional teams and were constructed by the same contractor, but with different construction teams on each frame. At a design level, whilst the structure's spatial footprints/layouts were different, net floor areas were similar, 775 m² to 767 m². The numbers of storeys per structure (Echo 1: 15 storeys and Echo 2: 12 storeys) also differed, however subsequent comparisons were based on a rationalised figure (m³) which served to remove this variability. An arrangement was made between the contractor and the Industrial Sponsor to allow access to site and provide cost information for both structures.

3.3.2 KEY CONSIDERATIONS IN THE CONSTRUCTION PROCESS

When constructing with SCC, approaches used in constructing vertical elements, except for the removal of the need to compact, are broadly consistent with those used for conventional concrete. It is the construction of slabs where significant change occurs. Conventional concrete needs to be manipulated manually to conform to initial formation levels, followed by extensive compaction with vibrating tools, typically pokers. Level checks are required to ensure compliance with final levels, after which the slab can be floated to a semi-finished state prior to power floating. SCC, due to its

fluid nature, requires significantly less manipulation, no compaction is required, levelling demands are reduced and it is finished through a process of ‘dappling’ where shallow and surface waves are created to develop a flat finish. There are however some additional considerations for SCC that are not present with conventional concrete, such as formwork pressure and formwork integrity/quality, that do need to be considered as discussed earlier (Section 1.3.2).

In this case, the concrete frame contractor agreed to the decision to use SCC in the Echo 2 frame approximately four weeks prior to the commencement of construction works, at which point all major design work, resource allocation, planning and programming had already been completed. The concrete frame sub-contractor’s planning and resource allocation had been based upon historical and past project experience, with both the Echo 1 and Echo 2 structures approached as per typical concrete frame construction. Similar approaches were taken for each, however for the construction of Echo 2, the sub-contractor was using a non-typical concrete material, i.e. SCC, for the first time in a major structural application, a full multi-storey frame.

This was therefore an ideal opportunity to investigate SCC, in the context of conventional practices, so any intervention from the material supplier to optimise for SCC was minimal. No changes were made to try and realise SCC’s supposed improvements or indeed counteract its potential shortcomings (Section 1.3.6). Some planning and scheduling adaptation was required when supplying the SCC however; while the use of SCC was supported by Lafarge at a national level (Lafarge Agilia™ Product Development Manager), some change was required by the local team running the batching plant, who had initially planned to supply conventional concrete. Literature suggests that SCC production is more demanding and sensitive to subtle material changes (Section 1.3.2), with consequent potential detrimental effects on supply and performance, thus requiring a closer relationship between supplier and end-user.

The SCC produced for Echo 2 required a wet batch process to ensure quality, where the concrete was batched in 2m³ volumes before being discharged into the readymix truck and repeated, until the full truck capacity was reached. The conventional concrete, having a more robust mix design, could be dry batched, where the

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constituent materials are loaded dry into the readymix truck and with the mixing taking place in the drum en route to site as the water is added, typically halving the typical batching time. Truck capacity was also reduced due to SCCs fluid nature (due to potential spillage), which, combined with increased batching times, increased the demands on delivery (Lafarge Leeds Readymix Sector Team). This highlighted the issue that effective and consistent supply could be a detrimental factor in fully realising the proposed advantages of SCC, such as faster construction times (The Concrete Society and BRE, 2005). Increased co-ordination and communication was therefore required between the site teams and supplier. Late involvement of the supplier however, and a lack of changes to on-site planning, may compromise co-ordination and communication and as such, prevent further improvements such as savings in project overheads being realised (Holton, 2003).

Formwork, an issue still unclear in literature (Section 1.3.2), was also subject to discussion on the project; Lafarge stated that all formwork was required to be designed to accommodate full hydrostatic pressure. In the case of vertical elements research assurance was sought from the formwork supplier (for the cores) to ensure compliance. For columns and walls it was established that the conventional concrete approach taken by the concrete frame sub-contractor provided sufficient excess strength to withstand the any increased formwork pressure due to SCCs use. In horizontal applications the depth of slabs was not significant enough to provide any additional concerns other than conventional issues of supporting the dead load.

A steep learning curve was encountered, not only with formwork, but also with adapting methods typically employed when placing conventional concrete. In early pours the Echo 2 project manager reported that material loss occurred due to a lack of water tightness in the formwork, resulting in an increased demand in formwork quality, an aspect identified in literature (Holton, 2003). However, when the Project Manager was challenged on this, it became apparent that quality did not need to increase per se, rather that formwork construction standards had dropped to an absolute minimum, but one which would still allow conventional concrete work to be successful. Approaches were also adapted as the on-site team progressed along the SCC learning curve, demonstrated in changes to vertical element stop ends. Conventionally on a horizontally sectioned wall pour the formwork used to create the

end around the starter bars is of a comb design. For SCC individually notched segments were created by the carpenters, when employed they were placed directly on top of each row of horizontal formwork leaving smaller openings which could be blocked more easily by the SCC (Figure 3.7).

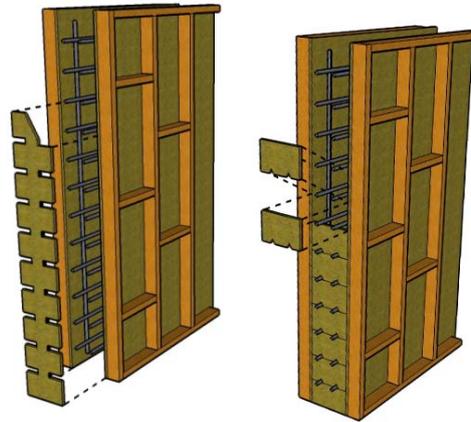


Figure 3.7 Illustration of changes to formwork practice (conventional left, SCC right) based on Echo 2 site team experiences

The learning curve on SCC extended into the start of placement activities. Lacking any prior experience, it was only once activities commenced that some changes were enacted. On Echo 1, the stiffness of conventional concrete meant it essentially stayed where it was placed, so reinforcement fixing and formwork construction could continue at the far edge of a slab. However on Echo 2 all formwork activities had to be completed prior to placement, according to the Echo 2 Project Manager because SCC has much greater flowability. As a result, the planning and scheduling of pours on Echo 2 had been based on the schedule for Echo 1, so this resulted in the late commencement of works, with knock-on effects for material suppliers and also for the material quality (The Concrete Society and BRE, 2005). Delays in the commencement of placement resulted in the queuing of trucks to waiting to discharge, subsequently creating a backlog of other works at the plant, delaying the ability to provide following loads (Lafarge Leeds Readymix Sector Manager). This then creates a stop in the placement process reducing the opportunities to save time and optimise labour. This emphasises the need for early changes to construction scheduling/planning processes and better communication between the on-site team and material manufacturer.

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Overall, it was difficult to ascertain if any changes in resource allocation were employed or if any changes were viable. It was noted by the sub-contractor's project manager for Echo 2 that the concrete gang for the placement of SCC could be reduced from five operatives to three, improving their productivity for concrete operations. However, it was also stated that concrete was not poured continually and that all five operatives were required to fulfil other roles and duties on the project as well, so there was some reluctance to reduce the gang size, in principle.

During the post construction phase of the project the project managers for both structures and the main contractor's project manager noted that the vertical finishes achieved with SCC showed a significant improvement over conventional concrete. The main contractor found that honeycombing on the conventional concrete core of Echo 1 (due to congested reinforcement), was not seen in the SCC application. Horizontal applications presented difficulties for both materials and highlighted increased construction quality demands. On the Echo 2 slabs, plastic shrinkage cracking occurred on the majority of floors, resulting in remedial works to seal cracks (though the sweeping of neat cement into cracks) to avoid any deleterious material ingress that could cause future problems such as corrosion (Echo 2 Project Manager). Plastic shrinkage cracking was seen to be a result of insufficient curing or the dilution and movement of sprayed-on curing agent through rain and wind, due to the exposed nature of the site. Echo 1's conventional concrete slabs presented some instances of non-conformance to specification. Both structures were subject to the same specification, but remedial works of grinding down to achieve a flat and level surface was required for the Echo 1 slabs. Over the two projects, the sub-contractor stated that remedial costs totalled £52,500, at a ratio of 5:2 in favour of the SCC structure (Managing Director of the Concrete Frame Sub-Contractor).

3.3.3 OUTLINE COST COMPARISON

It was clear that the late introduction of SCC on the Echo 2 project will necessarily have negatively influenced the likelihood of observing a fair, like for like comparison between SCC and conventional concrete for a structural frame. In data supplied by the contractor there was also a lack of sufficient detail to explain the build-up of cost

information. This precluded a detailed comparative analysis, but it was possible to draw out some tentative findings.

Based on the data provided by the contractor, Table 3.3 shows that the replacement of conventional concrete with SCC saved £2.25 per m³, or a reduction in construction costs of 1.65%. It should be noted that these costs do not consider the difference in price that exists between materials, i.e. the supplier's price per cubic metre. This simple analysis indicates that the effects derived from the (partial) adoption of SCC did have some value, albeit only at £2.25 per m³. Hence, SCC is not a viable construction option for the contractor as the higher price, sometimes up to 50% more than conventional concrete which can be purchased between £65-80 per m³ (material supplier), is not balanced. It does however reinforce earlier findings that the method of SCC construction can reduce costs.

Table 3.3 Outline costs for concrete frames in Echo 1 and 2.

Cost Category	Diff (£/m ³)
	£/m ³
<i>Labour</i>	
Carpenters	-4.48
Concrete	-0.13
<i>Plant</i>	
Concrete	-1.09
Pump	6.52
<i>Material</i>	
Timber/Plywood	0.03
<i>Other</i>	
Remedials	-3.11
<i>Total</i>	-2.25

* This table represents true projects costs, as of 1st quarter 2008.

Further analysis of the cost data, however, identified a significant discrepancy with respect to pump costs. This was consequently corrected through the interrogation of material supply records and plant hire costs were updated accordingly. The implication of this correction can be seen in Table 3.4, which shows a more accurate benefit from SCC, in this case: £7.06 per m³. While this still does not fully address the discrepancy between the material prices, the gap is certainly reduced.

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Table 3.4 Breakdown of costs resulting from the adoption of SCC with corrected pump costs

Cost Category	Diff. Echo 2 vs Echo 1
	£/m ³
<i>Labour</i>	
Carpenters	-4.48
Concrete	-0.13
<i>Plant</i>	
Concrete	-1.09
Pump	1.71
<i>Material</i>	
Timber/Plywood	0.03
<i>Other</i>	
Remedials	-3.11
<i>Total</i>	-7.06

* This table represents true projects costs, as of 1st quarter 2008

On-site it was acknowledged that the operatives required for placement operations could be reduced from five to three (Echo 2 Project Manager), reflecting statements made in literature (Section 1.3.6). The concrete labour costs for the project were subsequently revisited and adjusted. Table 3.5 shows the change within the context of the total concrete construction costs.

Table 3.5 Breakdown of savings resulting from the reduction on concrete placement labour

Cost Category	Diff (£/m ³)
	(Echo 2 - Echo 1)
<i>Labour</i>	
Formwork Carpenters	-4.48
Concrete Labour	-10.54
<i>Plant</i>	
Concrete Plant	-1.09
Concrete Pump	1.71
<i>Material</i>	
Timber & Plywood	0.03
<i>Other</i>	
Remedials	-3.11
<i>Total</i>	-17.48

* This table represents true projects costs, as of 1st quarter 2008.

Had these changes to operative numbers been employed, a significant change in the value of the SCC method would have been experienced. The implementation of these

modifications led to a significant change in the final comparative analysis, with saving increasing from 1.65% to 12.71%.

This study therefore provides further, indicative evidence of the potential to make savings by considering SCC as a method for construction, albeit based on incomplete data. It does not however fully expose the effects of constructing with SCC, because Echo 2 was not planned to apply SCC from the outset, so it could not have been undertaken to exploit the benefits offered by SCC. Nevertheless, this analysis provides the first, robust and transparent as-built costs comparing SCC and conventional concrete for frame buildings, and as such this study offers an important insight and contribution.

3.3.4 REVIEWING THE SELECTION OF SCC FOR ECHO 2

The application of SCC in Echo 2 was purely as a direct material substitution for conventional concrete and there was either a lack of acceptance, ability or time, to adapt or develop the construction processes to attempt to exploit its potential. The method of placing SCC is different to conventional practices and there are associated changes required to labour, plant and equipment that must be made to obtain any savings in time, materials or labour. Yet in order for these alterations to be made, SCC needs to be considered at an earlier point in the project, prior to decisions being taken on programming and resource allocation. For this reason, SCC should be treated as a method, not just a material, as discussed in the existing literature (Section 2.4). Indeed, it soon became apparent in Echo 2 that the introduction of SCC represents more than just a material substitution, as changes to the construction process were required. Paper 3 (“*Developing an ideal scenario for SCC: New findings from the UK*”) in Appendix B (Rich et al, 2009) describes these changes in further detail and describes an ideal scenario for SCC in the future.

On the basis of this study, it is therefore legitimate that SCC should be considered as a *construction method* rather than a *construction material*, thereby confirming and clarifying a concept which has been identified previously, but going beyond the

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previous understanding of the idea as presented within the literature (which was essentially a theoretical position based on incomplete evidence) (Section 1.3.2).

3.3.5 SUMMARY

The initial limited desk based study suggested that there were potential benefits to be obtained through the use of SCC as a replacement for conventional concrete, in the context of the on-site construction process. It did also highlight that significant subsequent research was also required. In assessing the Echo projects it was clear that the late decision to use SCC detrimentally affected the potential to realise any apparent changes to construction processes, as highlighted in literature (Table 1.3). The supplier's role in the success of major SCC projects had not previously been highlighted (only demands on physical material production Section 1.3.6). Scrutiny of this construction project demonstrated that closer and improved working relationships are required between on-site team and supplier to allow the full implications of SCC's replacement of conventional concrete to be assessed. Without the early and upfront consideration of SCC a significant onsite learning curve was encountered which could have been avoided through closer working relationships. Claims made in literature about the improved quality to be gained from SCC (Section 1.3.6) were achieved when compared to conventional concrete, on both vertical and horizontal elements, although some technical issue highlighted in literature were also encountered. The live project comparison of SCC versus conventional construction reinforced initial findings from the desk study. When the costs of the construction process of SCC are evaluated fully, it is evident that SCC can provide improvements in construction costs. This in turn provides some new empirical grounding to the idea that SCC should be viewed as a construction method, rather than a construction material.

As a result this section has addressed Objective 2, *to explore how SCC affects on-site construction*, by undertaking a desk study to validate the potential effect of the SCC method on on-site construction; identifying the requirements and challenges of implementing SCC in on-site construction and; determining the effect of SCC on on-site construction. It has also identified a number of obstacles that exist in enabling the effective implementation of SCC.

3.4 PROGRAMME AND COST QUANTIFICATION OF THE SCC METHOD

3.4.1 INTRODUCTION

The previous sections have established that deploying SCC as a construction method has implications for on-site planning and project organisational structures, but the question of quantification of the construction effects of SCC has not yet been addressed fully. While possible improvements are cited in many publications, the author has only been able to identify a limited number that provide any data. For instance, Table 1.3 identifies some reportedly ‘clear’ savings however, without an in-depth interrogation or evidence of their derivation, it is difficult to fully assess validity. This results in a significant shortfall in robust quantified data on the effect of using SCC as a replacement for conventional concrete, which continues to be unanswered through mainstream SCC research, which remains focused primarily on physical and structural performance properties (Section 1.3.7). Hence, this section of the thesis focuses on addressing this important gap and to quantify the effect of using SCC as a replacement for conventional concrete on-site (Objective 3, Section 1.4.2).

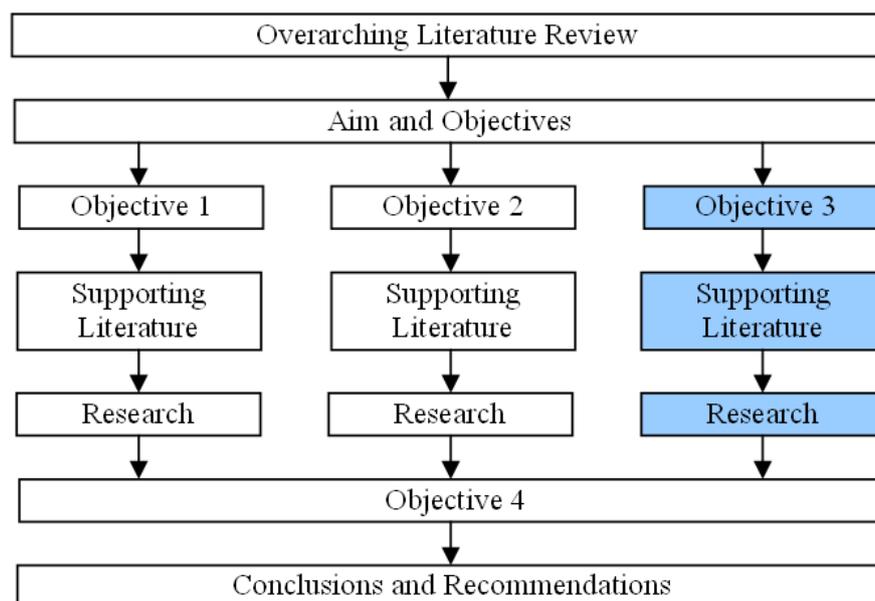


Figure 3.8 Layout of thesis structure identifying aspects covered in Section 3.4

3.4.2 SELECTION OF A SUITABLE CASE FOR QUANTIFICATION

It was clear from interviews undertaken with SME contractors, that SCC was being used regularly by them in the construction of housing slabs or oversite slabs. That said, it was not used exclusively, which suggests a lack of consensus over its suitability for that application. It is assumed that a threshold point for its use exists, i.e. a point when SCC becomes clearly advantageous over other options, but no sources were found in the literature to provide definitive, robust or quantified evidence about how, when or why this critical/tipping point occurs.

Prior to describing the precise technical design of such slabs, it is important to characterise the general nature of the housing market and the construction setting, such that the SME contractors' decision to include SCC as one of their preferred construction methodologies is made more apparent. First, the mass market house building in the UK is grounded on repeatability and standardisation of design to aid construction speed and delivery time, maximising the developer's return on investment (on the land value). This creates an inherent commonality in design between developments. Secondly, in the construction of house slabs and oversites, the concrete sub-contractor has full responsibility for placement, with the sub-contractor's employer (the main contractor), being more concerned that the chosen method delivers the completed slab on time, at the correct strength and at a suitable degree of flatness. Hence, the concrete sub-contractor is comparatively free to make changes to the methodology and material, so long as the specification is satisfied. This is not dissimilar to circumstances seen in the precast industry (Section 1.3.5), where one party has control.

Given this situation, structural concrete topping to residential suspended slabs (comprised of insulated block and beam construction) was the case selected as the subject matter for the quantification of the SCC process. There are two distinct forms of slab construction for residential developments: suspended (SS) or ground bearing (GB), for the comparison suspended slabs (SS) were measured. The increased supply cost of SCC makes SS more appealing than GB as less concrete is used due to the thin topping layer. The SS that were the subjects for comparison were precast concrete

beams with polystyrene infill blocks and a structural concrete topping layer (see Figures 3.9 and 3.10).

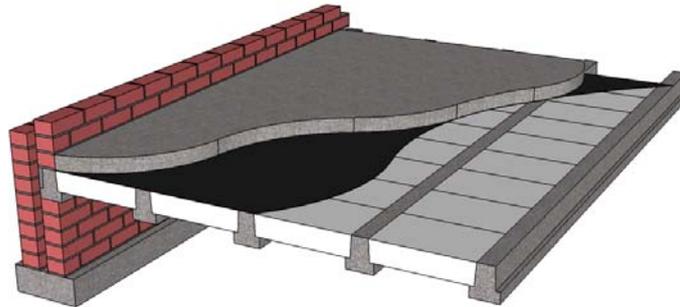


Figure 3.9 Illustration of in situ SS design

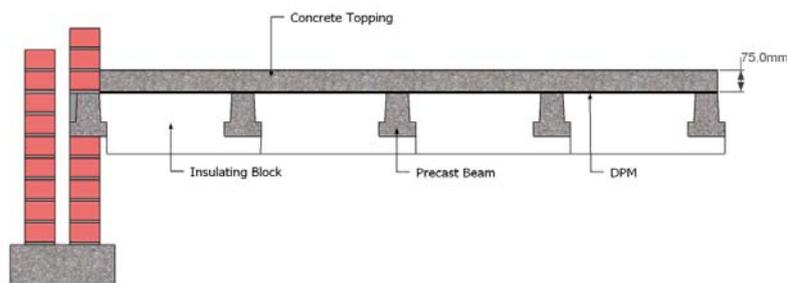


Figure 3.10 Section through typical SS block and beam construction

The construction of SS, based upon insulated block and beam systems, require a structural concrete topping in order to satisfy structural performance criteria (Hanson, 2010; Cube 6, 2012; Collectra, 2012). This precludes the use of self-levelling screeds, but both conventional concrete and SCC are used as they are able to provide the necessary mechanical properties and structural strength. Such topping slabs must therefore conform to British and Eurocode standards. However, alongside these, a most house building contractors also comply and register with National House Building Council (NHBC) Standards which provides home owners with a 10 year warranty and insurance (NHBC, 2011).

Clearly, the construction of housing slabs and oversites is only a small proportion of the potential market for SCC and only accounts for one circumstance for its use. Moreover, only the actual on-site construction activity associated with SCC is to be

analysed in this case; any wider implications, such as total project duration, changes to the critical path or changes to project team relationships, would not typically be examined within a work measurement study (as explained in Section 3.4.3). It is also possible that, on application in other settings, the technical or managerial implications from selecting SCC would differ from the chosen case,

Whilst it was not feasible to undertake such a study in this research, an ideal subject would be a mixed use development consisting of low and high rise developments for a range of uses i.e. commercial and domestic. This would present multiple opportunities for the application of SCC within complex project management structures. However developments of this nature are uncommon and it was not possible to identify such a case within the time available. Furthermore, when high rise projects are constructed they are typically one off, unique undertakings, making it unlikely that directly comparable builds would emerge (the aforementioned Echo 2 project is one such rare case, Section 3.3). This is in contrast to low rise which is typically based around repetition of design. In addition, whereas housing slabs and oversites (repetition of design) have only one party from whom buy-in is required, the complex nature of a high rise build requires agreement across the whole project team. The ability for a tier 2 supplier (such as an SCC supplier) to have sufficient leverage to facilitate this commitment (and to be engaged within a project at an early enough stage to recommend this course of action) would be extremely rare. In conclusion, the combination of these circumstances provides justification for the selection of housing slab and oversite concrete slabs and reinforces the validity and practicality of such a research strategy.

3.4.3 OVERVIEW OF THE WORK STUDY AND MEASUREMENT PROCESS

This section reports on a work study and measurement task which was undertaken on 14 housing projects in the 3rd quarter of 2010, with slabs varying from 37m² – 70m².

Work Study is a useful method of undertaking a comparison of construction methods. The overarching aim of a work study is to improve the productivity of a specific application or activity in a given environment, through a process of measurement and

intervention. Work study can be broken down into two distinct elements, Method Study and Work Measurement (Currie, 1977; Drewin, 1982; International Labour Organization, 1979), the former directed towards establishing the best method of carrying out a task and the latter determining the time required to carry out such a task. Method study is utilised to establish the ‘best’ or ‘most efficient’ means of carrying out a specific task. However in this case we are directly comparing two contrasting methods of construction, SCC and conventional, therefore a method study was not required. There may, however, it may be desirable for further method study at a later date to establish if there is a need for methodological improvements.

Work Measurement is used to establish the time required for a ‘qualified’ individual to carry out a specified task at a defined level of performance (BS 3138:1969), as such the method has formed the basis of this research. There are a number of methods that can be used for work measurement for which further detail can be found in the associated paper (Paper 5, “*Self-consolidating / compacting concrete: construction time and cost data from UK residential projects*”, Rich et al, 2012, Appendix E). Of the possible measurement options, a time study was deemed to be the most suitable.

The time study process requires the breakdown of the construction operation into a number of individual elements or activities (see Figure 3.11, these were timed and combined to create a total construction time. The construction operation employs more than one operative and there can be a number of activities carried out concurrently. Therefore, to ease analysis the on-site concrete construction process was filmed, with observations made when reviewing the films. For each pour, a number of observations were made:

- total pour time
- the time from initial material discharge to curing
- times for each individual construction activity
- labour times: time on the pour and time actively working.

Alongside the collating of time data, a number of additional records were kept including: slab dimensions and construction details, material design, labour and plant, and ambient conditions (see Appendix K). These details were collected to identify any

significant differences in the construction protocols and if any anomalies were present.

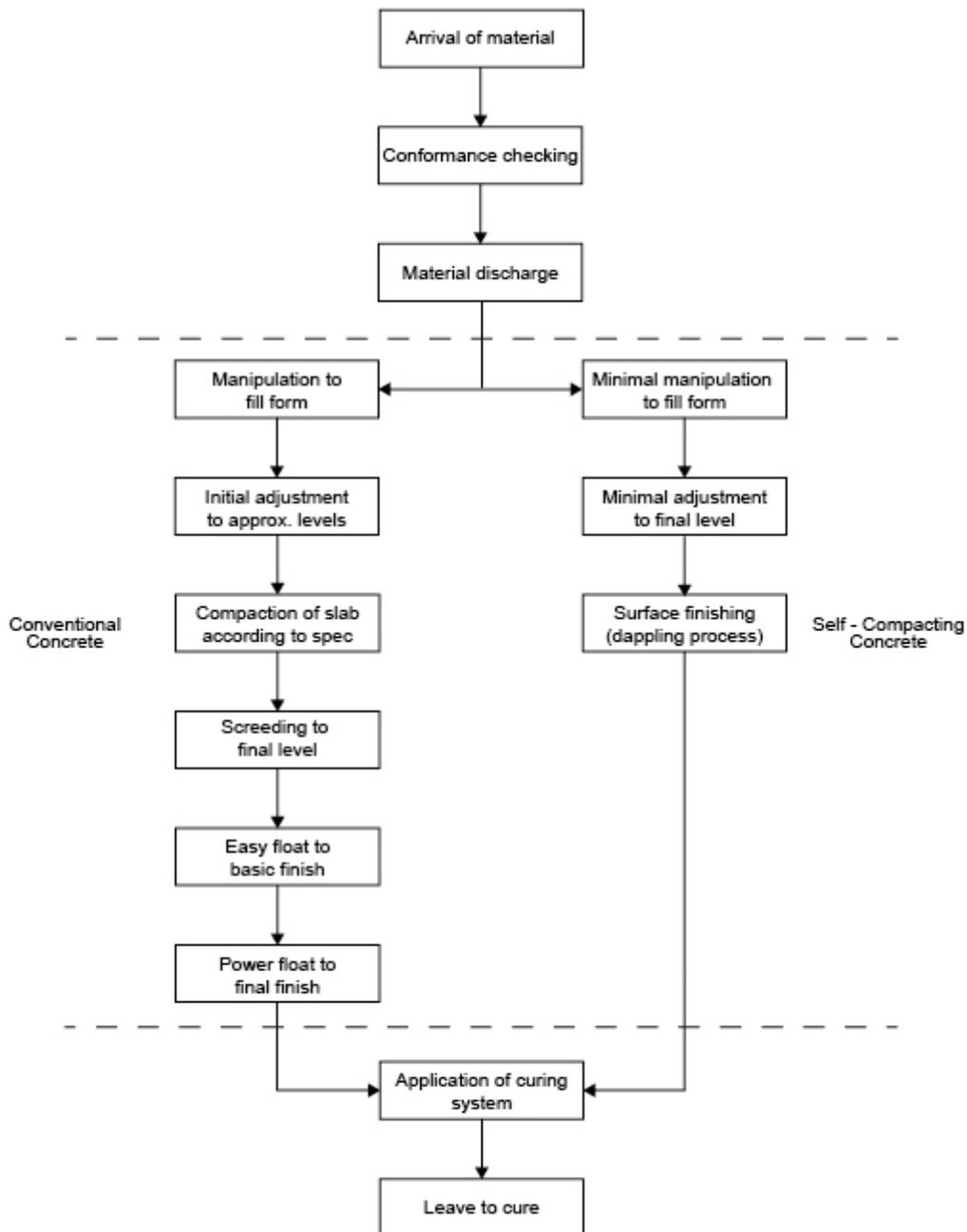


Figure 3.11 Flow chart illustrating and comparing the steps of conventional concrete and SCC placement in the construction of SS structural topping layers.

Figure 3.11 identifies the distinct stages that exist in the both construction approaches. The significant simplification that SCC brings when compared to conventional concrete construction is clearly highlighted through the removal of several steps in the conventional placing process.

An interesting observation was made on the variability of material supplied to fulfil the slab topping requirement for the housing projects. With SCC, it was clear that the mix had been standardised and developed for this specific application, as a proprietary product, with all sites receiving SCC that had been designed to a strength class of C28/35, utilising polypropylene fibres to combat drying shrinkage and a specified slump flow of 650mm. Conversely, the conventional concrete, supplied to the design of those placing the materials, varied significantly when compared to the SCC. Here, specified design strength ranged from the strength class of C16/20 to C28/35, with no consensus on the use of fibres for shrinkage and slump requirements varying from 70mm to 125mm. Furthermore, in two thirds of the conventional concrete pours observed, water was added by the sub-contractor on delivery to aid workability, yet this could have had a detrimental effect on gain and final strength^{††}.

Observations provided a range of data which recorded the time taken to place concrete in a SS structure. For each pour, it was possible to establish a total construction time, from initial discharge to the final application of curing protocol, along with intermediate breakdowns of each distinct phase of the operation: i.e. placement, tamping, screeding, floating, power-floating, dappling and curing. This data gave an in-depth description of the each pour, but it did not enable direct comparisons to be made, due to variations in slab sizes. So, the data was rationalised to a per m² rate to permit such comparisons. Subsequently it was possible to calculate an average construction time (ACT), per m², for both SCC and conventional concrete methodologies. Tables 3.6 and 3.7 present the rationalisation of construction times to enable specific comparisons of placement to be undertaken.

^{††} In circumstances where water has been requested to be added, it is the material supplier's policy that the contractor receiving the material must sign a waiver absolving the supplier of any responsibility should the material not perform as specified.

Table 3.6 Rationalisation of observed construction timings for conventional concrete construction.

Slab	C001	C005 – 1	C005 – 2	C006 – 1	C006 – 2	C007	ACT (min:sec) /m ²
Pour Time (mins:secs)	82:54	86:05	80:15	87:57	87:07	84:15	
Area (m ²)	41.83	37.80	37.80	16.50	16.50	56.77	
Volume (m ³)	3.14	2.84	2.84	1.24	1.24	4.26	
(mins:secs)/m ²	01:59	02:17	02:07	02:54	02:51	01:29	02:16

Table 3.7 Rationalisation of observed construction timings for SCC construction.

Slab	A002 – 1	A002 – 2	A003	A004 – 2	A004 – 3	A005 – 1	A005 – 2	A005 – 3	ACT (min:sec) /m ²
Pour Time (mins:secs)	28:40	23:15	45:40	23:15	30:50	22:15	23:30	40:50	
Area (m ²)	36.73	49.49	69:31	42.80	42.85	46.33	41.46	63.70	
Volume (m ³)	3.67	4.95	5.2	3.21	3.21	3.47	3.11	4.78	
(mins:secs)/m ²	00:47	00:28	00:40	00:33	00:43	00:29	00:34	00:38	00:36

Direct comparison of the ACT, on a like-for-like basis, illustrates that SCC can contribute to create a significant time saving over that of conventional concrete. The difference in pour time (T_{T2} = Total pour time per m²) and labour time (T_{L2} = Total labour time per m²), is significant, with SCC being some 73.5% quicker to place overall (see Figure 3.12, showing T_{PT2} = Total pour time including power floating per m²). Labour allocation is also reduced by 70% when final finished slabs are compared, when considering the placement of the slab topping (see Figure 3.12, T_{PL2} = Total labour time on slab topping activity including power float per m²), this is the amount of time in man hours spent by operatives allocated to the pour.

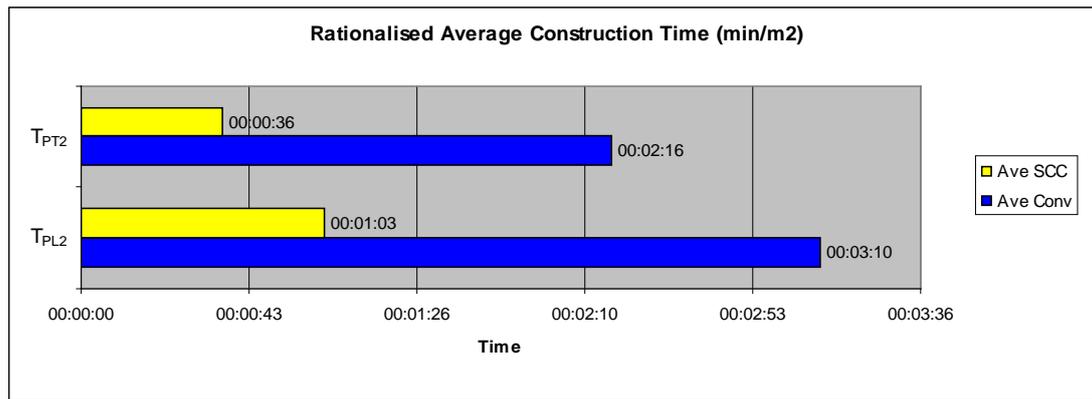


Figure 3.12 Direct comparison of conventional concrete and SCC construction methods to place and finish 1m² of topping (including power floating operation)

These results have been derived from direct observations of on-site construction practices and are successful in responding to a shortfall of SCC-related project data in the literature. This is the first research to study and document SCC practice and time in this way and it is evident that SCC can bring time savings to the construction process for this application, as shown in detail in Paper 5 (*“Self-consolidating / compacting concrete: construction time and cost data from UK residential projects”* (Rich et al, 2012), Appendix E). This data can also be extrapolated, which is discussed in the next section.

3.4.4 APPLICATION OF BASE DATA TO PROJECT SCENARIOS

The results reported above only identify a construction time saving per m² or per whole slab topping, if scaled up. However, this does not address one of the regularly cited barriers to SCC application, i.e. that the upfront material cost is more expensive than conventional concretes.

The application of the observed construction timings to construction scenarios enabled propositions to be made regarding overall construction costs. Three scenarios were developed from observations and analysed, and shown in Figure 3.10:

- ‘Best case’ conventional slab
- ‘Worst case’ conventional slab
- SCC case

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The two conventional cases were used to illustrate the effects of the power floating operation, for which completion is dependent on the rate of curing, as dictated in part by ambient conditions. Costs and timings have been based on the construction of a residential SS of a similar design (area: 9m x 5m, depth 0.075m), to those from which initial data was collected. The difference between the worst case and best case is largely down to ambient temperature. This is because the time after completion of the pour to the start of power floating is dependent upon the hardness of the slab surface and the time taken to reach this hardness can vary significantly.

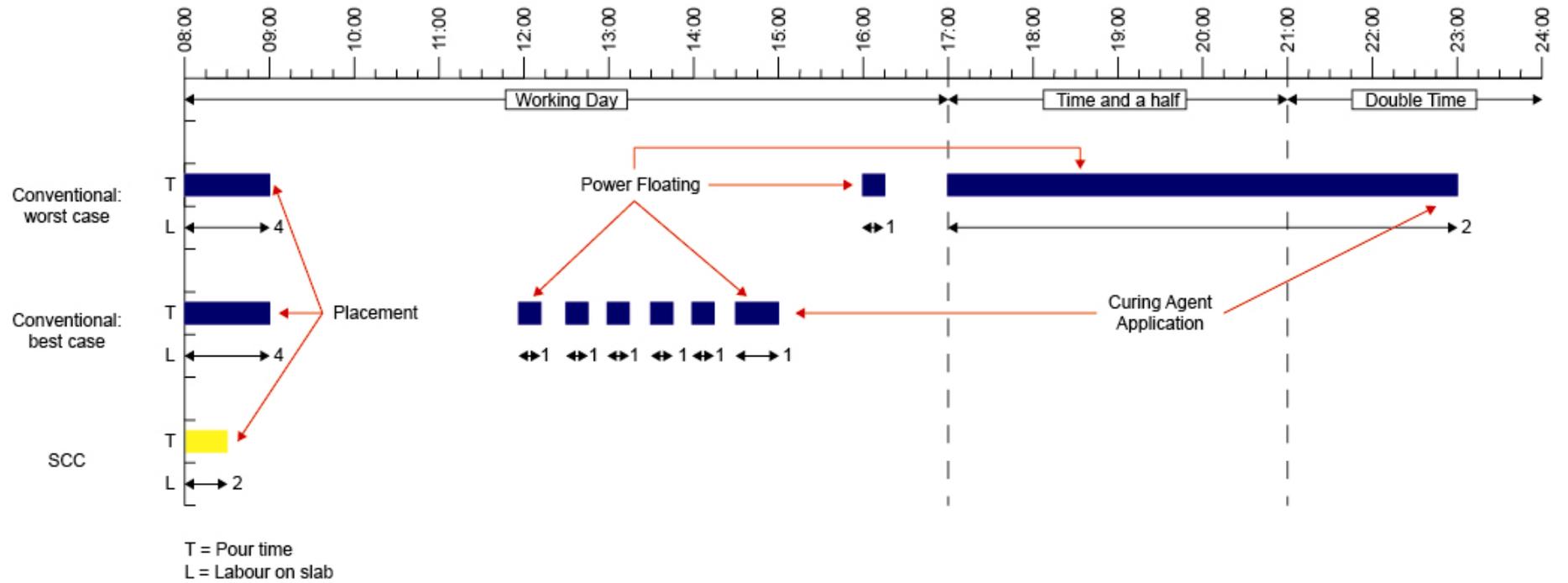


Figure 3.13 Gantt chart displaying the idealised construction scenarios for SCC and conventional concrete construction, with time, T, and labour, L, requirements

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Figure 3.13 shows that, in addition to a faster placing time, the main time and cost benefit lies in the fact that SCC does not require a power floating operation to achieve the required flatness and surface finish. This affects the costs significantly since, in the worst case scenario at least, the power floating continues into the ‘out of normal hours’ working, which results in additional labour costs.

Scenario results have been based on the ‘time to construct’ data; however additional aspects have also been considered to create industry relevant examples (Table 3.8).

Table 3.8 sets out a description of several specific considerations which have been applied to improve the quality (and internal validity) of the cost comparisons. The results of applying this to the previous scenarios (Figure 3.13) can be seen in Table 3.9. It has therefore been possible to draw more fulsome conclusions on the use of SCC for construction of concrete topping layers.

Table 3.8 Specific considerations included in the build-up of construction costs.

Cost	Description	Details
Material	Material price for both materials included. Costs were average UK retail costs of concrete supplied by Lafarge Readymix.	Costs: SCC £112.78 per m ³ , Conventional £74.84 per m ³ . Based on survey of Lafarge Readymix, 18 sectors operating throughout the UK.
Overheads	Encompasses all the plant and equipment costs for each construction method.	Costs from nationally operating tool hire companies. (Rakes, Dapple bar, Sprayer, Shovel, Level, Float, Tamp Bar, Power Float)
Curing Agent	Cost for the amount of curing agent applied to the slab topping layer. Whilst this can be technically included in the overheads category it has been identified separately to identify the requirement to cure concrete.	Curing agent cost provided by Lafarge Readymix at a price of £0.10 per m ² , applied to all construction scenarios.
Placement	Conversion of work measurement time data to costs, based on the application of CIJC ^{‡‡} recommended rate of pay (Up to but not including power floating activity). Based on observations the SCC pour utilises two operatives where the conventional requires four.	CIJC (CIJC, 2010) provide industry/union agreed minimum rates of pay. Skill Level 4, concrete operatives, has been used in calculations £8.35 per hour. On costs for labour employment has been set at 100% after discussion with Quantity Surveying consultant Turner and Townsend.
Power Float	Cost for the labour commitment required to undertake the power floating operation.	
Curing Labour	Cost for the labour to apply curing agent.	Observed conventional concrete slabs were left untreated contrary to best practice. Labour timings for this activity were utilised from the SCC method.
Out of Hours	Cost of labour used in out of hours working, based on CIJC rates of pay for out of hours working. When working out of hours a minimum of two operatives must be present on health and safety grounds.	CIJC rates of pay set out the working hours and the subsequent rates for work exceeding these, first four hours time and a half followed by double time.

Note: All costs current at 1st quarter 2011

^{‡‡} Construction Industry Joint Council

Table 3.9 Costed^{§§} construction scenarios illustrated in Fig 4.11, identifying the total cost of the concrete topping element of slab construction.

Cost (£)	SCC	Conventional Concrete	
		Worst case	Best case
Overheads	2.00	43.33	43.33
Placement	15.22	57.02	57.02
Power Float	0.00	2.37	14.20
Out of Hours	0.00	334.00	
Material	380.63	252.59	252.59
Curing Labour		Included in O/H	2.09
Curing Agent	6.75	6.75	6.75
Total As-Built	404.60	696.05	375.97
Difference from SCC	n/a	+ 291.45	- 28.63

It is clear from Table 3.9 that construction with conventional concrete is susceptible to significant variation in the cost to construct, as a result of the power floating operation. In the worst case scenario, costs are 85% greater than SCC, which if encountered on a number of slabs would significantly increase total project costs. It is in comparison to as-built costs where, once again, significant improvements can be seen. SCC provides a substantial saving, £291.45, for the completed slab construction, over the worst case scenario of conventional concrete. NB: as the delay before power floating is mainly dependent on ambient temperature, the worst case scenario for conventional concrete is more likely to occur in colder winter months.

However, compared to the conventional best case scenario, which is more likely in warmer summer months, SCC is more expensive by £28.63. So, it is possible to identify which factors are prevalent in determining the most suitable method. With respect to SCC, material price is the most significant factor. The determining factor for conventional concrete is labour and out of hours working has a significant influence on final cost.

^{§§} Overheads see Table 3.10 Placement costs are a function of Labour time illustrated in Figure 3.13 and labour rates see Table 3.10. Out of hours working is based on the presence of two operatives for health and safety requirements. Material price has been derived from average national rates per m³ provided by Industrial Sponsor: SCC £112.78 and Conventional £74.84, and are current at 1st Quarter 2012.

So, the conclusion from this study is that the relationship of material price to labour cost determines the tipping point between conventional concrete and SCC for this application. Having established this, it has been possible to establish the maximum permissible premium (P_{\max}) per unit volume (m^3) that can be applied to SCC, on the part of the supplier, such that the contractor can achieve parity between the complete, as-built costs for both conventional and SCC construction methods (and therefore be at no overall disadvantage from using SCC).

In the best case scenario example, P_{\max} is determined with respect to slab size and labour rate (based on the construction of a 75mm deep topping on block and beam), parity is achieved at a P_{\max} of £29.46 per m^3 . Further appreciation of the cost interactions can be seen in Figure 3.14, which illustrates the relationships between material cost, labour rate and slab size. Using this graph (based on the scenario slab design and conventional concrete cost), it is possible to determine P_{\max} in regards to the operative rate of pay. The graph also enables the determination of as-built cost saving (or additional cost) if P_{diff} (cost premium of SCC over conventional concrete) and operative rate of pay are known.

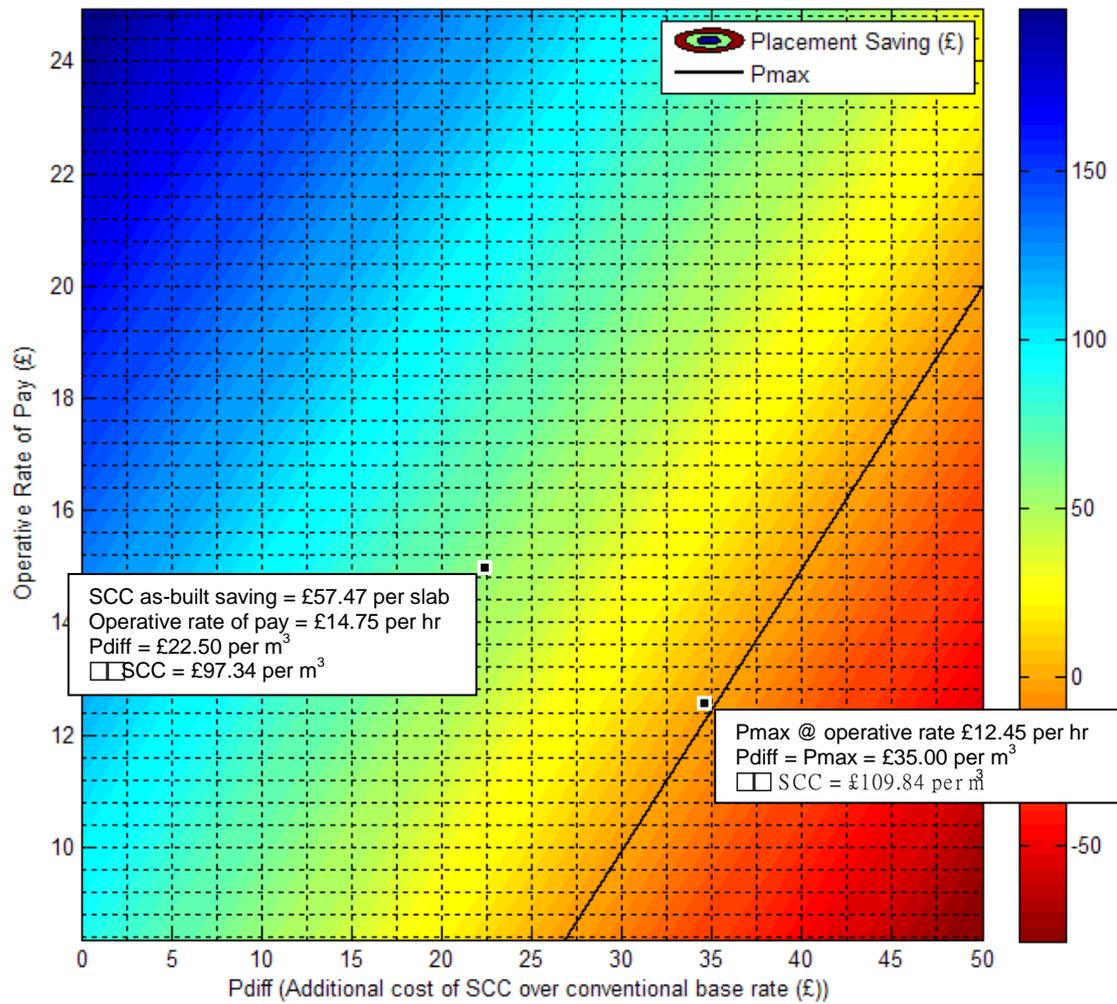


Figure 3.14 Graphical representation of P_{max} relationship and as-built cost, with respect to operative rate of pay and additional material cost of SCC.

(Conventional Base Rate £74.84, Slab Area 45m², Slab Topping Depth 0.075m, Best Case Scenario)

Figure 3.14 shows the relationship between additional cost of material and labour rate for a specific slab design. It allows the reader to determine P_{max} at a range of labour rates and SCC costs, and clarifies if any savings or additional costs would be incurred by using SCC. In principle, this enables the on-site team to make a balanced decision on the suitability of SCC for specific construction applications.

Further, detailed analysis indicates a distinct relationship between slab size and P_{max} (Figure 3.15); as slab size increases, P_{max} decreases, effectively reducing the cost benefit offered by the SCC method. However, at low labour rates, P_{max} is small because of the relationship that exists between material and labour cost; material price is the significant variable for SCC, and labour is the key variable for conventional

concrete. When the labour rate is low, the difference between material and labour is at its greatest, which reduces the viable P_{\max} , as this is a function of the difference in as-built construction costs, which are determined by material and labour costs. As labour costs increase for the same sized slab, material costs remain constant. This, in turn, reduces the as-built cost difference between methods and enables parity to be achieved at higher values of P_{\max} . As previously stated, as slab size increases, P_{\max} decreases, however for the same slab, it is possible for there to be two distinct timings and costs resulting from extended working hours, due to colder ambient conditions. In light of this, the relationship between P_{\max} and slab size in these circumstances may vary.

If out of hours working is incurred during construction with conventional concrete, when compared to SCC (as in Table 3.9), the relationship between material cost and labour rate will vary. Here, the difference in constructed costs will reduce to a point where conventional construction costs will exceed SCC, i.e. the worst case scenario. The amount of out of hours working is determined by two factors, firstly ambient conditions and secondly the slab size. If ambient conditions were to remain constant for a number of slabs of increasing size, the increase in out of hours working would be proportional to slab size. P_{\max} is directly related to these factors and there would, once out of hours working is undertaken, be a change in the relationship, with slab size increasing, rather than decreasing, and so improving the as-built cost benefit of SCC.

More detailed analysis of the relationship between operative rates, material cost and slab size enabled the development of a simplified P_{\max} relationship graph (Figure 3.15).

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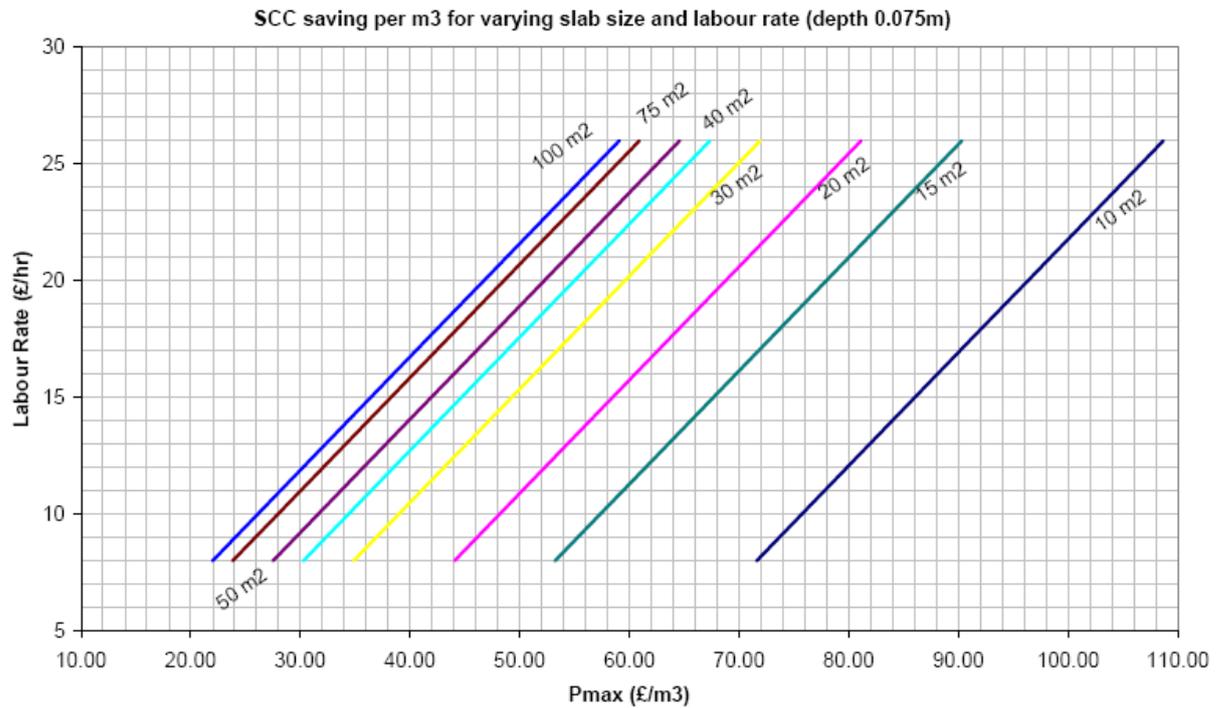


Figure 3.15 Simplified graph of P_{\max} relationship for varying slab size and labour rate (for a slab topping depth of 0.075m)

Figure 3.15 shows the variation of P_{\max} against operative rate with respect to slab area, based on a particular slab design. Here, it is clear that a significant reduction in P_{\max} would make SCC undesirable for the producer as this impinges on its commercial viability. However, a high P_{\max} detrimentally affects viability in terms of parity between methods and potential savings for the on-site team. Subsequent research, into the adaptation of P_{\max} for concrete frame flat slabs, enhanced the understanding of the relationships between these factors, as explained in section 3.4.6 and within Paper 5 (*“Self-consolidating / compacting concrete: construction time and cost data from UK residential projects”* (Rich et al, 2012), Appendix E).

As a result of this research, the maximum permissible premium, P_{\max} , is a value that can now be defined for residential suspended slab construction; this clarifies the cost and time characteristics of SCC construction and provides a mechanism for an SCC supplier to overcome the problem of higher initial price compared to conventional concrete. Whereas existing literature (The Concrete Society and BRE, 2005) has stated that the material cost of SCC is prohibitive to its selection, it is now feasible for the on-site team to deploy P_{\max} as a clear and holistic method of determining the real

limits of when SCC will and will not be a viable option. It will be of particular value for projects in which out of hours working is likely and can be determined.

Alongside the quantified benefits of construction time and cost, certain other aspects were noted from site observations and analysis. The first was SCC's ability to improve the predictability and reliability of the construction process. This was ascertained through the examination of the standard deviation of time for each construction method (Paper 5, "*Self-consolidating / compacting concrete: construction time and cost data from UK residential projects*" (Rich et al, 2012), Appendix E). Standard deviation (SD) is a measure of the variability of a set of results and measures the dispersion from the average of said set of data, Table 3.10 shows SCC SD to be significantly less than conventional concrete.

Table 3.10 Standard deviations for conventional and SCC construction methods.

Standard Deviation (SD)		
	Conventional	SCC
T _{T2}	33	7
T _{L2}	36	16
T _{A3}	18	14

Where T_{T2} = Total pour time per m²

T_{L2} = Total labour time per m²

T_{A3} = Total active labour time per m²

While SCC provides a definitive construction time benefit, this statistical analysis shows that it is possible, by comparing placement rates, to draw conclusions on predictability and reliability. The outcome is that the planning and programming of the construction project can be improved and can be more efficient. Selection of the SCC method means that there is an increased degree of reliability that work will adhere to the construction critical path and therefore offers the contractor the opportunity to reduce risk. Again, no previous research has interrogated SCC in this way, so this is a new finding, albeit tentatively based on observations from 14 sites.

3.4.5 INTERPRETATION FOR CONCRETE FRAME FLAT SLAB CONSTRUCTION

As explained previously, the work measurement investigation focussed on residential slabs. However, this section broadens this aspect to flat slabs within larger, framed structures.

This analysis was based upon slab information from the Echo 2 structure (as described earlier in Section 3.3) which was constructed with SCC, and information had been obtained from previous research by the author (Section 3.4.3). The original construction plan divided each floor slab into two pours to create a more efficient method of construction that enabled the cycling of formwork and falsework, providing a constant supply of work for concreting operatives, carpenters and general operatives. These slab areas were 387.5 m² and based on a depth of 0.25m, required 96.875m³ of concrete. Figure 3.16 shows the floor plate of the Echo 2 structure which was used as the basis for subsequent analysis.

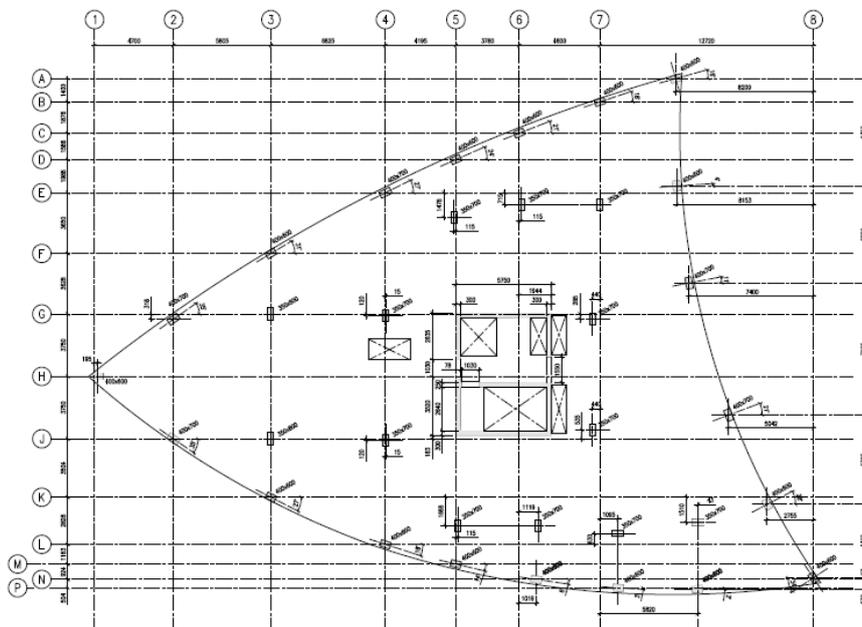


Figure 3.16 Floor plate of the Echo 2 structure

From observations of Echo 2, the SCC placing process was very similar to the residential slab pours. The depth of the Echo 2 slab was greater but, as the concrete was delivered by pump rather than the bucket of an excavator, the overall placing time was very similar. The delivery rate from the supplier was also increased to match the placing speed. The residential slabs did not have reinforcement seen in Echo 2, however, the SCC flows around the steel without any manipulation by operatives and so the placing activities were similar. Subsequent operations such as dappling were the same in both the residential and Echo 2 slabs and, once again, the SCC slabs did not need power floating to achieve the required finish. Therefore the timings for the Echo 2 slabs have been taken as the same as the residential slabs and increased pro-rata based on the surface area. Similarly for conventional concrete, the residential processes and timings have been taken and applied to the Echo 2 scenario. However, it is acknowledged that, had Echo 2 used conventional concrete, then poker vibration would have been necessary which would have added hire cost and an activity (however, this extra operation has not been included in the subsequent calculations).

Alongside construction rates, material costs, plant, equipment, pump and curing agent costs have all been revisited to provide up to date and relevant costs for the Echo 2 comparison. Out of hours labour rates have been included as it would not be possible to complete the construction operation within standard working hours. Figure 3.17 illustrates the scenarios that would be encountered during the placement process for the construction of the idealised Echo 2 floor slab, based upon the residential slab research findings.

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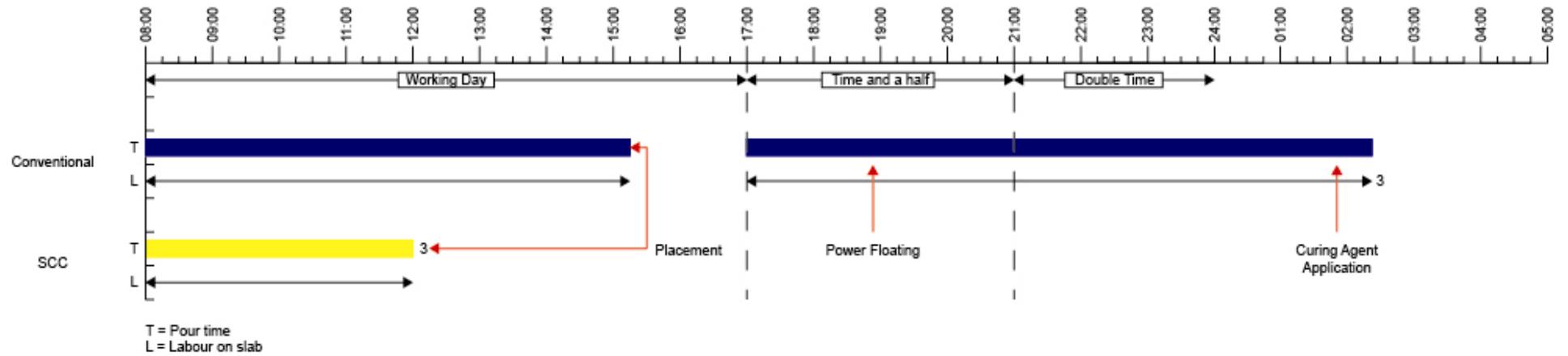


Figure 3.17 Flat slab construction Gantt chart displaying scenarios for both SCC and conventional concrete construction, with time, T, and labour, L, requirements

The comparison of construction approaches for flat slabs shows that SCC, in this specific case, is more expensive than conventional concrete (Table 3.11). The SCC option is 26% or £2,521.48 more expensive than conventional concrete. However, the addition of the costs for the poker vibrators on the conventional option would close the gap somewhat. Table 3.11 takes into account the aspects that are directly linked to the placement operation, identifying the specific areas where improvement can be sought.

Table 3.11 Comparison of costed construction approaches, as illustrated in Fig. 4.15, illustrating total cost of construction.

	Conventional	SCC	
Concrete Cost (£)***	7071.875	11431.25	
Plant Cost (£)	105.12	28.12	
Curing Agent (£)	58.13	58.13	
Pump Cost (£)	871.20	544.40	
Labour Cost [In Hours] (£)	613.73	196.56	
Power Float Labour (£)	Incl. Out Hrs.	N/A	
Curing Labour (£)	Incl. Out Hrs.	N/A	
Labour Cost [Out Hours] (£)	1016.92	N/A	
Total Cost (£)	9736.98	12258.46	
Cost Difference (£)		+ 2521.48	Difference
Cost per m ² (£)	25.13	31.63	26 %

Based on these findings in isolation, SCC does not present itself as a viable construction option for these suspended slabs. The deliberate scheduling of extended out of hours operations is unusual. However, out of hours working demonstrates the inherent variability that exists with conventional concrete approaches and in a way, a worst case scenario. The susceptibility of conventional concrete approaches to changes in working conditions, such as temperature, means that out of hours working sometimes cannot be avoided.

In light of these issues it is worthwhile exploring the effect that the SCC construction method has on the accumulated as-built construction costs, which has shown some interesting outcomes. Table 3.12 illustrates where the major costs for constructing

*** Material costs: SCC £118.00 per m² and conventional £73.00 per m², Lafarge Nottinghamshire sector, current as of 1st Quarter 2011.

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with either conventional concrete or SCC occur, providing a clearer understanding of the financial benefits of SCC.

Table 3.12 Illustration of cumulative construction costs, demonstrating the build-up of costs from first (material) cost to as-built cost.

	FS Con £/m ²	Change	FS SCC £/m ²	Change	SCC – Con Difference £/m ²	Change
Material	18.25	n/a	29.50	n/a	+ 11.25	n/a
Plant / Equipment	18.52	1.4 %	29.57	+ 0.2 %	+ 11.05	- 1.8 %
Time and Labour	20.61	11.3 %	30.23	+ 2.2 %	+ 9.62	- 12.9 %
Pump Cost	22.86	10.9 %	31.63	+ 4.6 %	+ 8.77	- 8.8 %
Out of Hours	25.13	9.9 %	31.63	0 %	+ 6.50	- 25.9 %

Considering the construction method significantly reduces the effect of initial first cost, material price, of SCC. Construction costs are reduced by 42% or £4.25 per m³, which is a significant improvement. With the change in cost being considerable, as before, it is worthwhile considering P_{\max} for this slab. Based on the material costs used in the flat slab scenario, Table 3.13 identifies that the cost of SCC for parity would be £91.97 per m³.

Table 3.13 P_{\max} for concrete frame flat slabs.

	Value
Cost Difference (£)	1837.89
Slab Volume (m³)	96.875
P_{\max} (£/m³)	18.97

The relationship between P_{\max} and contributing as-built costs has once again been explored, as shown in Figure 3.18.

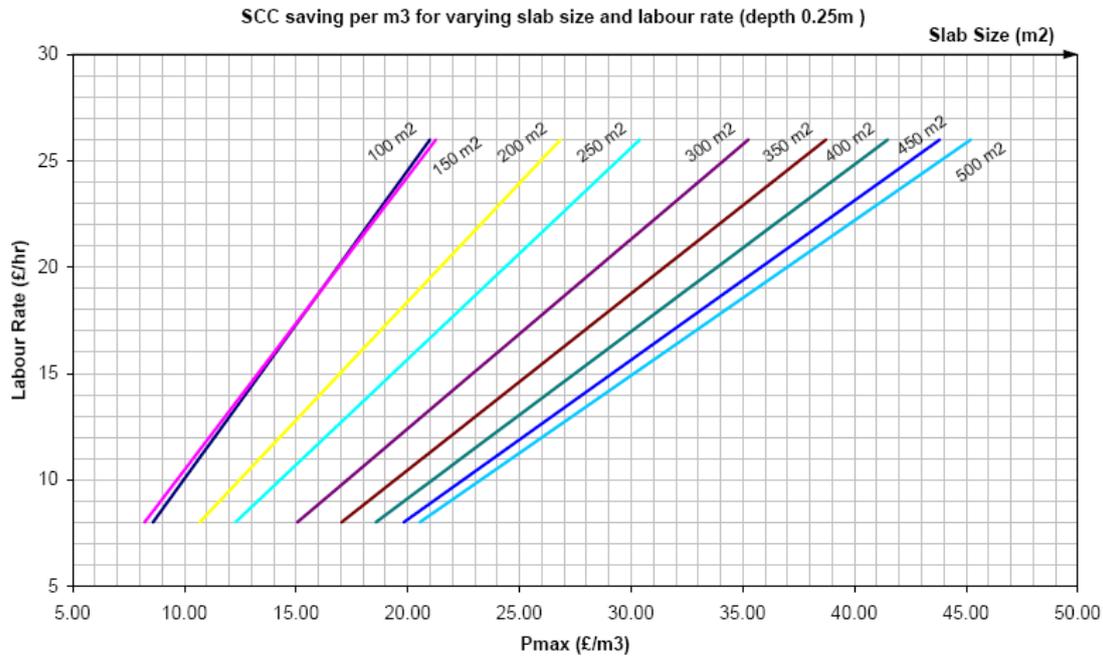


Figure 3.18 Simplified graph of P_{max} relationship for varying slab size and labour rate (depth 0.25m)

The P_{max} graph (Figure 3.18) is the reverse of what has been seen for residential slabs; as slab size increases, P_{max} also increases, which means SCC becomes more viable. This trend reversal is a direct result of including out of hours working, which changes the balance between material cost and labour cost. Out of hours working not only sees an increase in the rate of pay for operatives, but for health and safety reasons requires additional operatives to be present on site. If the worst case scenario was considered in the residential slab scenarios, a similar trend could be expected, were it to be applied in flat slabs. Once out of hours working is encountered, the shift in the balance of costs sees larger slabs become more viable for SCC (Figure 3.19) due to the increase in the cost of labour.

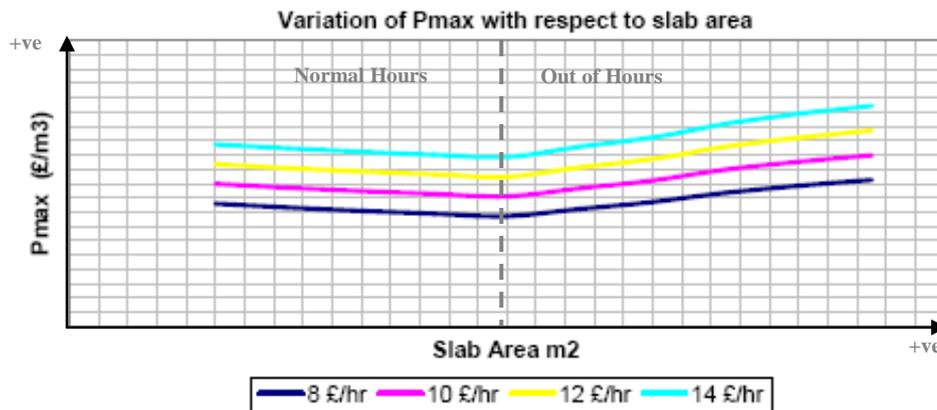


Figure 3.19 Illustration of the effect on P_{max} caused by the requirement to undertake out of hours working

As slab size increases, the time requirements for placement increases, they are directly proportional (Figure 3.19); when out of hours is subsequently incurred a step change occurs in labour pay. Out of hours sees labour costs change to 1.5 times the standard rate initially then two times after four hours. The significance of this is that the SCC premium remains constant whilst labour rate increases, and as slab size and placement time increases. As a consequence, as slab size increases, the labour rates account for a larger and larger percentage of total costs, which reduces the impact of the initial SCC premium.

It is clear that through the determination of P_{max} , the concept of P_{max} and its definition in specific construction applications the threshold between SCC being a viable or unviable method can be transparently and accurately identified. When viewed solely as a construction material the use of SCC could be defined an expensive 'luxury', due to its increased cost over and above that of conventional concrete. However, this research has shown that, when considered as a construction method, with the changes that this brings to the construction process, it is possible to overcome this initial cost barrier and identify where savings can be obtained from the use of SCC and the amount of money that can be saved by so doing.

3.4.6 QUALITATIVE OBSERVATIONS OF THE CONSTRUCTION PROCESS

Throughout the data collection process observations of a qualitative nature were made on the processes that were carried out by the site teams. These observations provided additional context and answers to questions raised within literature, such as SCCs success in pre-cast (Section 1.3.5) and skill levels in the placement process (Section 1.3.2). Parallels between this application of SCC and its use in the precast industry could be seen; with respect to the repeatability that was observed in the placement process of the topping layers. Precast has seen a significant uptake of SCC due to the repeatability of processes and the development of operative skills, consistency of activities and the optimisation of the placement process (Section 1.3.4). It could be argued that a single housing site displays some similar characteristics to a precast factory; repeatable similar activities (topping of block and beam) and specialisation of operatives who can optimise the process, a possible driver for the realisation of improvements. However, this resemblance cannot be identified as the only reason, as insitu applications are subject to significant variations in placement conditions which can have far-reaching implications (best case and worst case, Section 3.4.4)

Additional risk reduction can be achieved through the adherence to construction standards; a number of contractors involved in the study were working on National House Building Council (NHBC) accredited projects and are therefore required to comply with NHBC standards.

In accepted good practice and in accordance with NHBC's Standards 2011 (Part 2 – Materials: 2.1 – S10, (c) placing), no water should be added to a concrete mix unless approved and under the supervision of the concrete supplier, as this can cause deviation from specification and performance properties. In two thirds of conventional concrete pours observed water was added in order to aid workability, requiring the waiving of the supplier's liability by the contractor should the material not perform as specified. Compaction, part (f) of the standard, states that it is acceptable to compact slabs less than 150mm in depth via manual or vibrating beam, however slabs exceeding this depth are required to be mechanically compacted, i.e. vibrating pokers etc. Whilst the slab topping layers in this study conformed to the preceding

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requirements, three slabs of a depth greater than 150mm were also observed. In these cases only manual compaction was employed. Throughout the study it was also observed that no slabs constructed with conventional concrete, unlike those with SCC, received any form of curing, contrary to requirements of NHBC (part G) Protection after placing. SCC can therefore be said to reduce construction risks by ensuring quality and compliance with construction standards.

3.4.7 SUMMARY

This section has addressed Objective 3, *to quantify the effect of using SCC as a replacement for conventional concrete on-site*, by measuring the on-site processes associated with the SCC method when used as a replacement for conventional concrete.

The work study employed in the generation of the findings presented in this section is a robust approach that has not been identified in the SCC literature (Section 1.3.6). This approach has enabled a clear definition of the scale of saving and when those savings can be realised by employing SCC as an alternative to conventional concrete. Conventional concrete construction has been shown to exhibit significant variance in construction processes which is not evident in the SCC construction method. SCC has been illustrated to be more predictable than conventional concrete construction which has been demonstrated in the application of costs to real life scenarios.

For the first time the relationship between influencing costs (material and labour) and construction time has been determined in the form of P_{max} . P_{max} allows the on-site team to make balanced and informed decisions on the suitability of SCC. It identifies precisely the circumstances where parity exists between conventional and SCC construction costs. It is the first time that research has been undertaken which can openly provide and calculate details of the relationship between on-site practices and the cost of construction for SCC.

3.5 SCC AS AN INNOVATION: EXPLAINING THE ADOPTION GAP

3.5.1 INTRODUCTION

The preceding research has provided a quantitative clarification of characteristics that SCC presents when considering it on-site application. This section aims to draw together these findings and provide an overarching interpretation of the results, in order to create a broader understanding of the adoption and use of SCC. The intention is to identify the current position of SCC as an innovation in UK construction industry (Objective 4, Section 1.4.2) in relation to the preceding findings and identify if its level of use reflects the scope of potential benefits identified or, if not, what changes might be required to construction practices.

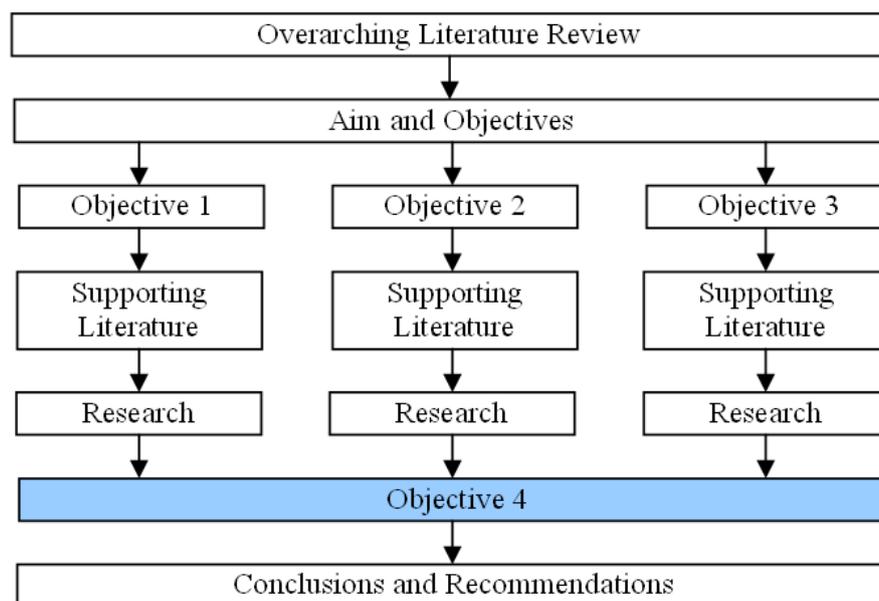


Figure 3.20 Layout of thesis structure identifying aspect covered in Section 3.5

3.5.2 THE USE OF MATURITY CYCLES TO EXPLAIN ADOPTION OF INNOVATION AND THE SCC ADOPTION GAP

Useful perspectives on the uptake of innovative technologies can be taken from the use of maturity cycles, which chart the development of a technology innovation from

initial conception to widespread acceptance. One such maturity cycle is the Gartner Hype Cycle (Gartner, 2012), which aligns specific stages of development to industry perceptions or visibility and is shown in Figure 3.21.

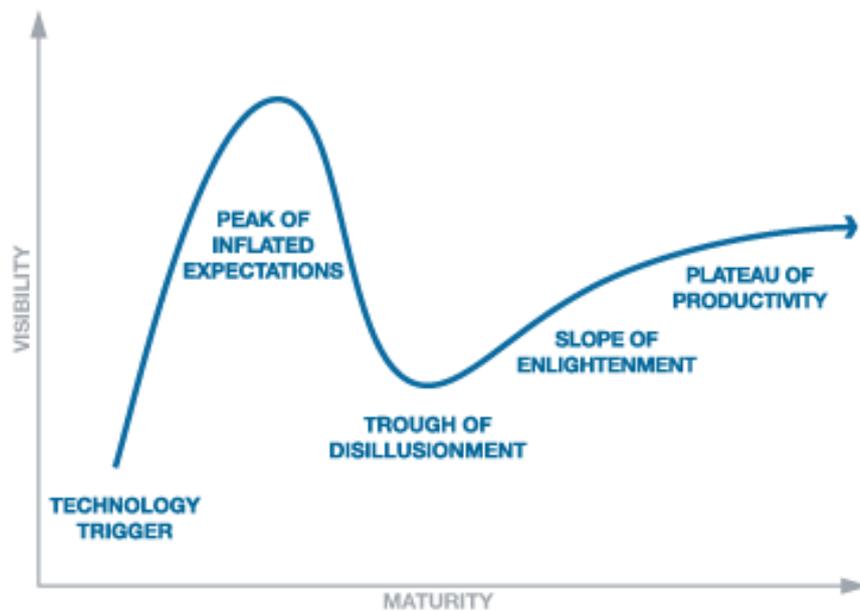


Figure 3.21 Gartner Hype Cycle (source Gartner, 2012)

Essentially, Gartner (2012) presents a model that charts the development from initial creation to the peak of inflated expectations as a period of time where many benefits are widely publicised with few successes, but many failures. This is rapidly followed by a downturn based on experience, termed the trough of disillusionment, as interest and uptake wanes. If the innovation or new technology is worthwhile however, it will see an increase in instances of use and realisation of benefits (the “slope of enlightenment”) progressing to a point where it has broad appeal and clear benefits, i.e. Gartner’s (2012) final stage, the plateau of productivity.

Reflecting on the model, it is possible to offer some explanation regarding the development of SCC, based on the Gartner cycle. The cycle has been beneficial to help frame this section of the research, but as it has not been fully explored through this particular theoretical lens, the account here is necessarily concise.

It has been clearly established in the literature that development of SCC was in response to issues that existed within the Japanese construction industry (Section 1.3.2). Similar circumstances were also experienced outside of Japan which helped the market expansion of SCC, and led to the identification of a number of potential benefits associated with its application (Section 1.3.6), which should have helped facilitate its successful uptake. However, through the discussions with concrete frame contractors (Section 3.2), it was made clear that they were not able to achieve such benefits and thereby utilise SCC in a wide range of applications. Hence, they stated that its use was *'application-led rather than a conscious decision'* and that SCC was able to *'resolve and remove problems'*, replicating only the initial development path witnessed in Japan. Improvements reported in literature (Table 1.3) appear to be linked primarily to large construction projects and although this might suggest that the concrete frame contractors could have viewed SCC in a favourable light, this was not the case in practice.

The position of SCC prior to the undertaking of this research could be described through understanding the maturity of specific SCC applications as well as onsite construction as a whole, yet a clearer understanding can be derived by considering specific applications. Where the role of SCC as a specialist, reactive or problem solving material is concerned, its use in these cases is described and supported in literature and through interviews with contractors (Section 3.2.5) SCCs role as a problem solver was fundamental in its inception, reacting to industry needs, its uptake across the world, and in response to the recently-completed projects. For instance, Architectural maturity can, like the structural topping in domestic applications, be placed on the "slope of enlightenment" (Figure 3.21). Literature states that SCC has benefits for architectural applications (Section 1.3.5), and its application in projects, before and during the research, such as The Collection Lincoln (Figure 1.3), Hepworth Gallery (Figure 3.2) and London Olympic Diving boards, indicates that these benefits can be realised.

It is clear that there are significant differences in the maturity of SCC which are application-dependent. It is on major projects, where the initial benefits surrounding SCC have yet to be realised or determined to be viable. With problem solving, SME-

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led housing, and architectural applications, it is generally understood how the benefits from SCC can be gained. Hence, an adoption gap exists which has inhibited the understanding of SCC's effects across the concrete construction sector, particularly in structural frame applications.

The literature which exists on successful SCC application in large projects would infer that its position on the maturity cycle would be on the “plateau of productivity”. What has become clear in the UK concrete frame market, is that its position could be better described as in the “trough of disillusionment” (Figure 3.21). Concrete frame contractors noted two primary issues that hindered use of SCC as their ability to influence and the material cost. Ability to influence was related to contractors' roles within project organisational structures; i.e. having a short lead time until on-site activities commence allowing them to give only ‘*suggestions on materials*’ and very little opportunity to advise on the actual construction process (see Figure 3.22).

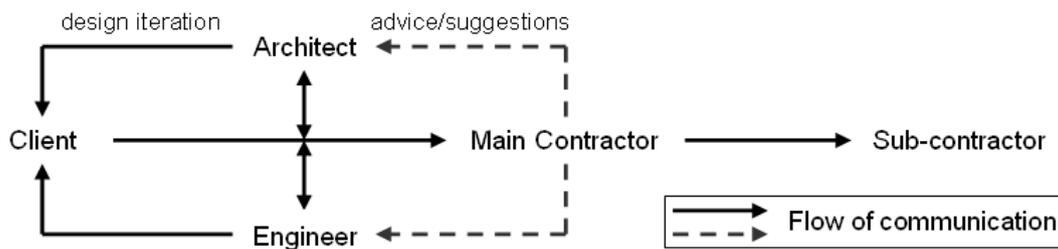


Figure 3.22 Illustration of existing project organisational structures and the flow of communication with respect to materials decision making (by author)

Cost concerns were related to the tendering process that drives contractor selection. When the design has been completed the contractor's primary concern is to present the cheapest possible tender to secure the work. Consequently, the increased material cost of SCC is prohibitive, when compared to conventional concrete. Industry stated that they were still price-driven, with ‘*more talking about value than actually considering it*’. The circumstances surrounding these statements and opinions voiced by the concrete frame contractors is reinforced by the findings from the Echo 2 study, where it was not possible for the existing project to be adequately adapted in order to explore the potential improvements associated with SCC.

Nevertheless, SCC use has continued in the UK, via the SME organisations who have been able to find value in the material, unlike the larger concrete frame contractors. It has been possible for the SMEs to take a further step along the progression of SCC use on-site, as laid out by Figure 3.3 that had clearly not been viable for the larger organisations. The reasoning for this has been linked to their agility in change and control over their construction activities (Section 3.2.4). As such, SME contractors were able to characterise SCC as making it *‘possible to reduce both time and manpower’* and to become *‘faster and more accurate’*. There still remained contradictions however, with one contractor stating that benefits could not be proven on paper, but another stating that *‘a cost comparison with conventional concrete, combining labour and material cost balanced against’* the increased price of SCC would be beneficial.

However, by measuring the application of SCC by SME contractors (via structural topping layers), this research has demonstrated that a *time* saving is possible, but has also identified a relationship in terms of P_{\max} which links material, labour costs and construction time (Section 3.4.3). P_{\max} defines the threshold point at which the contractor can achieve parity between SCC and conventional concrete approaches. The sensitivity of P_{\max} to changes in material cost, labour rates and pour size also demonstrates why SCC is not always used by SME contractors. Finally referring to Gartner (2012), it seems that this application of SCC by the SME general builders does present a tentative example of the product starting to ascend Gartner’s “slope of enlightenment”.

3.5.3 HOW THE ADOPTION GAP COULD BE MINIMISED OR CLOSED

The adoption gap exists because the purported benefits initially associated with SCC seem not to have been achievable in either perception and/or reality (Table 1.3). In fact, a range of barriers have been identified to inhibit utilisation which has resulted in a downturn in perceptions of its potential (Table 1.4). The lack of influence that has been possible on the part of knowledge holders in project structures has been identified as one such barrier by large specialist contractors, although the same situation has not been encountered by SMEs due to their inherent differences (Section

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3.2.5). The potential for greater use of SCC on the part of SMEs has been demonstrated through the residential slabs P_{max} , however these projects only represent a small proportion of the industry potential and it may not be applicable in all circumstances. As such, if the initial large scale benefits associated with SCC are to be achieved, then it is larger projects where improvements or changes will need to be implemented.

Research into the use of SCC on a large concrete frame project Echo 2 (Section 3.3) did demonstrate that the SCC could create financial savings (Section 3.3.3). While these savings would not outweigh the additional first cost of the material, it did serve deliver the first quantitative study of the potential of SCC in large projects, backed up by real-life, commercial data. Implementation of SCC in Echo 2 did not take advantage of any possible benefits to construction processes, due to the late stage at which SCC was selected. This can however be said to be representative of the issues with project structure, highlighted in Section 3.5.3, where knowledge holders are typically only involved at a stage where they only have minimal influence (Figure 3.22).

Aside from SCC, if any improvements are to be brought to a project, by either material or method changes, it is necessary for those who hold knowledge to be involved at such a time where change can be implemented. SCC needs to be considered as a construction method and, therefore, requires change to occur to construction design and planning practices. SCC therefore needs be considered upfront at the time when design decisions are being made. For this to be possible, contractors as knowledge holders need to be integrated into the project at an earlier stage, which has consistently been proposed as a good idea (Gaimster and Foord, 2000; Clear 2006). It would also be beneficial for specialist product suppliers to be engaged at a similar stage due to the knowledge and experience which they hold (Section 1.3.4). Early project involvement is a concept that has been widely adopted within other industries and provides additional benefits in updating teams on innovations and developments (Gill et al, 2000). Figure 3.23 presents a simplified, idealised project organisational structure, developed from Figure 3.22, illustrating the integration of the contractor into the pre-construction phase of the project.

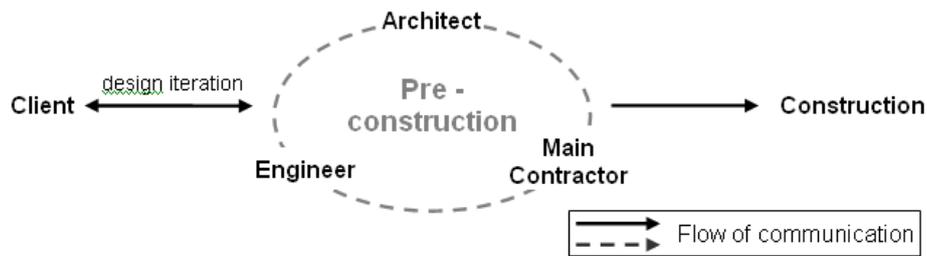


Figure 3.23 Idealised organisational structure of a construction project, with respect to materials decision making process (by author).

Structuring a project in this way does not mean that SCC will certainly be chosen or specified, but it should enable it to be considered ‘by rights’ and provide the opportunity for any potential benefits to be achieved. Early involvement of contractors has been stated to improve performance with respect to cost, time, quality, innovation and the working environment, along with improving their effectiveness (Eriksson and Westerberg, 2011). This structure also facilitates the transfer of knowledge to design and architectural teams, with the opportunity for on-going improvement in future projects.

Based upon the incorporation of the contractor into the design and construction decision making process the circumstances surrounding the on-site team’s development in using SCC can be revisited (Figure 3.3). This can now be adapted to show a 4th stage in the on-site team’s progression of knowledge and experience, pre-project integration (Figure 3.24).



Figure 3.24 Development of three stage circumstances for use of SCC with pre-project integration forming the fourth circumstance

Other than the recognition of the stated methods of acceptance through early introduction, it has been seen that construction could benefit from the transfer of conventional and well-established approaches from within the industry itself. For instance, there remains an approach taught and accepted in industry regarding site

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investigation, i.e. that an upfront expense to carry out a full a detailed site investigation will result in saving over the duration of a project, as there will be a reduction in unforeseen problems. The approach of upfront investigation could also be applied to innovative materials or methods, where early consideration of their construction effects may result in subsequent construction savings. Acceptance of this straightforward technique is an example of how the SCC adoption gap could be closed.

3.6 SUMMARY

Objective 4, *to identify the current position of SCC as an innovation in the UK construction industry*, has been addressed by drawing together preceding research streams to create an overview of findings and to identify areas of shortfall highlighted through the comparison of findings.

It has been possible to identify barriers that exist which have hindered the uptake and acceptance of SCC by the on-site construction team. These hindrances have been linked to project organisational structures and the ability of organisations, due to their size, to adapt and realise potential improvements. The case of SME adoption of SCC on residential projects has been used to demonstrate that when SCC can be implemented, the method can deliver improvements; therefore, stated benefits are both viable and achievable.

The robust method of measurement used has addressed a longstanding issue surrounding SCC, i.e. the dearth of transparent, readily available and reliable data. Here, the data is presented in the form of a work study focused on the construction of structural topping layers in residential slab construction. It has identified P_{\max} which describes the point at which the on-site team can achieve parity between SCC and conventional concrete construction methods. The data has been extrapolated to consider applications undertaken by larger contractors, who expressed shortcomings with the manner in which they become involved in projects. As with the research on the live concrete frame project Echo 2, savings were demonstrated relating to the

changes in methods associated with the replacement of conventional concrete. The Echo 2 project also highlighted the difficulties identified by the concrete frame contractors regarding their ability to influence choice, even as key knowledge holders. Significant change is required to allow larger contractors to focus on the early adoption of different materials and methods and to consider their effects on a project. Necessary changes to project organisational structures have been identified to allow the consideration of SCC (as an example of an innovation) in design and the approach of pre-project integration has been put forward, which may permit early predictions of SCC's broad value and applicability in industry to be realised.

Overall, this research has provided new data that quantifies and explains the direct effect that SCC can have on construction activities. It is a specific dimension of the body of knowledge on SCC that has been under-researched in the literature. These findings can now function as a base-line for future decision makers, regarding the suitability of SCC for a particular application. Through these findings, significantly better informed decisions can be made at any stage of a project, whether for pre-project planning, pre-construction or during actual construction itself. This work also can be used as a template for further studies of SCC for use in slab construction or other in-situ concrete elements.

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4. CONCLUSIONS AND RECOMMENDATIONS

4.1 INTRODUCTION

Based upon the aim and objectives set out in Chapter 1, this chapter intends to identify and describe the extent to which those objectives have been satisfied along with the key findings that have emerged from the research. The contribution to knowledge has been detailed along with identifying the impact of the research on the Industrial Sponsor. Recommendations for the Industrial Sponsor, the wider industry and academia are also presented. Limitations of the research are discussed, in the form of a critical evaluation addressing their impact on the study and the steps taken to reduce or mitigate them.

4.2 ACHIEVEMENT OF THE AIM AND OBJECTIVES

The aim of this thesis is *to determine the effect of SCC on on-site construction processes when used in place of conventional concrete*. The aim and associated objectives were introduced in Chapter 1 in order to present industry and academia with a range of novel findings that would improve and extend the knowledge base on SCC. This was in response to identified shortfalls in and limitations of existing academic and industry knowledge (Section 1.3.7).

4.2.1 OBJECTIVE ONE – TO UNDERSTAND THE SITE TEAM’S PERSPECTIVE IN DETERMINING THE ADOPTION OF NEW OR INNOVATIVE CONSTRUCTION METHODS AND MATERIALS SUCH AS SCC

It became apparent that the mainstay of published work on SCC had concentrated on establishing mechanical and rheological performance properties. Whilst research that been carried out focused on projects, there was a shortfall in the assessment of direct effects and the currency of such research (Section 1.3.7). Material or method had been discussed (Okamura and Ouchi, 2001), but with little research available based on the opinions of those actually using SCC, on-site and in-situ. In response, the focus for

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this objective was the decision making process surrounding innovation, material and method selection; and the ability of on-site teams to influence these decisions.

A series of interviews was undertaken to explore this matter, as reported in Section 3.2. It was thus established, primarily with large contractors, that the best method of construction is selected first, with materials selected to suit methods. SCC thus requires a change to this approach to better facilitate its adoption – ideally it needs to be considered as part of the process for selecting the best method of construction. Of the SMEs and large contractors, SMEs were more inclined to accept SCC, due to their increased flexibility, engagement on projects with simplified project organisational structures and their subsequent ability to influence and implement change. As a consequence of this difference it was possible to identify three specific circumstances for SCC use. These circumstances describe not only the extent of its use, but also a development path from understanding to expert knowledge illustrated by contractors. An observed trend, although not directly cited by on-site teams, was the change in perspective to accept SCC as a method, through a balanced assessment in order to realise its potential. This reinforced statements in the literature regarding the need to avoid viewing SCC as a material. It was clear that a focus on project organisational structures was required as a means to explore where changes might need to occur.

4.2.2 OBJECTIVE TWO – TO EXPLORE HOW SCC AFFECTS ON SITE CONSTRUCTION

A case study of a live construction project, Echo 2, comparing SCC against conventional concrete formed the basis for the completion of this objective. The Industrial Sponsor supplied SCC to the project specifically to understand more about its financial cost implications as a direct replacement for conventional concrete. To help understand how SCC affects on-site construction, a desk study into construction costs was also carried out. This desk study along with the analysis of project costs demonstrated that some value could be gained from the deployment of SCC.

It determined that, when the material cost of SCC is discounted, cost savings were possible due to the changes that SCC had enabled in the construction process. Although the results presented are not incontrovertible, they did identify that the SCC

as a method can create cost savings, establishing a need for further research. The complexity and late introduction of SCC on the Echo 2 project precluded any adjustments being made to 'normal' construction procedures, which may have facilitated the improved implementation of SCC.

The role of existing long held and accepted approaches to on-site construction was identified as an important factor in inhibiting uptake. The importance of the relationship between the site team and supplier was found to be more relevant to SCC than when using conventional concrete. Clear communication of expectations and requirements were required to ensure that concrete operations were not detrimentally affected by unforeseen issues.

As a result of the above, the effects of SCC were, in part at least, clarified and established. While not exhaustive, this has provided information sufficient to better guide the introduction of SCC into a project. Full implementation as a method will undoubtedly uncover other effects, but this case study has served to create an initial understanding. Due to shortfalls in the data provided from Echo 2, subsequent work was clearly needed to fully understand the cost implications of the SCC method.

4.2.3 OBJECTIVE THREE – TO QUANTIFY THE EFFECT OF USING SCC AS A REPLACEMENT FOR CONVENTIONAL CONCRETE ON SITE

The lack of clear, robust quantified research on the cost of SCC was a recurring theme in both literature and preceding work. Due to the complexity of major projects and the wide range of aspects that SCC has been identified to influence, a simplified cost study was needed. The study needed to establish some fundamental aspects of SCC construction to create new and definitive results which could act as a base for consideration in more complex projects. On completion of this study of SCC, in structural topping layers for residential slabs, it was possible to confirm the validity of several (previously only hypothesised or perceived) improvements:

- SCC can reduce construction time and reduce the number of operatives required in construction, without affecting the rate of construction.

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- SCC can reduce and remove the uncertainty that exists with conventional concrete construction costs.
- As-built costs favouring SCC were obtained primarily when conventional construction was subject to significant variation and incurred out of hours working, either due to slab size or the delaying of finishing operations.
- Risk and uncertainty are reduced with SCC; if variation and uncertainty is experienced, detrimental effects on planning and costs could be experienced.

The extrapolation of these results to concrete frame construction, based on the Echo 2 floorplate, found similar savings in construction time and further emphasised the relationship between material price, labour cost and pour size in determining the cost viability of SCC.

4.2.4 OBJECTIVE FOUR – TO IDENTIFY THE CURRENT POSITION OF SCC AS AN INNOVATION IN THE UK CONSTRUCTION INDUSTRY

The research findings which satisfied objectives 1, 2 and 3 respectively have provided a repository of new information on the on-site application of SCC. However, it was not possible to draw distinct conclusions from these findings on the trajectory of SCC's development, or indeed identify steps to facilitate its wider use. By drawing together these three streams of research it has been possible to create an understanding that charts the specific development of SCC with regards to its on-site application (Figure 3.18).

The acknowledgement of an adoption gap enabled the context of the findings of the preceding research to be understood and allowed the identification of the key barriers which inhibit further uptake. The adoption gap is at least partially explained by differences between large and SME contractors regarding their ability to influence, the complexity of projects in which they are involved, and their inherent view of SCC as either a material or method. It was also possible to learn from the approaches taken by SME contractors to identify a suitable process for enabling the SCC method to be realised by larger contractors. Changes have been recommended to project

organisational structures (Figure 3.25), that may not necessarily encourage the use of SCC, but will at least more readily facilitate its consideration.

4.2.5 AIM – TO DETERMINE THE EFFECT OF SCC ON ON-SITE CONSTRUCTION PROCESSES WHEN USED IN PLACE OF CONVENTIONAL CONCRETE.

The aim of this research was developed in response to the identification of a significant shortfall in available, robust and verifiable research that had considered the implication of on-site in-situ applications of SCC. The effect of SCC in on-site applications can be broadly expressed as relating to practical placement and project organisation. This research has explored both of these elements through its supporting objectives. Project organisational elements have been understood through Objectives 1 and 2, and practical elements through Objective 3, with Objective 4 adding significant context to these findings. Through this research and in line with the aim, SCCs effects have been described with respect to demands placed on project structures, to facilitate the application of SCC, and the obstacles that exist in current structures. The research has also identified changes that could more readily allow the introduction of SCC into projects. Where practical effects have been explored, robust and verifiable quantitative data has been provided which has measured the construction process itself. When these elements and the more detailed responses to the supporting objectives are considered the effect of SCC on on-site construction processes has been well documented.

4.3 CONTRIBUTION TO KNOWLEDGE

All contributions to knowledge emanating from this research have emerged in response to the specific problem of a lack of robust and verifiable research on the on-site team experience of SCC (Section 1.3.7). SCC and its associated construction methodology has been identified to provide a number of improvements to on-site construction, although an almost equal number of problems have been presented which inhibit their viability (Section 1.3.6). This research has been able to provide an up-to-date understanding of the perspectives and views held by on-site teams and how

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this relates to perceptions described previously in literature (Section 3.2), making it possible to broadly chart the development of SCC. It has been possible to identify new issues relating to on-site adoption and areas requiring further exploration in project team structures (Section 3.3). The position of SCC as a method of construction has been explained and its importance has been demonstrated for the first time through the detailed comparison of application by SME and large contractor organisations (Section 3.2). Development of knowledge associated with the acceptance of the 'SCC-as-method' approach by the on-site teams has been explained and clarified (Section 3.2.5).

Financial savings have been shown to exist in the substitution of the conventional concrete method with the SCC method, illustrated with clear and verifiable real life costs from a live construction project (Section 3.3.3). Through the case study associated with these project costs, key issues relating to site practice and also in the supplier-user relationships have been identified (Section 3.3.2). Following initial research which identified that financial savings were viable, this project has provided the first research to critically analyse the time saving that SCC can provide (Section 3.4.3). SCC has also been shown to offer significantly more predictability in construction than conventional concrete approaches which it replaces (Section 3.4.4). Further analysis enabled the determination of P_{max} . This describes the relationship between material cost, labour rate and pour size and the point at which SCC becomes a viable construction option for the on-site team (Section 3.4.4).

4.4 IMPACT ON THE SPONSORING ORGANISATION

Since completion of the research, it is important to note that Lafarge in the UK is now known as Lafarge-Tarmac, but the name Lafarge is used in the thesis, as it was the company name at the time of the research.

The research provided Lafarge with a range of findings that have answered specific questions which were the catalyst for the EngD. Lafarge's primary objective was to understand and identify the effect that SCC can have on construction with respect to construction costs and time. This has been achieved and additional evidence has been

provided to highlight that project and organisational structures need to be addressed for SCC to be accepted more widely along with the need for their early involvement.

Through this EngD, a number of tools have been created to enable the dissemination of results throughout the business along with external publications to raise the profile of SCC and Lafarge’s role in its technical and commercial development. These can be separated into two categories, customer-facing and internal tools. The customer-facing tools have focused on construction time benefits, illustration of the simplified construction process and the cumulative impact on construction projects. Internal tools were developed to educate staff to approach SCC as a construction method and to provide guidance on understanding the effect of cost on the viability of the customer to choose to implement SCC. A screen shot of one of these is shown in Figure 4.1).

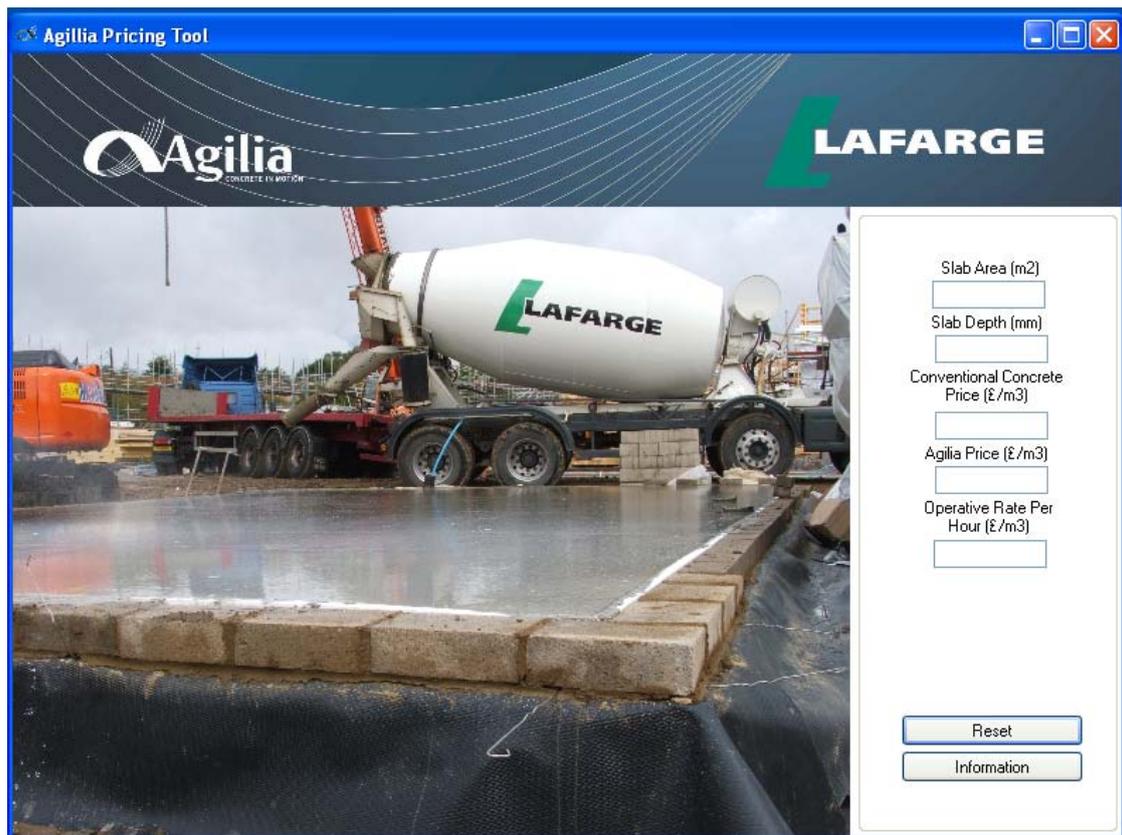


Figure 4.1 Lafarge construction comparison tool (created by the author), based on the relationship between P_{max} and as-built costs (see Fig. 3.14)

Together these tools and guidance should enable Lafarge to develop its market strategy for SCC, increasing its viability as a mainstream construction option and encouraging contractors and others to make an informed decision on when to select SCC in preference to conventional concrete solutions. The wider implication for the company is that higher cost concretes, such as SCC, seem to need to be commercially presented to potential customers in a different way to that which sales staff may have become accustomed. This may have ramifications for presentation of cost information and training of sales staff, which is discussed further in Section 4.5. A more specific implication for Lafarge is that its marketing approach on SCC may need to be tailored more carefully. For example, by applying the P_{\max} approach to a range of different slab scenarios and building types, it may be possible to identify particular situations where SCC is very competitive. This would provide opportunities for targeted marketing efforts in the future.

4.5 RECOMMENDATIONS

Although the research has answered some significant questions on SCC and has made a noteworthy contribution to knowledge, there still remain some questions to be answered on the practical application of SCC. In light of this a number of recommendations have been made.

4.5.1 RECOMMENDATIONS TO LAFARGE

The overarching aim for Lafarge, with respect to SCC, is to increase its commercial viability through increased acceptance and hence greater demand from the UK construction industry. Based on the findings of this research, Lafarge should implement a proactive and extensive internal programme of educating employees on the philosophy that SCC is no longer to be considered as a construction material, but as a method of construction.

Approaching SCC as a method should be combined with a better understanding of the need to develop and adapt current construction processes, in order to realise any of the proven construction improvements. Lafarge should also make a decision on the

identity of their target user/s for SCC: is it to focus solely on proven applications, (e.g. residential slab construction) or to expand into large volume projects such as concrete frames? If expansion of the user base is targeted, then the approach demonstrated here (for establishing the implications in residential construction) should be extended to concrete frame construction. Lafarge should also consider the directing of resources to establish 'best practice processes' for the integration of SCC into construction. This might entail tackling the inclusion of knowledge holders at the design stages and construction, providing clear guidance on what needs to change in construction practices and specifically to move along the three-stage model (shown in Figure 3.3).

4.6.2 RECOMMENDATIONS TO THE CONSTRUCTION INDUSTRY

Within the construction industry in its broadest sense, it is known that there is a need for the historical construction project organisational structures to undergo change and become more forward thinking and inclusive (Figure 3.25). This is particularly important for innovations like SCC to enable the development of implementation from reactive to strategic to specification to pre-project integration. Integral to this is the need for collaboration between parties and consideration of value in construction; all this requires a change in approach to accept early adoption. While this is not a new message, it is one that is worth repeating.

Collaboration on design and construction needs to expand to include those who provide materials that form a major element of the project. In the pre-construction phase it is possible for these suppliers to impart knowledge on how the project can be improved. This would allow for strategic change and in later projects, where knowledge has been transferred to constructing parties, to include it at a specification stage. This change can be further encouraged and aided by changes in approach to project costs. Cost needs to be replaced by a proactive understanding of value, developing the difference between a headline cost and a total project cost. Early project investment presents the opportunity to understand value through exploring changes in materials and methods, by evaluating their effect on a complete project. Implementation of these changes should enable projects to obtain the best results from not only SCC, but all new or innovative construction materials and methods.

4.6.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Following the completion of this research several areas can be identified as key to the further development of SCC, these are:

- 1) Expansion of the residential house construction study to explore the effects that SCC construction can have over the entirety of the construction phase, e.g. in respect to the requirements of follow-on trades and activities.
- 2) Diversification of research to consider SCC's effects on concrete frame construction. Subsequent research should follow the framework set out in Section 3.4.
- 3) Review of the role that construction project organisational structures have on the use of SCC. For example, during the pre-construction stage the manner of engagement between construction parties and key material or method expertise holders: how do architects and engineers effect and facilitate the change in materials and methods?
- 4) Development of an on and off site best practice protocol that explores the methods for implementing SCC into construction projects, identifying precisely where change needs to occur.

Efforts should also be made to address the sustainability issues and environmental profile of SCC, as highlighted in Section 1.3.5. To begin to answer this, a life-cycle assessment could be used initially to assess the cradle to factory gate element. This would create a base case for the 'material' environmental impact of SCC compared to conventional concrete and offer the opportunity for both cradle-grave consideration of the 'method' to balance out these impacts, and perhaps also a multi-criteria assessment to take into account the wider aspects of sustainability; economic, social and environmental (Damtoft et al, 2007).

4.7 LIMITATIONS AND CRITICAL EVALUATION OF THE RESEARCH

All research has its limitations, for example relating to sample size, range of participants or geographical scope. Good research identifies these limitations to enable a balanced understanding of the findings to be achieved. Limitations can relate to the methods employed, data collected, interpretation of the data, research resources and bias.

4.7.1 METHODOLOGICAL GAPS IN THE SCC LITERATURE

Published research prior to this investigation was limited with respect to the on-site application of SCC and the quantification of the professed benefits and limitations of SCC use. This lack of research meant there was a lack of data or comparable methodological approaches present in literature. A strategy had to be devised to deliver a sound set of results, from a relatively modest research programme in terms of time and resource availability. Consequently, the construction of a single concrete element (topping of a slab) was chosen as the focus for quantification.

This lack of extensive existing research required the primary focus of the investigation to form a fundamental base level of knowledge, thus limiting the ability of the findings to create a more holistic picture of the role that SCC can play in concrete construction. It is in light of these aspects that the scope of the research undertaken has been limited to on-site applications; however, this has produced well-grounded, robust and accessible data on the direct effects to be addressed. Wider questions do however remain unanswered, for example how improvements in slab topping construction time might influence follow-on trades and in turn the total project time and cost. Through this research a methodology for the assessment of the effects of SCC on construction activities has been created. The creation of this methodology and its application to other forms of construction will allow further conclusions to be drawn on SCC.

4.7.2 ADDRESSING KEY LIMITATIONS OF CHOSEN RESEARCH METHODS

Every research method has characteristics which enable it to develop significant findings. However, allied to these attributes, can be a number of limitations which should not be ignored and need to be presented such that the research findings can be fully contextualised.

Literature review and archival Research

Through a literature review significant volumes of information can be evaluated, which allows a wide range of existing findings to be considered. However, this presents a major limitation as it is not possible to understand or assess current or actual trends present at the time of undertaking the review; it is only possible to draw conclusions on the past. With respect to the literature itself, the focus or purpose of the publication needs to be addressed, for instance, has it set out to present a balanced case or has it been authored by a party who has vested interest in the subject and what is the experience of the author (Yin, 1994). These limitations were addressed in part by undertaking the research project together with the critical evaluation of literature, thereby exploring the credentials of publications and establishing their contribution, within the context of live building projects, active contractors and current cost data.

Case Studies

While highly suitable to develop in-depth findings on a single subject, case studies can present shortcomings when considering the generalisation and dissemination of results to other cases (Fellows and Liu, 2008). The uniqueness of the case may not always be established and it is difficult to be confident if the circumstances experienced in the studied case are present in other cases. Such circumstances limit not only its applicability, but its verification through repetition. Any documented findings may also be dependent on the subjective opinions of the researcher (Yin, 1994). Throughout this research, each activity was reinforced by the preceding and subsequent activity, allowing additional context to be provided. Whilst it was not possible to undertake repetitions of the work surrounding the Echo 2 project due to its

size the number of studies (14) undertaken to ultimately determine P_{\max} provided robustness to these case studies findings.

Observations

Direct observation, and all forms of observation, can influence the manner in which the observed activity is carried out, with those participating changing the manner in which they undertake a task due to presence of the researcher (Trochim, 2006). In this research, multiple observations of participants were carried out to familiarise and remove the novelty of the presence of the researcher, creating a more natural environment. It is also possible that the researcher themselves may exhibit bias in the recording of information, only recording specific aspects which may not present the complete picture. It is also not always possible for the researcher to determine the events that influence the observed activities and therefore determine if these have had a critical effect of the observed practice (Bryman, 2004). For this reason, the camera was set at a point to view all activities and left running throughout the construction period. Thereafter, all activities completed by the site staff working on the slab were noted carefully and checked prior to any data analysis taking place.

Semi-Structured Interviews

As one of three types of interviews, semi-structured interviews are very effective in drawing out in-depth comment and knowledge. However they can lead to a lack of breadth on the subject which may make it difficult to establish the cause and effect of a participant's stance or opinion (Burns, 2000). Yet the openness of semi-structured interviews also provides a forum for exploring detailed subjects, but this can lead to difficulty in analysis, drawing conclusions and comparisons with other participants and limiting applicability. While it is also impossible to guarantee the honesty of the participant and to be certain that any responses provided are not being expressed solely for the benefit of themselves or the researcher (Bryman, 2004), a range of participants can help reduce the potential for the unwanted effect of narrowing the subject area due to in-depth interrogation. Difficulties in identifying trends can also be addressed by the expansion of participant numbers, and this was used here to ensure that any less noticeable comments were repeated, thereby increasing their visibility

and ability to be identified. Although the sample size of interviewees in the research was 48, the participants were selected to create a broad representation of the concrete contractors. To encourage the honest answering of questions participants have remained anonymous in this research, as no answers, which could be seen as damaging, can be attributed. It is hoped that this has addressed the issue of honesty and the providing of responses which the participant may think that the interviewer wants to hear.

Quasi-Experimental

By its nature, quasi-experimental is not a pure experimental method, it is subject to circumstances and influences which are not possible to fully control, predict or measure. This can lead to a level of uncertainty with the results that are derived from this form of measurement, however in many practical situations it is the only viable experimental approach. It is this uncertainty and inability to demonstrate full control which can affect the comparability of findings (Fellows and Liu, 2008). Narrowing down of the experimental subject, to its component parts, can help minimise external influences, reinforcing the reliability of research findings. For example, in the work study described in Section 3.3, the focus was on a single construction activity in a complex project, rather than the project in its entirety. The observations were made at the time of the construction activity however the key analysis was done away from site through the reviewing of filming of the construction activities. This added a level of control over proceedings as all aspects of the placement process could be observed and measured with the opportunity to repeat these measurements if issues arose. Variability was also addressed through large sample size, the analysis of each activity during placement is a time consuming one, however 13 sites in total were visited with observations being made on 14 concrete pours to form the experimental research. This repetition provides a robustness to help counteract the variable which cannot be fully controlled.

4.7.3 ENSURING THE ROBUSTNESS OF THE RESEARCH FINDINGS

A number of interventions helped to ensure that quality of research data and findings were robust. When undertaking the work study, the process, data capture and data

analysis was conducted solely and consistently by the author. While the process has been clearly defined in terms of method, this approach may present discrepancies if it were to be applied to other applications for SCC. The process itself did require a small degree of subjective interpretation, a factor of human nature which may vary between researchers. That said, if more than one researcher had been involved, a larger number cases would have been required to minimise discrepancies.

Findings from the observational work study were based upon only a relatively small sample of observed sites (14), due to the complexity and length of the data capture process and corresponding analysis phase, which prevented additional cases being included. Additional resource could have increased the data sources collected to help further validate the research findings and may have presented the opportunity to expand the scope of the research into additional and wider applications. However, 48 interviews were undertaken with a range of contractors, as detailed in Section 3.2, so the robustness of the research was also reinforced by obtaining data from experienced and expert practitioners.

4.7.4 VIABILITY OF RESEARCH FOR EXTRAPOLATION

Clear, concise and robust results were generated for the application of SCC in constructing the topping layer of block and beam residential slabs. It was shown that these results could be extrapolated to other concrete slab construction activities; although care needs to be taken in the generalisation of these results. While similarities may exist between construction methodologies, it would be necessary to determine if any additional steps should be included to reflect differing construction approaches, e.g. discharge methods, volume and subsequent delivery implications. In cases where differences do exist, the research can only act as an estimate or base case for comparison and should not be substituted for rigorous adaptation and additional research. For example, this research required this type of diligence to be exercised on two counts in the work study, because both SCC and conventional work processes had to be mapped, for which no template existed in the literature.

4.7.5 RELIABILITY AND VALIDITY OF RESEARCH FINDINGS

Reliability and validity are intrinsically linked to the repeatability of research; findings can be defined as reliable if the same set of results could be established by repeating the same research action (Yin, 1994). Validity responds to determining if ‘an indicator devised to gauge a concept really measures that concept’ (Bryman, 2004). Both of these issues were addressed through the development of the research methodology. The nature of the research subject, concrete construction, is inherently variable, affected by factors that are not only outside of the researcher’s control, but also at times outside the control of personnel responsible for the construction. It is therefore not unexpected that the reliability and validity of the research could be challenged. When considering the validity of the research, three aspects have been considered measurement (or construct), internal and external validity (Yin, 1994).

Throughout the thesis the processes utilised for all research activities have been documented to enable repetition and to ensure reliability (Section 2.3). This enables process stability (a key facet of reliability (Bryman 2004)) consequently allowing any further repetitions to accurately match the original research method. Interviews were semi-structured, but followed a set of fixed questions (Appendices H and I) on a number of key topics (Section 3.2.3). Quantification and case study work was focused around a process (Section 3.4.3) and unmanageable or significant variables excluded where possible. All of these support the fundamental requirement for repeatability and reliability.

Measurement validity is verifying if the methods used allow the subject to be studied and is primarily linked to quantitative research (Bryman, 2004). Aside from the limitations identified in Section 4.7, it can be accepted that this has been satisfied. In the case of the work study, the measured process was broken down and direct comparison of approaches allowed conclusions and differences to be identified. The focusing of observations purely on the on-site placement activities reduced the influence of uncontrollable circumstances, facilitating the study of the process alone. Where concrete frame construction was considered, the comparison of the two forms

of construction allowed real, not theoretical, conclusions to be drawn based on robust evidence.

Internal validity is concerned with the links between research findings and the causality of the links and if they can be reinforced (Fellows and Liu, 2008). Links of this nature were drawn out through the use of interviews in addressing the research objective focused on understanding the perspectives on the use of SCC. The robustness of the research method had been used to address this potential issue, by surveying a large sample and the targeting of different sizes organisations (nationally operating concrete frame contractors and SMEs). These groups provided overlaps in experience, knowledge and work areas creating not only a broad area of research focus, but also depth due to the sample size.

Although attempts have been made to extrapolate selected findings to other applications for SCC (Section 3.4.6) these are subject to external validity questions, primarily ‘are they suitable for this application?’. While assumptions can be made and listed, addressing this question of validity can arguably only really be answered through further research.

4.7.6 VALIDATION OF RESEARCH FINDINGS

For research to be considered successful it must address existing gaps in knowledge and, through this process, be accepted by both academia and industry. This research has addressed significant gaps in the body of research on SCC (Section 1.3.7). It has also captured and clarified some of the opinions and perceptions that are held on SCC in both academia and industry, but has been able to do so whilst being backed by rigorous and robust research. Research outputs required by the EngD have been accepted by academia through the successful publication and presentation of peer assessed papers, with one nominated for the Institution of Civil Engineers award for their best published paper of 2012. Findings have been adopted by the industrial sponsor for both internal and external purposes, incorporated into technical data

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sheets (Appendix L) and through the development of a construction comparison tool (Section 4.5).

4.7.7 POTENTIAL FOR BIAS IN RESEARCH FINDINGS

The potential or opportunity for bias is present in any research involving human responses and has the potential to have a significant bearing on the reliability of any findings. One potential for bias is the close involvement of Lafarge as the Industrial Sponsor, potentially presenting an overly positive image of SCC, particularly during the development of the case studies. Precautions were taken during the onsite observations so that the least favourable case was included, to ensure that claims of favouritism were avoided.

The interviews with contractors to assess the status and perceptions of SCC presented the opportunity for in-depth data collection, but may also be subject to bias. Typically those who participated (CONSTRUCT members) will have had a professional and/or personal interest in the subject which could have affected the balance of results. By definition of being members of the CONSTRUCT group they should necessarily be interested in exploring ways to improve construction practice. While this was addressed in part by the participation of those who were not regular users of SCC, these individuals were contacted via Lafarge which may in turn have pre-selected interviewees who were pro-Lafarge. However, the mixture of responses on the suitability of SCC would suggest that this was not the case.

With face-to-face interviews there remains the risk that the participant will state what they believe the interviewer wishes to hear. Similar circumstances can be said to occur with regards to the observation of practical construction activities in the work study. For example, those observed may have sped up their operations when observed, which may result in non-representative observations (Bryman, 2004). Steps were taken to mitigate this effect by observing operatives on more than one occasion to familiarise them with the process.

Throughout the research project there was a potential for bias, however every attempt was made to reduce the impact of bias.

4.8 SUMMARY

Through the course of the research, the key aim and objectives have been met and a number of new and interesting findings have been identified. The research has substantially addressed a question that has remained unanswered throughout SCC's commercial application, namely its definitive effects within the on-site construction context.

SCC has been found to offer savings in construction time and cost, project risk reduction and a four-stage model to describe the uptake and acceptance of SCC has also been developed. As a result of these findings it is hoped that research, academic or industrial, will continue to explore and examine, in a quantifiable manner, the practical implications of employing SCC across a greater number of applications. While this research has focused on one sector of the construction industry, the intra-industry extrapolation of results has highlighted the need for further examination and research. It has also shown that integral to the future development of SCC is the role of the project organisational structure in the acceptance of SCC.

It is believed that the impact of these research findings could be wide-reaching as the work has provided previously unavailable quantitative data. The key findings have the potential to act as a base case for industry to undertake more balanced and informed decisions regarding the suitability and applicability of SCC within projects. These findings could also be built upon by researchers and expanded by following the research methodologies presented within this thesis or by the adaptation and implementation of other methods.

Finally, the research has provided the sponsoring company with a number of tools that should enable the more effective use of SCC in the construction industry. It has also provided recommendations and findings, but the success of this research, any future

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industry change and further research is dependent on the acceptance of one core concept, that SCC is a construction method, not a material.

5. REFERENCES

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APPENDIX A

To SCC or not to SCC? UK contractors' views

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TO SCC OR NOT TO SCC? UK CONTRACTORS' VIEWS

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ABSTRACT

Self-Compacting Concrete (SCC) is a construction material that has yet to be fully exploited within the UK construction industry. Whilst SCC has been utilised by a large number of contractors, its overall take-up does not appear to reflect that seen in other European and International markets. Benefits to contractors have been identified in many publications but the material still remains underused in the UK. As such, it is necessary to establish the reasons for the material's current status in the UK market and the potential for future market development.

This paper presents the findings from an extensive programme of interviews with UK contractors (48 participants), ranging from large multi-nationals to small/medium regional contractors, which aimed to investigate the issues surrounding the use of SCC in the UK and to help obtain an understanding of the role that SCC plays within contracting organisations. Previous and current perceptions of the material are discussed along with the drivers and processes for material selection and how these are influenced by the structure of the individual organisations and the wider industry.

This interview study has identified a number of conclusions with regard to SCC and its position and role in the industry. It has been made clear that SCC is currently viewed as a material which has a detrimental effect in considering the materials subsequent effect on the whole construction project, which can add subsequent value. It is the concept of value that is difficult to encourage due to the industries current and hereditary obsession with lowest cost.

Keywords: Self-Compacting Concrete, construction industry, UK, contractor, interview

INTRODUCTION

The UK construction industry has been characterised over the years to be resistant and slow to change, a characterisation that can be said to hinder the uptake of any new or innovative construction methods. Self-Compacting Concrete (SCC) could be categorised as one such innovation, whilst present in the industry since the 1980's (1), its take-up as a construction method has been limited. The situation in the UK is contradictory to that which is experienced with European and International markets where it is used more readily within construction.



Figure 1. SCC in action (courtesy of Lafarge)

To date globally and within the UK, research has predominantly been directed towards the establishment of physical and structural performance criteria (1,2,3), with work into SCC construction methods limited to subjective and indirect studies (4,5,6,7,8). In light of this a research programme was created to clarify the effect of employing SCC in projects and to produce tools and guidance to aid adoption within mainstream construction. This paper presents some initial findings, on SCCs implementation in construction projects and discusses how project structures affect the selection process.

BACKGROUND

It has already been acknowledged that the majority of SCC research has concentrated on structural and physical performance characteristics; but as regards to on-site applications the situation is less clear. Literature currently states that SCC is selected as a problem solver (9), where its intrinsic properties enable the material to perform in a manner or situation where conventional concrete cannot. It is this approach to SCC that has supported the perception of a material for special or one off occasions (10), which can be linked to use as an architectural tool (11). Whilst employment as a problem solver is presented as the mainstay of works using SCC there are numerous reports of the gains that can be achieved with the introduction of SCC into fundamental elements of concrete construction projects. Labour, a significant overhead in construction, can, according to Damtoft et al (4), Gaimster and Foord (5) and Goodier (6), be reduced and the impact of work also reduced, due to the ease of

placement and the removal of key elements of placement, for example vibro compaction (12). In conjunction with these gains SCC has also been cited to make it possible to 'guarantee' quality by removing the reliance on workmanship, primarily compaction, providing dense and homogenous elements which in turn can improve durability and robustness (8, 13). Further to these benefits, fiscal savings have also been identified, not only with labour and reduced site plant, but on a larger scale through the ability to speed up construction processes, thus reducing project time and creating significant savings over the project lifespan (5, 6).

Whilst these benefits alone should make a compelling case for the uptake of SCC there are several barriers in the market that could be responsible for low uptake. Most significant of these is cost, with SCCs typically being twice as expensive as an equivalent conventional concrete; which makes it difficult for contractors to look past this headline cost (14). Ability to include SCC in projects has also been identified as a challenge based on the grounds of a lack of standards and guidelines to ease the material into specifications (7). While this was supposed to be addressed by the incumbent European Guidelines for Self-Compacting Concrete (15) and Concrete Society's and BRE's technical report 63 (14), this has been unsuccessful (9). Furthermore, contractors are thought to be unprepared with construction practices biased towards traditional construction methods and conventional concrete (1).

METHODOLOGY

The findings presented in this paper have been drawn from two distinct groups of participants, the first, members of the CONSTRUCT organisation, representing large nationally-operating contractors and the second, smaller locally based contractors. These two groups were targeted in order to give a comprehensive synopsis of the UK construction industry and their experiences of SCC. Of the CONSTRUCT members, those who are part of the Specialist Concrete Contractor (SpeCC) scheme were selected due to adherence to minimum quality standards, annual audits and the overarching modus operandi of 'improving the efficiency of building in-situ concrete frames'. The smaller contractors were chosen not only to broaden the participants, but as an attempt to counter act the aims of CONSTRUCT, which may have led to a majority of participants favouring innovative materials and methods of construction. The second group of participants were drawn from a database of customers who had been supplied with SCC by Lafarge, within the UK, with the focus on identifying non, occasional and regular users of SCC, to once again reduce potential bias and consisted primarily of general builders, house builders, ground workers, concrete frame contractors and screeders.

Interviews were chosen as the method of data capture due to their flexibility and their capability to derive a large amount of information. In the process of designing the interview protocol, semi-structured interviews were identified as most appropriate. This provides a basis of transferable questions, whilst retaining the option to explore responses and redirect questioning (15). Interviews were carried out through two approaches, either by telephone or face-to-face and participants were questioned on a range of subjects to obtain a full view of their experiences and opinions of SCC, with the primary focus on:

- The perceptions that are held of SCC as a construction material and option

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- How the decision is made to use SCC and/or conventional concrete and any other construction innovations
- The influence of the timing of construction decisions on the choice of material and method
- The rationale for such decisions and the identification of those responsible

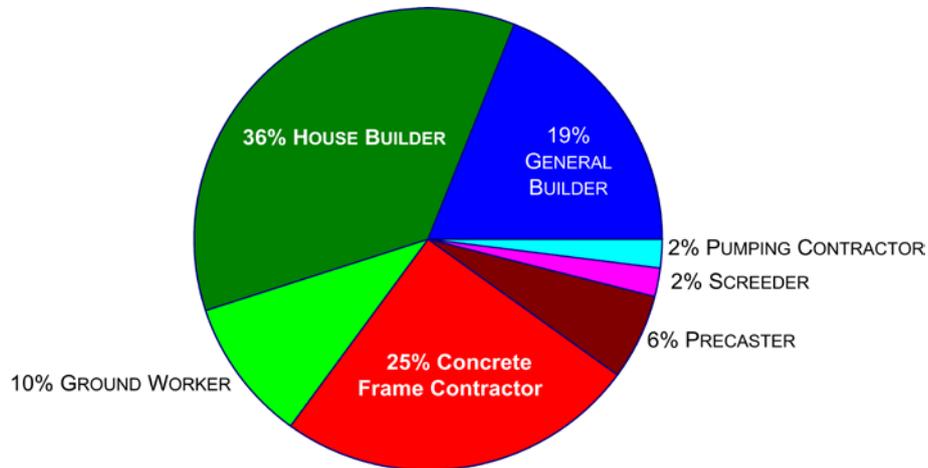


Figure 2. Breakdown of contractors interviewed

RESPONSE

Overall 82 participants were targeted from the two groups; 22 SpeCC frame contractors and 60 smaller contractors, in response to this, 10 of the SpecCC contractors were interviewed and 38 of the smaller contractors, giving an overall response rate of 59% (figure 2).

FINDINGS

Through the interviews a number of different aspects were considered and discussed, however it quickly became clear that two elements were most prevalent and needed to be considered in more detail. The first was the use of SCC in construction, regarding methods and the manner of implementation and its effects. The second factor was the decision making process for the selection of not only construction materials, but also construction methods.

Implementation of SCC

It should be noted that 83% of those interviewed as part of this study had experience of using SCC, however the range of applications was somewhat limited and can be said to be due to a lack of universal applications for SCC or a misunderstanding of its potential. The majority of use (53%) was in slab applications, principally with house builders, general builders and ground workers. Concrete frame contractors typically used SCC as a reaction to emergent problems or in situations where a conventional concrete could not achieve the desired results.

There was no consensus on ideal applications or opportunities for SCC where it particularly added value to a project. 'It is difficult to see where you can actually making savings' (house builder) or contradictorily costs 'can be returned through time saved, reduced labour and removal of powerfloating' (housebuilder), however generally the material was viewed positively.

With respect to these comments it is not surprising that 40% of participants stated that 'cost is prohibitive to use' and it is the 'main problem with the material' (house builder). In this respect cost is used to describe the headline cost of the material, which can fail to identify savings from other aspects of the construction process. 'Construction is price driven' said one concrete frame contractor more contractors 'talk about value than actually consider it', and that regardless of market buoyancy or economic downturn the cheapest option will always be chosen. Indeed, when participants were asked to consider project value rather than cost, 21% responded to say that they could also see no value in SCC. The concept of value requires participants to look further into construction practices and with this response it is clear that SCC is considered to be a material rather than a method, which would necessitate different approaches to planning and implementation. The particular concept that could be potentially vital for SCC relates to the process with which materials and methods are introduced into construction projects and programmes/schedules. Time to implement change and flexibility were identified as major factors in assessing the viability of new methods of working, where viability can be judged as an overall positive effect on the project. SCC has 'made it possible to reduce both time and manpower' (general builder), remove construction activities and 'needs to be judged on its effects on the critical path' (concrete frame contractor). In large projects reductions and realigning the critical path enables the greatest savings to be made, in respect of project duration and associated site overheads, so it is this aspect where SCC must demonstrate its potential to contractors.

Decision making

Any change in construction processes or practices requires the buy in of all parties involved in the project decision chain, the client, architect, engineer and contractor. In the case of SCC the decision to employ SCC typically arises from three circumstances:

- 1) A strategic change from conventional methods as part of a balanced assessment of the material and its effects on construction
- 2) Deliberate specification of the material, or it being taken on board as a preconceived construction option
- 3) Reactionary, in order to address a specific issue or problem

Overall, 14 interviewees referred to the decision to use SCC as a strategic one, with five stating that SCC was able to add value, but its use in this respect needed to be made on a job by job basis. Ten contractors had used SCC as a reactionary tool, stating that this is its only viable use and only two had had experience with the material being specified.

As has been established previously, irrespective of the circumstances surrounding use, project decision makers still need to be convinced about SCC. Typically, without

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specification, application is driven from site level upwards by the contractor, who need to believe 'the role SCC can have in construction and the reasons for inclusion' (concrete frame contractor) and convince those higher up the project hierarchy. As a reaction the case is relatively straight forward, SCC solves or removes an issue affecting continued construction, but the challenge remains to move towards more strategic implementation.

Indeed, strategic change requires decisions to be made based on the complete role of SCC in construction, not only as a change in material but also as an influence on current construction methods and processes. It requires SCC to be viewed on a job by job basis and not as a wholesale replacement for conventional concrete, but there is a problem. It is actually construction teams typically retain the most knowledge of construction materials and how these can potentially influence and effect construction and the project as a whole. However currently project organisation sees the contractor becoming involved, normally, once the design has been completed, at which point they are only able to 'make suggestions on materials' but generally can only give a 'best price and advise' (concrete frame contractor) on construction. For the contractor to have the opportunity to provide real input and change construction practice would require a lead time of '2-3 months rather than 4 weeks' (concrete frame constructor), which is rarely a desirable timetable in construction.

DISCUSSION

Not only as a result of opinions and views presented throughout this research but also in light of literature it is clear that there is no apparent consensus on the role for SCC in construction and there is a distinct lack of quantified information on its application. Literature identified two circumstances for use, as a problem solver (1, 9) or as an architectural tool (11), only one of these circumstances was explicitly identified but the latter can also fit into three new and clearly identified categories: as a strategic change, a problem solver or when specified. However SCC is still widely seen as a problem solver which signifies that perceptions have yet to change.

A large number of the initially identified benefits presented in literature have been confirmed during this study, relating to time, labour, workmanship and quality (3,4). However on cost there still remains a contradiction, literature clearly states that SCC can have a positive effect on cost (5,6) whilst within industry the situation is less than clear with responses ranging from it being prohibitive to savings being made on a balanced assessment.

The process of undertaking a balanced assessment dovetails with an understanding of SCC being approached as a construction method, implying more forethought, rather than a material. SCC as method requires change not only in on-site practices as referred to by literature (1), but throughout the whole project life and at all levels.

CONCLUSIONS

There has been little research carried out to date focused on establishing the role for SCC in construction. As a material it is clearly viable in projects, but its use is dictated by the type and scale of such projects, and whether it is perceived to offer value.

How, when and where to incorporate SCC into a project poses a major research question, with respect to decision making, process planning and timing of construction. The historical structure and organisation of the construction industry are as a cause for concern, i.e. management structures, project control and project implementation. All of these aspects influence the use (or not) of SCC, particularly the time at which contractors are involved in projects, those who are responsible for decisions, fiscal arrangements and project procurement.

Processes surrounding construction decisions, with regards to how a project is constructed, are focused (and correctly so) on selecting the 'best' method, with material choice usually a secondary consideration. SCC is currently considered as a material, which does not encourage the contractor to consider the wider effects and benefits of SCC. If SCC is considered as a method however, there is recognition that SCC needs and requires greater planning and understanding. In order for the material and its associated benefits to reach its full potential it is essential that the material is viewed and considered in this regard, rather than as a simple like-for-like material.

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APPENDIX B

UK contractors' views on SCC in construction

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Title: UK contractors' views on self-compacting concrete in construction

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Abstract

Self-compacting concrete (SCC) is claimed to offer faster construction, safer sites and more consistent concrete quality, but little corroborative research data exists on performance advantages, particularly in comparison with traditional construction. Industry opinions also appear to be divided. For these reasons, an extensive interview programme was undertaken with UK contractors - from large national concrete frame contractors to small, locally based housebuilders - to assess whether benefits were being achieved and to try and understand the reasons why SCC is, or is not, being used. The 48 participants reported that decisions on the suitability of SCC were inherently complex and, if selected, there were challenges in understanding 'how' construction should be planned and managed to accommodate the use of SCC and to fully utilise its advantages. The findings identify the need for a step change in the industry's perception of SCC, such that it should be considered as a construction method, not simply as a material.

Notations: SCC – Self-Compacting Concrete

Keywords: Concrete technology and manufacture / Buildings, structures and design /
Research and development

1. Introduction

Despite its traditional culture, innovations can be found in the construction industry, with a select few acknowledged as enhancing construction processes. Self-compacting concrete (SCC) is one such innovation due to its effects on the construction process. Whilst still regarded in the industry as a recent innovation it has been available in the UK for more than ten years, with the technology being available even before the creation of the term SCC.

Simply explained SCC is a concrete that requires no external energy input (Damtoft, 2008, The Concrete Society/BRE, 2005 and Holton, 2003) in order to achieve full compaction, vital in achieving robust and durable concrete. For a concrete to be considered a true SCC it must possess three distinct properties; resistance to segregation, which is self explanatory, flowing ability and passing ability. Flowing ability refers to the concrete's ability, under its own self-weight, to flow and completely fill the form into which it is placed. When used in applications consisting of complex shapes or with dense reinforcement there is a need for the concrete to have greater passing ability through and around obstructions without causing blockages, which can result in internal voids (RILEM Technical Committee, 2006, Goodier, 2003 and Gaimster and Gibbs, 2001). Together these properties are particularly helpful.

However, since its inception and commercialisation SCC has remained somewhat under used. Extensive research has been carried out into the material's structural and physical performance criteria (e.g. work by Shobha, M. et al, 2006, Okamura and

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Ouchi, 2003, Khayat, 1999, Bartos, De Schutter, 2008), but research on the effects of SCC on the construction process has generally been more subjective and indirect (e.g. Damtoft et al, 2008, Gaimster and Foord, 2000, Goodier, 2003, Henderson, 2000, Walraven, 2003).

In response to this, a project was established with the objective to identify the implications that SCC can have on construction, whilst providing information and tools for exemplar use. Results presented here form an integral part of this research by considering the views held by a range of contractors within the UK construction industry.

Due to the low uptake and lack of information on practical applications, the aim of this research was to clarify the views and perceptions of contractors and to understand SCC's effects on construction. Research was directed at establishing the reasons and drivers for using SCC and whether these align with views and findings within academic and industry literature. Other aspects considered were the decision-making process surrounding new methods or innovations and planning of the construction phase. Through these results a more fulsome and up-to-date understanding of the industry's views on SCC were obtained; an important research study that has not been replicated previously. This research forms part of a wider programme of research which is focused on assessing the implications of SCC in construction, and will move on to establish direct, quantifiable results linked to its application.

2. Background

SCC is seen as a specialist material (Holton, 2003, Clear, 2006) but one that is gaining more recognition within a wider range of construction applications (The Concrete Society/BRE, 2005). Some view SCC (Figure 1) as a material whose use is limited to situations where it can perform as a problem solver (Okamura and Ouchi, 2003, Clear, 2006) or as an architectural tool due to the high quality finishes available (Grimes, 2005). Several factors identified previously as drivers for the uptake of SCC are; improved durability, versatility, skilled labour shortages and improvements in performance. Durability and versatility are enhanced by the physical properties of the material; the flowable nature enabling greater confidence in formwork-filling and final quality (Grimes, 2005, Walraven, 2003); these in turn result in more uniform and dense elements (Skarendahl, 2003), subsequently improving the resistance to chloride diffusion, sulfate attack and freeze-thaw problems (De Schutter et al, 2008). The ability of SCC to be placed without compaction has removed the need for skilled labour input and decreased impact on operatives (The Concrete Society/BRE, 2005, Damtoft et al, 2008). Financially, the material can be cost effective if a holistic calculation is made, taking into account SCC's ability to reduce labour, remove plant, reduce remedials and, as a result of improved rates of casting, to reduce project time (Gaimster and Foord, 2000, Goodier 2003).

Whilst onsite, insitu use of SCC is not widespread, according to Holton (2004) in 2004 60% of the structural pre-cast sector employed SCC, rising to over 75% in 2008 (Goodier, 2008). Key to this uptake is the result of all operations being in one place, with the entire batching and casting operation under total control of a single organisation (Skarendahl, 2003); as such, any changes are easy to manage and benefits easier to measure and obtain.

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Application has not been replicated to this extent in insitu applications due to the gearing of site practices towards traditional vibrated concrete (Okamura and Ouchi, 2003). If SCC use is to increase, change is required in the early project stages, conceptual and preliminary design and also specification (The Concrete Society/BRE, 2005). A number of publications have been made available to address the aforementioned issues, not least the European Guidelines for Self-Compacting Concrete by the Self-Compacting Concrete European Project Group (2005) and the Concrete Centre's and BRE's joint report into SCC, TR62 (2005).

Sustainability is a major concern within the construction industry and therefore needs to be considered with regard to SCC. The increased cement volumes in SCC suggest an increased environmental impact (Gaimster and Gibbs, 2001) due to the CO₂ emissions during production. However, SCC can improve productivity, improve the work environment, reduce repair and replacement, and as such the overall environmental impact of the project is reduced (Damtoft et al, 2008).

However, based on current literature the case for SCC remains unclear. Recent literature on the application of SCC is over five years old and no recent work has been undertaken to revisit and re-research the case for SCC in the UK industry. Some of the key literature to date (IP3/04 (2004), BRE (2005)) used to further the case for SCC can, in part be said to lack validation, for example canvassing opinion across the industry. It is this lack of wider consultation, together with the age and nature of available information on SCC that have served as key drivers for the research presented here.

3. Methodology

This research aimed to establish current industry perceptions, opinions and ideas on SCC, including:

- the perceptions that are held on SCC as a construction option and material;
- how the decision is made to use SCC and/or conventional concrete and any other construction innovations;
- how the decision-making process surrounding material and method can be improved;
- the influence of the timing of construction decisions on the choice of material and method; and
- the rationale for such decisions and the identification of those responsible.

Interviews were chosen as the method of data capture due to their flexibility and their capability to derive a large amount of information, when compared to questionnaires. It was the lack of ability to interrogate and expand on responses combined with an inability to encourage contractors that were less enthusiastic about SCC to participate that supported the selection of interviews. In the process of designing the interview protocol, semi-structured interviews were identified as most appropriate. These provide a basis for transferable questions, whilst retaining the option to explore responses and redirect questioning (Bryman, 2004).

Distinct approaches were adopted in order to identify potential interviewees. Initial participants were members of the Construct organisation, representing large

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nationally-operating contractors (Construct is an association of UK organisations looking to improve the efficiency of in-situ concrete frame construction. www.construct.org.uk). This also includes concrete frame contractors operating under the Specialist Concrete Contractor (SpeCC) scheme. The SpeCC scheme was devised to raise standards within the concrete frame industry (Figure 2), and acceptance is dictated by adherence to minimum standards and annual audits to ensure compliance. Initial contact was made via letters to technical directors or their equivalent, explaining the research and giving an indicative set of questions. Subsequent to this, follow-up telephone calls were made to arrange in-depth, face-to-face or telephone interviews.

To obtain a broader sample from the contracting industry, a further group of small locally based UK contractors were also interviewed (Figure 3). These were drawn from the UK-customer database of a global construction materials supplier, through which it was possible to obtain a direct link with the contractors. These firms included general builders, house builders, ground workers, pre-casters, concrete frame contractors, screeders and pumping contractors (pumping contractors are contractors typically who only provide pumping services but in these cases have expanded their business to include concrete placement). Those interviewed ranged from onsite general operatives to directors and owners of said contractors.

Construct's aim is to 'improve the efficiency of building insitu concrete frames and associated structures', which may be reflected in the willingness of the SpeCC members to participate. However this data should be treated with care as, by their nature, such organisations are inclined to be proactive in the development of new

products and the transfer of information, which may not be representative of the wider construction industry. The second group of contractors were selected and categorised based on their being either:

- (a) Regular users of SCC
- (b) Occasional users of SCC
- (c) Former users or non users of SCC

This approach provided a range of balanced and representative views. Within these groups a potential for bias exists (particularly group (a)), in that interviewees happen to be more interested in SCC and construction innovation than the wider industry. Therefore, steps have been taken to mitigate this through interviews with non users, as can be seen in Figure 4. Group 1 (Construct members) were selected to provide information on larger-scale projects and Group 2 (other contractors) to address the smaller-scale and less complex projects, which currently represent the majority of applications of SCC within the UK.

In group 1, out of 22 companies two Construct members declined to participate and ten did not respond. The remaining ten contractors took part fully providing a response rate of 45%. In group 2, 38 participants were interviewed, out of 60 approached (63% of the sample).

The combination of participants provided an overall response rate of 59%, i.e. 48 participants, representing a range of contractors and specialist firms, the breakdown of contractors is shown in Figure 5.

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Most of the respondents were located in England, with three contractors each in Scotland and Wales (in the areas surrounding Glasgow and Cardiff). Within England a significant proportion of participants were based in the North East (27%), South and East Midlands (23%) and London and the South East (10%). The Construct participants (20%), whilst having headquarters mainly in the London and South East, typically operate nationally and so are not limited to a particular geographical area.

4. Results and data analysis

This section presents an overview of the results of the interview programme and includes verbatim quotes where appropriate, with the respondent's role indicated in brackets after each quote.

4.1 Reasons for using SCC

There seems to be a clear distinction between knowledge and experience of SCC - experience being based on practical use and knowledge based on one's impression of the material. Whilst most study participants (83%) had some previous experience of SCCs, the range of applications was limited. This limited use suggests either a lack of specific or universal applications for SCC or a lack in understanding of its potential. Of the drivers and applications cited for use, two were most prevalent - as a 'problem solver' and for housing slab construction. SCC was said to be able to 'resolve and remove problems' and enable 'risk reduction' (concrete frame contractor) according to 23% of participants. The majority of use by concrete frame contractors can be described as reactionary, i.e. when conventional concrete could not achieve the

desired results, typically where there is congested reinforcement, poor access, site restrictions or a need for a high quality finish. Slab applications (Figure 6) accounted for 53% of previous use; principally with house builders, general builders and groundworkers.

There was no coherent overarching view of SCC, with participants stating 'it is difficult to see where you can actually make savings' (housebuilder) or that cost differences 'can be returned through time saved, reduced labour and removal of powerfloating' (housebuilder). No single ideal opportunity for the material was presented.

SCC was generally viewed as a positive option but contractors were discouraged by certain problems. It is in response to this that some said the material could only be used if specified – in other words, many contractors did not want to take the responsibility for its selection.

It is interesting to establish the perceptions of SCC, both positive and negative. Participants identified that SCC could reduce 'effort levels in placement' (general builder) and enable 'faster and more accurate' (general builder) construction whilst mitigating 'workmanship issues' (concrete frame contractor). These comments corroborate existing literature (Damtoft, 2008, Goodier 2003, Henderson, 2000 and Gaimster and Foord, 2000). Following these positive statements, reflection of knowledge in literature can also be said to be present regarding weaknesses. However, in certain cases these have been contradicted, one such example is that 'labour skill changes are not correct' a 'traditional concrete gang' (concrete frame contractor)

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would still need to be utilised, where literature states skill levels can be reduced (Goodier et al, 2002).

This however must be put into context; if the material is only to be used on a single application then this action is understandable. However, the issue in question is the use of the material as part of a larger programme of works; in other words, is a significant reduction in labour only viable once SCC is used to a large extent across a whole project?

Nearly 40% of participants maintained that 'cost is prohibitive' to use and is the 'main problem with the material' (house builder). Cost was often used to describe the first cost or tender price; this interpretation fails to identify savings in other parts in the construction process, which result from using SCC. Typical project costs were said to be approximately '15% concrete, 15% steel, 33% labour and 33% overheads' (concrete frame contractor) which, if no clear value can be attached to SCC, presents a significant barrier.

So, to negate a focus on cost, the concept of value was put forward to interviewees, where value was described as SCC's impact on a whole project. 21% responded that they could see no value in SCC in construction, suggesting they saw SCC as a material rather than a method (necessitating a different approach to planning and implementation). Further to this its inclusion was said to be detrimental to the acquisition of work, due to increased tender prices. Whilst the concept of value was clearly prevalent in the industry, it has yet to be integrated into projects with 'more talking about value than actually considering it' (concrete frame contractor). In pre-

cast applications it was said that companies 'cannot justify savings on a balance sheet, but they do exist'. However, overall within the industry 'cost is king' (concrete frame contractor) and in this respect it was said the cheapest option will always be chosen, regardless of market buoyancy or economic downturn.

4.2 Decision making

The decision to employ SCC in a project appears to originate from three circumstances, with the first two most prominent:

1) A strategic change from conventional methods as part of a balanced assessment of the material and its effects on construction.

2) Reactionary, in order to address a specific issue or problem.

3) Specification of the material or being taken on board as a preconceived construction option.

The strategic decision to use SCC was referred to by 14 contractors, of which five found that, on balance, SCC in a specific application could add value. It is clear that use and value needs to be judged on an application by application basis. Ten stated that SCC was used as a reaction to an issue or problem, with one citing that the only viable solution on these occasions was SCC. Only two participants had experience of being required to use SCC, with seven saying specification was the only route to application.

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‘The material is rarely in a specification, (there have only been only a) few cases of specification. Used only on jobs when a problem occurs, application-led rather than a conscious decision. Need to balance risk versus reward, rework potential associated with conventional concrete in an application; strike a balance (between materials)’ (concrete frame contractor).

Whether SCC is chosen as a reactionary solution, a strategic change or a preconceived option, the main decision makers were reported to be the client, architect and engineer and contractor – so it is they who need to be convinced about its adoption. Without SCC being specified, introduction occurs at site level, where approval is then sought from senior personnel in the project management structure. This can present problems with ‘educating the client or engineer on the material, the role it can have in construction and the reasons for inclusion’ (concrete frame contractor). The rationale that SCC was seen as a problem solver is more straightforward than in any other application. ‘Narrow column design with high levels of reinforcement raised the potential problem of limited poker access’ (house builder), SCC is chosen to perform when or where a conventional concrete cannot.

Selection based on a considered change from conventional concrete appeared to be grounded in decisions driven by a balanced assessment of construction effects, considering not only costs, but also changes to methods and practices.

‘(The) material was selected to speed up construction times; (we) undertook a cost comparison with conventional, combination of labour and material cost balanced against SCC. (Its) selection was based on time, effort, labour and finish quality.’

(groundworker)

The selection of SCC in these cases is on a job by job basis showing that the material is not a direct replacement for conventional concrete. Selection in this manner requires an understanding of the design process. Indeed, it was clearly stated by one concrete frame contractor that material choice is second to construction method when designing or developing a project, with the best construction option selected first.

Construction teams (who typically retain most knowledge of SCC and methods of innovative construction) are involved once a design is completed. It is at this point where they can ‘make suggestions on materials’, but generally can only provide ‘a best price and advise’ (concrete frame contractor) on construction, creating an inbuilt barrier to innovation and SCC use.

4.3 Use of SCC in pre-cast

A general indication of views from the pre-cast industry was provided by three pre-cast plant operators. The perception and use of SCC has changed significantly over the last 10 years when it was ‘not possible to achieve prescribed results’ and the ‘additional cost made the material unviable’ (pre-caster). All three manufacturers responded positively to SCC, stating it was now possible to realize ‘savings in labour, time and plant’ (pre-caster), with another reporting it is ‘possible to reduce placing

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time from 3 hours to 45 minutes or 1 hour' (pre-caster). However, it was said that these benefits were difficult to quantify and reflect financially and in older factories a significant plant overhaul is required to improve standards to accept SCC.

4.4 Sustainability

Questions on sustainability were directed principally to the group 1 (Construct) participants, based on perceptions regarding membership and a desire to improve construction. Only two of the ten respondents were actively pursuing sustainability improvements. Other contributors identified typical industry characteristics as barriers, such as a resistance to change and the desire to reduce costs, based on the assumption that sustainable approaches were inherently more expensive.

With the industry requiring 'work to be carried out on a lowest cost basis' (concrete frame contractor), integration of 'green' initiatives were thought to increase tender prices and reduce work. As a result 4 of the 10 participants stated that the client must drive sustainability agendas.

Throughout the Construct interviews, a range of views were presented. SCC was seen as more sustainable because the 'need for additional finishes' (concrete frame contractor) had been removed, however it was also said to be worse 'as more CO₂ is generated' (concrete frame contractor) due to increased cement content. The most viable response is that 'not enough evidence or detail is available' and one 'still has the same concerns as with conventional concrete' (concrete frame contractor).

Since none could offer a coherent account of SCC's sustainability credentials, it is clear that either there is a problem with knowledge transfer or a lack of research into the subject.

4.5 Implementation

Time was identified as the overriding factor in the implementation of new materials or methods. It was said that the earlier a change is introduced the easier it is to assess its viability, where viability can be judged to be a positive effect on a project. In conjunction with time, project flexibility was cited to be essential in enabling design or construction methods to be altered.

Interviewees said that SCC had 'made it possible to reduce both time and manpower' (general builder), remove construction activities, but also 'needs to be judged on its effects on the critical path' (concrete frame contractor). Improvements to the critical path presented the opportunity to make dramatic savings in project duration and, in turn, overheads.

Change, on a large scale, required approval by the client, architect or engineer. SCC use was thought to be driven by contractors typically, who needed to influence and educate those higher in the project hierarchy, the engineer, architect and client. A lead time of '2-3 months rather than 4 weeks' (concrete frame contractor) was required as late involvement would result in an inability to develop and introduce change. Without early consideration of any new innovation or material the probability of inclusion is slim, unless it is used to address a specific issue. The lack of an upfront

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opportunity could be counteracted by review processes and post project appraisals. However, when participants were challenged on appraisals, there was a mixed response, with appraisals carried out in an ad hoc manner. On the majority of occasions when they were carried out 'there have been problems' and are 'typically focused on methods' (concrete frame contractor) which can leave SCC unconsidered.

5. Discussion

The results from the interviews present complementary and contrasting views on SCC when compared to existing literature. It remains clear that there is a lack of quantifiable information on the use and effect of SCC on construction. Literature has highlighted two distinct circumstances for the application of SCC. These were as a problem solver (Okamura and Ouchi, 2003; The Concrete Society/BRE 2005; Clear, 2006) or as an architectural tool (Grimes, 2005), but through this research it has been possible to clarify three circumstances for use, as stated within the results. SCC is still widely used as a problem solver which signifies that perceptions have not dramatically changed.

Strengths and weaknesses identified by literature relating to labour, quality and workmanship (Damtoft et al 2008; De Schutter et al, 2008) have, to an extent, been confirmed by responses. There remains a contradiction on cost and SCC's impact on construction costs, although it is stated in literature that SCC can reduce total project costs (Gaimster and Foord, 2000; Goodier, 2003). This is contradicted in part by our findings as its price has been cited as prohibitive; nevertheless a proportion still used the material after a balanced assessment, thus viewing SCC as just a material.

As a method, SCC takes into account wider implications and in this respect value can be considered rather than cost. For example it is useful to borrow a concept from preconstruction planning regarding site and ground investigations, where an initial capital outlay can have a dramatic effect on reducing unforeseen problems and in turn unforeseen expenditure. It is conceivable to apply this concept to above ground works to develop construction processes which can be adapted for SCCs and new innovations with the long term result being a net reduction in costs.

Pre-cast concrete, according to literature, has seen a considerable increase in use of SCC that has not been reflected in insitu applications. Although from a very small sample, it did seem that there is an increased willingness to use SCC, with all pre-cast participants having used or using SCC and looking to convert some or all of their facilities. All interviewees noted that SCC has improved, or could improve their processes but they have not been able to identify the exact 'value', monetary or otherwise, to their business. The inability to quantify these directly is replicated in the insitu industry where there is little robust information available.

On sustainability there is no clear position in either literature or the industry; several conflicting and contrasting views have been put forward.

Construction is geared towards traditional concretes and traditional methods. Early consideration was required to enable uptake of SCC, however this requires approval by the client, architect, engineer and higher project teams. So, education was stated to be key in changing the approaches taken by companies and to overcome conservatism

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(perceived to exist at higher levels in project teams). Conservatism could be interpreted as site teams not willing to fully understand SCC themselves, pushing decisions upwards and removing their risk. Where change was embraced, SCC had been perceived as a 'method', not just as a material. To ease this situation the industry 'needs to increase the knowledge of (SCC), how it works and how it can be designed into construction projects' (groundworker). For example, a balanced assessment or study of site based costs, technical information on the application of SCC, and guidance on how to adapt construction. A curious example was also provided in respect of current publicised guidelines and aids (e.g. European Guidelines for Self-Compacting Concrete (2005) and Technical Report 62 by the BRE (2005)). The interviewees displayed an apparent lack of awareness of these documents, perhaps suggesting that they are either not relevant or unknown, but on the other hand the documents may be so well-known that they are a given and so remain unmentioned. This may merit further study.

6. Conclusions

In the 5 or 6 years since the last significant work into SCC, regarding its application in the industry, it is clear that there has been little progression, there remains a lack of unanimous or general consensus on SCC and its role within construction processes. There has been little research on its effects on mainstream construction. SCC has been described as a viable material, that offers distinct benefits to construction projects, or hinders operation in a competitive market place but this is dictated by scale. Its position still therefore remains unclear and requires further research.

This research has gone part way to address the research questions of how, when and where to incorporate SCC into a project but a major research question, with respect to decision rationale, process planning and timing of construction remains. That said the historical structure and organisation of the construction industry were cited by industry as the basis for current management structures, project control and project implementation. All of these aspects influence the use (or not) of SCC, particularly the time at which contractors become involved in projects, those who are responsible for decisions and the fiscal arrangement of project procurement.

Processes surrounding construction decisions (i.e. how a project is constructed) are focused (and correctly so) on selecting the 'best' method, with material choice usually a secondary consideration. SCC is currently considered as a material, which does not encourage the contractor to consider its wider effects and benefits. If SCC is considered as a method (a distinctive step forward from previous works), there is recognition that SCC needs and requires greater planning and understanding, in order for the material and its associated benefits to attain their full potential. Identification as a method requires that the complete construction phase is geared towards SCC and adapted to suit its distinctive properties; it is a development from previous concepts that SCC is no longer part of the process (IP 3/04) but is the process itself. It is absolutely essential that the material is viewed and considered in this regard, rather than on a simple like-for-like basis with other materials, for its uptake to grow.

7 Recommendations

Industry recommendations:

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- Consider SCC as a construction method rather than as a material and interpret its implications on the wider construction process.
- Introduce contractors into the early (design) stages of projects to increase collaboration efforts and enable the uptake of new construction methods and innovations such as SCC.
- Increase upfront investment in projects, at the preliminary/conceptual stage to enable additional value to be sought through the assessment of innovations and new methods of construction, prior to the commencement of works.

Research recommendations:

- Develop and establish guidelines on how SCC, as a ‘construction option and/or method’, can be integrated into construction projects and determine the changes or adaptations needed in current construction practice.
- Ascertain the effect that SCC can have on the construction process by quantifying benefits and savings.
- Interpret and understand the roles and requirements of key decision makers within the construction chain. Establish industry views on risk to develop a strategy for contractors for implementing SCC into construction projects.

Achievement and adherence to these recommendations would enable the integration of SCC more widely into mainstream construction, and have broader potential to ease the development and inclusion of other innovative construction methodologies. The process of addressing these recommendations would help overcome several of the mainstream issues and barriers to SCC and support the further development of SCC in construction.

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APPENDIX C

Developing an ideal scenario for SCC: New findings from the UK

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DEVELOPING AN IDEAL SCENARIO FOR SCC: NEW FINDINGS FROM THE UK

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Key words: Concrete, frame construction, self-compacting concrete, research, UK

Abstract: *Self-compacting concrete is a material that has had a wide range of benefits attributed to it; however it is a material that is substantially different to conventional concrete. As such there is a need to understand how and where change needs to occur in current UK construction practices to enable the material to be more widely used.*

This paper identifies and discusses the key aspects that relate to the use of SCC in concrete construction, with a focus on structural frames. It also gives recommendations on how construction can change to enable the uptake of SCC and improve the organisation of project teams. The use of SCC in construction projects is also set out providing an idea of the how construction may change in the future to better integrate appropriate SCC practices.

This information and ideas presented are drawn from current literature and information received through discussions on a range of construction projects of varying applications. As a result of these discussions it has been possible and ideas presented within this paper to identify and target future areas of research that should assist the future development of SCC.

1. INTRODUCTION

This paper is one of the first public outputs of an ongoing research project being undertaken by Loughborough University and Lafarge Aggregates LTD, to look at the performance and sustainability benefits of self-compacting concretes (SCC).

SCC has been identified as a material which can provide improved performance characteristics when directly compared to conventional concrete. However it should also be noted that the material does also have some drawbacks compared to conventional concrete.

This paper aims to identify and establish the ideal scenario for the use of SCC within major construction projects, with a focus on large structural frames. Whilst considering the ideal scenario for the use of the material, the situations and circumstances where the use of SCC will not be of benefit or value to the project will also be noted.

Information and ideas that will be discussed have been drawn from experience of construction projects using both SCC and conventional concrete. These range from stand alone structures, such as a recently completed and award winning museum and art gallery that has embraced SCC as an architectural tool; a high profile iconic new art gallery, which is the first to encompass coloured SCC in the UK, in an architecturally challenging structure and construction of multi-storey high rise residential accommodation in a major UK city, which was in fact designed to initiate the research into the comparison of SCC and conventional concretes.

2. BACKGROUND OF SCC DEVELOPMENT

Existing research undertaken within the construction industry has been focused on the structural and physical performance properties of SCC's, with little quantified research directed towards the performance in practical application¹.

SCC has been identified as a material that has the potential to deliver a range of improvements in construction applications, such as structural performance improvements as a result of increased durability². There is also an opinion that the material can reduce construction duration through speedier casting³ and improved quality⁴. Links to sustainability issues are also recognised, with views that the material can reduce energy costs, through its easier placement³, shorter project duration⁵ and during life due to thermal mass benefits².

Whilst these aspects are advantageous, some major barriers exist such as increased cost^{6,7}. That said are attributes in the material's use that have been identified which can potentially reduce cost (these being labour reductions through placement operations^{4,8} reduced overheads, due to plant hire and project duration⁹, and finally a reduction in remedials resulting from increased final quality¹⁰). Further to this, there are also issues regarding the lack of experience of end users who view SCC as a specialist material^{11,12}. A final barrier to uptake is that current UK construction industry systems are geared towards the use of conventional concrete¹², so SCC may require changes to 'normal' practices⁴.

SCC as a material performs in a manner that is significantly different to conventional concrete and has different performance criteria. Using an SCC and realising its full potential requires a distinct change in the approaches currently undertaken in construction projects. In response to these requirements this paper sets out to establish the ideal arrangements for the effective use of SCC's and also identify the situations where the materials will prove less suitable. It considers an 'ideal' scenario under heading 3.7, specifically for large structural frame projects. This involves a range of different physical elements and encompasses a wide range of approaches and practices on site.

3. THE SCENARIO/METHODOLOGY

It is clear that SCC as a construction material is significantly different to conventional concrete and for this reason it may need to be approached and used in a different way, thus its effects have to be considered on all parties involved with construction. These effects and changes are to be discussed in the context of planning a large structural frame project, and then by providing a future scenario for the optimal use of SCC. This will be based on observations of construction projects which have utilised both SCC and conventional concrete and the findings from a confidential industry report, it is not possible to identify specific findings due to the commercial nature of the report.

3.1 Deciding to use SCC

The decision making process that surrounds the use of construction materials in structural applications is driven by the performance properties of the material and the knowledge of its suitability and use in previous applications. Materials are primarily chosen if they satisfy and suit the application, but choice is often limited. SCC, to date, has been selected over conventional concrete, due to its fluid nature, for special construction applications and problem solving⁴. There does not yet appear to be a trend to use the material as a common replacement for conventional concrete.

It is in this role (as a genuine replacement for conventional concrete) that it may be possible to realise the additional performance improvement characteristics identified within industrial and academic literature, such as The Concrete Society's Technical Report No. 62¹³.

3.2 SCC requires close partnerships

To use SCC effectively within a construction project parties involved need to work closely together and accept any change that SCC use may bring. They should be open with each other and effectively form a partnership for the construction which will need to commence as soon as initial work on concept, design and specification begins; failure to work together could have serious consequences on the success of the project. SCC requires a move away from traditional practices and the knowledge needed to implement change and improve practices will be held by many parties and only a close working relationship will enable this to be drawn together.

SCC should be considered at these early stages to ensure that improvements are realised, it is only then that SCC can be used as a proven replacement for conventional concretes. To ensure that this early collaboration occurs, it may require a

change in the contracts that are undertaken between parties and also the tendering process and the time at which parties become involved in the project.

Indeed, SCC is billed as a material that can provide improved value to a project¹³; however this can only be achieved if the aforementioned step is carried out; commercially available SCC is currently approximately 50% more expensive than its conventional equivalent. However, the material can also be used at later stages in a project if one of its particular characteristics enables unforeseen site or construction issues to be resolved.

3.3 Leading by design

An early decision to use SCC in a construction project has the ability to change the manner in which a structure is designed, i.e. architectural and structural properties. A prime example of this is a project currently being undertaken in the north of England, which is the construction of a concrete structure that is utilising, for the first time, coloured SCC, in an architecturally challenging design to create an iconic art gallery in honour of a local sculptor. SCC has been proven (through its use in several high profile projects) to offer a construction solution that is not possible using conventional concretes. This ranges from improved surface finishes, which can be combined with intricate detailing, to the use of heavily reinforced structural elements. The material then opens up further options for architects and structural designers to create structures which are significantly different to those that can currently be constructed in conventional concrete, hence new realms are viable with SCC.

If SCC is to be taken on by being driven through design, then the material needs to be listed within the contract specification, such as a clause in the National Structural Concrete Specification¹⁴, in order to achieve the desired results. For a construction project to be successful at this stage it is important that the parties who are contracted to carry out the construction project buy in to the use of the SCC and are able to tailor their working practices accordingly.

3.4 Contractors

The involvement of the contractor is critical, whether an organisation takes responsibility for the whole construction or a series of packages (the latter being the most applicable for the majority of construction projects, but makes the management and uptake of changes in practice harder to manage and implement). This is because the contractor is responsible for the activities that are carried out on site and it is with them that the responsibility lies to use the material properly, adhere to the guidelines that surround its use and obtain its benefits.

Coordination of the parties within the project needs to occur, as with the decision to use SCC, early in the project life. Each party needs to fully appreciate the role which they play in the construction programme, to understand the areas where they influence the construction process and the overlap with other parties.

Key within this category is the group who are directly responsible for the physical construction of the structure, i.e. site managers, construction managers and labourers.

3.5 SCC supply – confidence and capability

As with most construction operations the material supplier is often involved late when planning a project. In the case of conventional concrete this is acceptable, however when considering a relatively untried material on a large scale the suppliers knowledge is useful at an early stage. As the producer of the material they are best placed to provide advice on the effects that the material can have on the construction phase, both positive and negative.

The supplier of the material will be required, especially through the early development of projects that utilise SCC, to provide all members of the project team with information regarding the differences that exist between a SCC and a conventional concrete. When liaising with the design team the supplier will provide information about the performance criteria of the material, either in the area of structural properties or its quality as a finished and exposed material. The material's construction performance will need to be communicated to the teams responsible for the onsite works, in terms of planning and resources, but also areas such as handling and placing. Whilst this is already carried out to an extent, there will need to be added focus in SCC projects to ensure that those involved understand its implications.

3.6 Planning for construction using SCC

Once a structure has been designed the project responsibility is passed onto the principal contractor who is either directly responsible for construction or is facilitating the construction of the structure. At this stage the planning and resource provision for the construction phase can commence, this is a key area for change to occur when directly replacing a conventional concrete.

SCC has vastly different physical properties compared to conventional concrete and as result requires changes in not only how the material is handled, but also how a site operates. It is at this stage that the relationship between the constructor and supplier must be strongest. Planning and resource allocation is an activity that is multifaceted and requires a high level of skill and previous experience. In respect to programming structural construction, a facilitating principal contractor will establish a time frame for the completion of the project, into which a frame constructor will be required to fit their construction programme. In order to plan and resource a project using SCC it is necessary to understand how and where its potential can be exploited. It is at this stage when conventional methods of construction planning need to be re-considered.

The improvements that SCC can bring include placing, in terms of labour and the effects on labour, construction speed and project duration, energy costs, plant costs, structure durability and quality, and finally total project costs and it is the inclusion of these improvements which will test the relationship between the project team.

To reduce project time with SCC requires advanced planning to enable the saving to be achieved in reality. Conventional cycle times and the frequency of concrete pours many need to be reconsidered through close cooperation between the supplier and contractor, to ensure that demand can be met for pours which can be placed and finished quicker. Adaptation of resource allocation for the construction operation

needs to be explained and examples provided, on how these can be adopted without affecting the productivity of the project. Labour can be reduced through the less demanding and simplified process of placement, plant reduced due the removal of the need for compaction and reduction of project time, which can reduce construction overheads. The final finish of concrete elements can be used by constructors and designers to improve the value of a project. With respect to construction this can have a dramatic effect on the quantity of remedials required, which can have a detrimental effect on construction time and cost, aspects that are not always accounted for at the outset. The improved quality of SCC can enable additional surface finish layers to be reduced or as in other projects, complex formed faces to give the impression of other materials being used.

3.7 SCC in the future: 20 years on....

Let us consider a time in the future and speculate that the construction industry has changed to fully adopt SCC, this section describes such a future.

Acceptance and change within the construction industry has allowed SCC to become the material of choice when it comes to the construction of structural concrete frames. Since the benefits of its use have been identified and fully researched, providing quantified data that categorically identified the materials effect on construction, coupled with its inclusion into the latest issues of European standards use has increased exponentially, with a major increase in the numbers of projects where SCC has been specified early on as the preferred concrete option. Indeed collaboration between project partners is at an unprecedented level with parties becoming involved at earlier and earlier stages of a project in order to ensure that the best possible value is achieved, a trait that is now common throughout all construction projects, regardless of material used. The early involvement of project partners has moved selection away from the historical method of the lowest price to the selection of best value combined with the companies approach towards collaborative working. This scale of collaboration has seen the value of construction projects dramatically increase, with the benefits in the construction process being shared between each partner. Design and planning now fully accepts the use of SCC and as such the material has paved the way for new exotic and groundbreaking structures to be created, which prior to this acceptance would have remained unfeasible. There is now confidence in the ability of all parties involved within the construction project to cooperate with the goal to provide the best possible end product. So, it is coordination and knowledge that will provide SCC with the opportunity to flourish in the future UK industry.

4. CONCLUSIONS

This paper set out to identify the changes and steps that are required within current construction management to allow the successful use of SCC. It has identified a current trend within the UK industry to use the material as a “problem solver” rather than a viable normal construction option, but SCC does offer real potential for change to occur within the construction industry and provide improved value for all members of a project team, from the client to construction team. The project parties operate (and are responsible for) separate parts of the construction programme and the level of

interaction between the parties is somewhat minimal leading to a disjointed construction organisation.

However, to fully utilise SCC in future projects and achieve the full value that can be provided by the material it is necessary for closer relationships between the constructing parties to be formed. These relationships need to be formed at the early stage of the project and may require the project to be managed differently to conventional concrete projects. The need for change in the methods used in conventional projects stems from the inherent differences that exist between the two materials and the improvements that they can potentially bring. Traditionally phases of work are completed prior to the tendering for construction parties to become involved in the project; in the case of SCC knowledge needs to be shared to optimise the project, something which cannot be carried out once the works have been planned.

There has yet to be a project undertaken in the UK construction industry which has operated under such a scenario, but this may be the only method that will enable the full implications of an SCC to be understood and quantified. To do so requires the coming together of several parties who have a mutual intention to develop SCC. It is an aspect of future research that is to be explored as a part of the ongoing collaborative research project that is being undertaken with Lafarge and Loughborough University, with the desire to fully understand the performance implications of SCC.

5. ACKNOWLEDGEMENTS

This paper is the second output from an ongoing research project into SCC and as such I would like to thank those who are directly involved in the project at Loughborough University, Jacqui Glass and Alistair Gibb and those involved at Lafarge, Darren Williams and Patrick George, and to anyone else who has contributed to this research programme.

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APPENDIX D

SCC on site: Understanding the implications for construction operations

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SCC ON SITE: UNDERSTANDING THE IMPLICATIONS FOR CONSTRUCTION OPERATIONS

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Key words: Concrete, construction industry, self-compacting concrete, research, UK.

Abstract: *Self-Compacting Concrete (SCC) has been argued by some in academia and the global construction industry to be the most significant development in concrete technology for the last 50 years. SCC is a material which has undergone development since the 1980's and now is beginning to be recognised as having the ability to notably improve construction performance.*

That said, there is a need for clarification on the implications that its use can have for construction. In order to fulfil this objective it is necessary to understand potential effects on operations such as placement, finishing and projects as a whole.

This research has considered views from within the industry and academia on SCC, which have been drawn together to form a state of the art overview. In this paper the effects that SCC can have on construction practices is considered and the state of the industry with regard to new developments is examined. It is from this overview that it has been possible to draw out key areas for research and identify changes that are needed for SCC to be used more widely in the future.

1. INTRODUCTION

This paper is the culmination of a review of information that is currently widely available within the construction industry regarding SCC's and the subjects surrounding its use. The paper aims to bring together this information into a single document outlining the current position and status of the material within the UK industry.

Within the UK construction industry there is a well recognised reluctance to use new methods or materials. SCC can be seen as an example of this, as it is a development that has been available for some time, but has yet to be fully adopted. The material has been identified as having the potential to influence and improve construction performance but has yet to be accepted. This stagnation is beginning to slowly change as more organisations undertake a drive for value in construction projects and look for areas where benefits can be sought. The suitability of SCC in this respect is to be addressed through this paper, which will show where the benefits and issues lie with the material.

2. BACKGROUND OF SCC DEVELOPMENT

Self-compacting concrete (SCC) has been defined by many different authors in many different ways, but is widely accepted as a “concrete which, in its fresh state has superior flowing ability, allowing the material to completely fill a given form, whilst maintaining homogeneity and then consolidate without the addition of energy”^{1,2,3}.

The material has been labelled as “the most important innovation within concrete technology for the last 50 years”¹. Development of SCC like many other materials was initially needs-driven, however the presence of the need does not mean the solution will always be accepted, as identified in the ‘Rethinking Construction’ report published by the Construction Task Force in 1998⁴. It was initially developed in Japan during the 1980's and was a response to emerging issues within their construction industry⁵, development has since spread throughout the world. Indeed, during the

early 1980's the Japanese construction industry was experiencing a shortage in skilled workers⁵ and it was this situation which led to SCC.

A key application in the placement process of concrete, for which the operatives are responsible, is the compaction of the material in the form. It is widely accepted and noted that the quality of compaction achieved within a material is crucial in achieving durable concrete^{2,6}. Quality of concrete is further questioned by The Concrete Society and BRE², who state that a significant proportion of concrete is “never fully compacted”. This was seen, when combined with a reduction in skilled labour by Holton⁷, to have a detrimental effect on the quality of concrete within structures. Therefore the solution to this issue was to create a concrete whose hardened quality was independent of skilled labour, by removing the need for compaction, the result SCC^{2,7}.

These initial drivers for the development of SCC in Japan, according to the Construction Task Force's report⁴, are now seen in the UK construction industry; a shortage of trainees and workmanship⁸.

The identification of these issues in the UK construction industry by academia and industry meant that the UK therefore experienced a similar pattern of development of SCC. At the current time all of the UK's major concrete producers supply their own variants of SCC with differing levels of product development and success in the market.

So far the majority of research undertaken within the UK concrete industry has been focused on ascertaining the physical and structural performance properties of the material², rather than the implications of using the material in practice. Within other European nations the subject of practical application has now become the focus of development⁶ and there are some important issues to be investigated such as the human and societal, economic and sustainability effects.

3. IMPLICATIONS OF SCC ON THE CONSTRUCTION INDUSTRY

As has been highlighted in the first part of this paper, SCC is a relatively new development in concrete technology, with the majority of research focused on its physical and structural performance. There is however a range of evidence available which relates to the implications of using the material in practice, which indicates both positive and negative aspects but tends to be speculative or anecdotal in nature, lacking robust experimental or research proof.

That said, currently the use of SCC's is not widespread, with its selection tending to be as a result of a specific need, rather than a deliberate choice to use it as a direct replacement for conventional concrete^{9,3}, this makes research difficult. With most existing research focused on the material's physical and structural performance characteristics it is not yet possible to identify or measure the effects that the material can have on construction, in regard to time, cost and operations. Therefore the decision can not be made on the widespread use of SCC as a direct replacement of conventional concrete. So, this section presents a concise review of alleged benefits of using SCC.

3.1 Construction Benefits

In a significant number of cases where SCC has been utilised the rationale behind its use has been a result of a property or trait that has enabled it to outperform conventional vibrated concrete. SCC as a material can and does have the potential to offer improvements are a result of the physical properties of the material, but also advantages relating to societal, economic and sustainability aspects.

3.1.1 Physical

Essentially it is the difference in physical properties between an SCC and a conventionally vibrated concrete that offer the potential for improvements to be sought. An SCC has three defining characteristics which are the basis for any physical property improvements they are; flowing ability, passing ability and segregation resistance¹⁰. The claimed improvements relating to these provide the potential for the material to be used to create more complex and innovative structures, due to the

increased level of confidence in the material's ability to completely fill formwork^{11,6}, ability to flow, and to compact without an external energy input. The combination of these aspects leads to a further construction gain of accelerated casting rates and potential shortening of the construction programme⁸.

A lack of skilled construction operatives is an aspect identified as being one of the original drivers in the development of SCC and the process of compaction was recognized as requiring the most expertise. The omission of compaction coupled with the material's ability to flow has resulted in the potential opportunity to reduce the number of labourers on site without detrimentally affecting construction operations³.

Compaction was identified as a major cause of poor quality concrete due to the lack of the skilled labour and the inherent difficulty to establish if full compaction has been achieved². In addition, improved homogeneity and the potential for full compaction has been identified as a method for SCC to have an improved level of durability¹²; durability will improve as a result of improved cover compaction¹³, thus resulting in a material that is more resistant to sulphate attack, chloride attack and carbonation, due to reduced permeability⁶.

Claims of improved surface performance have also been identified with SCC elements showing a significantly reduced number of defects such as honeycombing and surface blow holes^{6,14}, due to the increased volume of fine fillers¹¹ in the concrete.

3.1.2 Human and Societal

These are linked to the people aspects of construction, i.e. the direct effect not only on those who are based on site, but also those in the local community surrounding a site.

Primarily SCC's site-based improvements are related to operative health and safety, through changes in activities and changes on site. The self-compacting nature of the material has removed the need for vibro-compaction tools, such as vibrating pokers and other compaction plant, the result of which is a reduction of the health hazard of hand arm vibration syndrome which can occur as a result of prolonged exposure¹⁵. With compaction removed it is conceivable that demand for construction plant can be

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reduced (and possibly removed) leading to a reduction in site-based hazards¹⁰. The possibility of reducing site plant has a secondary effect on site operatives and ties into an ongoing drive within the industry to reduce and remove aspects of manual handling¹.

A reduction in plant can also reduce noise in local areas surrounding construction sites¹⁰. Driven from the physical properties of SCC materials it has been highlighted that there is the potential for improved casting rates, leading to a potentially shortened project duration, which could result in a reduced period of disturbance to the local community⁶.

3.1.3 Economic

Cost and profitability is a major issue within the UK construction industry and it has been identified that any product that can improve the financial standing of a company will ultimately be accepted⁴.

Most economic improvements arise from the preceding improvements and are linked to changes in construction processes. The initial construction change is a reduction in labour that can be achieved as a result of the removal of the compaction operation^{1,6}. This also raises the possibility of plant reduction, which can reduce construction overheads with regards to hiring or purchasing plant.

Quality is a further aspect which has been identified by to improve through the use of SCC's and ultimately reduce the volume of remedial work, reducing cost in terms of materials and labour^{11,14}.

3.1.4 Sustainability

Sustainability is one of the key drivers within the UK construction industry¹⁷ and needs to be considered in detail for any emerging product. This is especially true of a product which, on initial observation, could have a greater impact than conventional products based on its constituent make up, in regard to increased cement content¹⁶ and the associated CO² burden. That said, research to date has considered the general

implications of the material on site and the potential to improve sustainability in this area. One of the key areas that have been identified is the capability to reduce energy use¹⁷. This can be derived directly from a reduction in site plant, for example in the removal of the compaction process, the ability to reduce energy overheads, due to faster placement and reduced remedials, shortening both construction programme⁸ and time on site.

In addition, SCC possesses the ability to potentially provide a material that in its hardened state is a uniformly dense homogenous mass¹². This lends itself to having improved thermal mass properties over conventional concrete and to enable passive ventilation to be achieved within structures¹⁷.

3.2 Quantified benefits

As mentioned, the majority of information on the benefits of SCC is of an anecdotal nature. However there is some quantified evidence of cost reductions, time savings, improvements in productivity, labour reductions, energy savings and finally improvements in tensile strength are available in the public domain, although its provenance is not necessarily clear, consistent or robust and often based on single, non-comparable projects (see Table1). These examples are detailed in table 1 and have all been reported within the referenced papers, the lack of a robust detailing requires these findings to be clarified and illustrates the need within industry of the provision of evidence that is transparent and can be challenged in order to fully circumstantiate the benefits of the material.

Table 1 Identification of quantified benefits of using SCC's

Benefit	Improvement	Detail
Reduction of Costs	15% reduction	Early decision to use material in Swedish construction. ²
	21.4% reduction	French comparison undertaken by Lafarge, SCC vs. convent. ²
	5 – 15% reduction	SCC's at design stage

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		derived from “experience” within Europe. ³
	5 – 15% reduction	Comparison of SCC vs. convent. bridge construction. ⁶
Reduction in Construction Time	2.5 months	French comparison undertaken by Lafarge, SCC vs. convent. ²
	20% reduction, 2.5 year build to 2 year	Live construction of Akashi-Kaikyo Bridge in Japan. ⁵
	22 months to 18 months	SCC on construction of LNG tank for Osaka Gas Company. ⁵
Improved Tensile Strength	10 – 30% increase	Reported results for SCC compared to conventional. ²
Labour Reduction	150 reduced to 50 operatives	Live construction of Akashi-Kaikyo Bridge in Japan. ⁵
Energy Saving	20 – 30% reduction also greenhouse gases.	SNRA report, result of reduced resources in construction. ⁶
Productivity Improvements	60% improvement over conventional concrete.	Observation of Swedish works on 19 bridges and house slabs. ¹⁹

3.3 Barriers

When considering the barriers to the wider uptake of SCC within the construction industry the most prevalent barrier is the increased cost of the material over conventional concrete^{2,3} prior to utilisation. The cost gap between conventional and self-compacting concrete has been significantly reduced¹⁸, however the increased cost is still present as a result of the increased material, development and support costs³.

Indeed cost still remains the most established barrier with the material still seen by some as a luxury or a product for ‘special occasions’⁹. This tag can only be removed once it is more widespread and established, however to do so, current practices in the UK need to be changed. This needs to occur not only on site (with changes to conventional methods of construction) but also higher up in the organisational supply chain, starting at conceptual stages of a project from design, specification and planning².

4. CONCLUSIONS AND NEXT STEPS

The majority of research to date has been focused on ascertaining the mechanical and rheological properties of SCC’s, with little research directed at quantifying its implications in practical construction. Whilst research on the scientific and technical aspects of the material is obviously important, understanding the practical application of SCC should not be overlooked.

Current research has identified areas and aspects in which SCC’s should excel and impart improved value to the constructing company; however there is a distinct lack of rigorously quantified data to back these claims. Table 1 illustrates the areas where improvements have been identified and quantified, however the quality of this information can be questioned due to manner in which it is presented. The data and information is not broken down, and the means and methods of obtaining this data is not identified.

The status of this available data therefore makes it clear that further research needs to be directed into the field of practical application of SCC’s. However, the research needs to be substantive, as any further studies which is not backed by rigorously data

will not assist the development of the material in the market. Indeed it is only research that has been carried out in a robust and transparent manner that will enable the continued development of SCC. This will enable the barriers that exist within the construction industry to be removed and allow the true commercial benefits and drawbacks of the material to be exposed. Driven by this need for robust data the research programme, of which this paper forms a part, will look to disclose the implications of SCC as an alternative to conventional concrete in large scale projects. The research programme seeks to understand the construction performance properties of the material through comparative research on live construction projects with a major UK concrete supplier and a structural frame contractor, in order to establish if SCC can provide any project benefits. It is expected that the opportunity will arise to undertake a programme of action research based on the use of SCC in structural frames. Following on from this aspect there is a desire to identify the sustainability implications of the material and how its performance compares with conventional concrete and how this can be improved.

5. ACKNOWLEDGEMENTS

This paper is the first output from an ongoing research project into SCC and as such I would like to thank those who are directly involved in the project at Loughborough University, Jacqui Glass and Alistair Gibb and those involved at Lafarge, Darren Williams and Patrick George, and to anyone else who has contributed to this research programme.

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APPENDIX E

Self-consolidating/compacting concrete: construction time and cost data from UK residential projects

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Submitted: 29/05/14

Title: Optimising construction with self-compacting concrete

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Abstract

Self-compacting concrete (SCC) or self-consolidating concrete (as it is known in North America) is used on the basis of its unique properties of flowability, passability and resistance to segregation. It requires no external energy to achieve full compaction, so is advantageous on site, but there is evidence that its higher cost is a significant barrier to greater adoption. The research entailed work measurement of 14 UK single family home residential projects (eliciting data on construction time and labour productivity) and cost modeling of three slab scenarios (exploring the relationship between material and labour costs). The study found SCC was placed up to 73% faster than conventional concrete and when labour and material costs are included, the supplier is able to price SCC to closely match conventional concrete, hence making SCC more viable for the contractor. This relationship between as-built costs for SCC and conventional concrete is clarified by developing P_{max} , providing a new mechanism for understanding project profitability and viability of SCC.

Keywords

Concrete structures, Planning and scheduling, Slabs and plate

1.Introduction

Self-consolidating concrete, also called self-compacting concrete (SCC) has been available in Japan, North America and Europe for over 20 years. It is used in many mainstream construction projects because of its flowing nature and early maturity, it is generally considered to be an innovative material that is more expensive than conventional concrete mixes. Higher initial material cost seems the most significant barrier to greater adoption (Concrete Society and BRE 2005; Rich et al 2010; Rich et al 2012), but its placement is claimed to be faster and more reliable than conventional concrete (Kyahat et al, 2001; Okamura and Ouchi 2003). Therefore, directly comparing SCC with conventional mixes, simply on the basis of material cost, is inappropriate and inaccurate.

Most extant SCC research focuses primarily on understanding and optimising physical and structural properties; with little examination of its effect on commercial out-turn measures, such as the construction cost (including materials, labour and plant). This paper reports on research on SCC and conventional concreting methods in 14 UK single-family home projects. Work measurement and cost modelling through scenario analysis captured data on material costs, placement rates, workers' activities and plant/truck movements, to identify any significant time and cost differences between SCC and conventional concrete.

2. SCC's commercial status in construction

2.1 SCC's physical properties and claimed benefits

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A self-compacting concrete (SCC) requires no external energy to achieve full compaction and is characterised by three distinct properties: resistance to segregation, flowing ability and passing ability and early strength gain (Goodier 2003; Skarendahl and Billberg 2006). An extensive, global research base on SCC's structural and physical performance aspects has built on earlier Japanese research (e.g. Okamura and Ouchi 2003; Khayat 1999; Shobha et al 2006; De Schutter et al 2008) and accepted test methods and standards/codes of practice have emerged (e.g. ASTM and RILEM). This is essential to encourage use and ensure consistency and durability of an emerging technology. SCC also facilitates more complex structures due to its ability to flow, fill formwork and compact without external input (Goodier 2003; Grimes 2005). Reports suggest improved quality and homogeneity, resulting in improved durability, resistance to degradation (Skarendahl and Billberg 2006; Henderson 2000; Goodier 2003). Furthermore, virtual elimination of surface defects, such as blow-holes and honeycombing (Goodier 2003; Gaimster and Foord 2000) is claimed through the removal of the compaction operation, which is dependent on operative ability (Holton 2003; The Concrete Society and BRE 2005), and should reduce remedial work (Grimes 2005; Gaimster and Foord 2000). SCC enables the contractor to use less site equipment (Damtoft et al 2008) such as vibrating tools that can cause hand arm vibration syndrome (HAVS) (Walraven 2003; Skarendahl 2003) and reduce operative numbers (Goodier 2003; Damtoft et al 2008). Yet despite these claims, there is relatively little evidence and data on SCC's practical application within construction (e.g. Gaimster and Foord 2000; Henderson 2000; Goodier 2003; Damtoft et al 2008) as summarized in Table 1. Extant publications are often subjective and imprecise, lacking detail about data derivation and often citing values from elsewhere

without justification. Hence, it is inadvisable to make a case for SCC based on such incomplete data.

Table 1. Summary of the benefits of SCC, from the literature.

Benefit	Level of improvement cited	Detail and reference source
Reduction of costs	15% reduction	Early decision to use material in Swedish construction (Concrete Society and BRE 2005).
	21.4% reduction	French comparison undertaken by Lafarge, SCC vs. conventional (Concrete Society and BRE 2005).
	5 – 15% reduction	SCC's at design stage derived from "experience" within Europe (Holton 2003).
	5 – 15% reduction	Comparison of SCC vs. convent. bridge construction (Goodier 2003).
Reduction in construction time	2.5 months	French comparison undertaken by Lafarge, SCC vs. conventional (Concrete Society and BRE 2005).
	20% reduction (2.5 years build reduced to 2 years)	Live construction of Akashi-Kaikyo Bridge in Japan (Okamura and Ouchi 2003)
	22 months to 18 months	SCC on construction of LNG tank for Osaka Gas Company (Okamura and Ouchi 2003)
Labour reduction	150 operatives reduced to 50	Live construction of Akashi-Kaikyo Bridge in Japan (Concrete Society and BRE 2005).
Energy saving	20 – 30% reduction. Greenhouse gases also reduced.	SNRA report, result of reduced resources in construction (Goodier 2003).
Productivity improvements	60% improvement over conventional concrete	Observation of Swedish works on 19 bridges and house slabs (Persson 2001)

2.2. Factors affecting the decision to use SCC

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SCC is considered a specialist material, only suitable for certain applications (Holton 2005; Clear 2006), but this view is slowly being dispelled through continued use in general construction (Williams 2008) and high profile projects, such as The Collection, Lincoln UK (Grimes 2005) and The Hepworth, Wakefield UK. Here SCC was selected in response to specific challenges, for instance to create very high quality, complex and detailed facades. SCC is rarely selected as a 'first choice' construction option in its own right, yet literature confirms that the material has a broader range of benefits than this 'single attribute' decision-making might suggest (Williams 2008). SCC should not be considered on first-cost alone (Holton 2003; Concrete Society and BRE 2005), however, misconceptions relate to poor knowledge and an apparent increase to project costs, as a result of material price (The Concrete Society and BRE 2005; Rich 2011; Rich et al 2012) as SCC tends to be more expensive than conventional concrete in cost per sales by volume. Rich et al (2012) developed this idea further, through case studies and industry surveys, by identifying three distinct circumstances for use:

- Strategic change from conventional methods as part of a balanced assessment of SCC and its effect on construction.
- Reactionary response to a specific issue or problem (problem solving).
- Specification of SCC as a pre-conceived construction option.

Rich et al (2012) conclude that strategic change is a direct result of considering SCC as a construction method rather than a material, invoking engagement with SCC earlier in the construction process during design and planning, with greater potential to adapt construction to realise other benefits.

2.3. Lack of practical evidence on construction process

Concrete slab construction has six steps, whether using SCC or conventional concrete: material discharge, manipulation of material, compaction, levelling, finishing and curing. However, SCC 'performs' the compaction process itself and the manipulation, levelling and finishing are simplified. This simplification can remove several steps compared to conventional construction (see Figure 1). SCC's free flowing nature reduces the requirement for manual manipulation. SCC exhibits self-levelling traits whereas conventional concrete requires extensive manipulation with rakes and shovels prior to compaction and striking off. Conventional slab finishing requires two stages: initial finishing by manual floating; then, once adequate curing has occurred, powerfloating. SCC finishing uses a 'dappling' process; small surface waves are created to achieve a smooth and level finish, equivalent to powerfloated flatness. Both methods then require curing.

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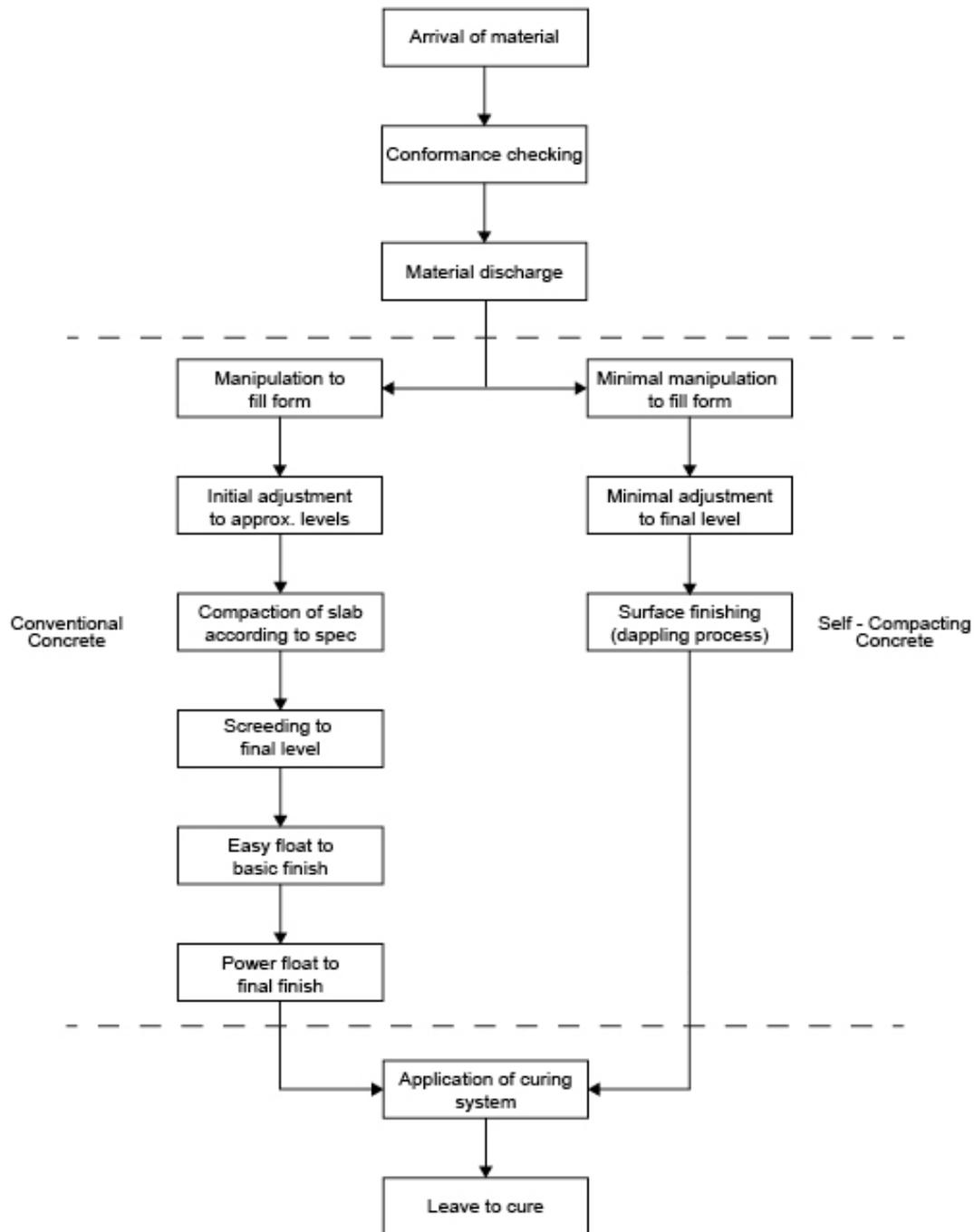


Figure 1. Breakdown of conventional concrete and SCC placing methods.

A good research base exists on SCC's physical and structural properties, but there is still a need to explore the effects of SCC's different approach on the construction process systematically on live projects. No one has yet explored SCC's effect on

project time and cost, including for example casting rates, labour efficiency and quality of construction. The next section explains the research approach, through work measurement and cost modelling of UK residential projects.

3. Research approach

The research aimed to compare SCC with conventional concrete, identifying differences in time and cost, using a series of residential projects to provide real-life data. There were two phases: work measurement and cost modelling.

3.1. Work measurement

Work Measurement establishes the time for a ‘qualified’ individual to complete a specified task at a defined level of performance (Currie 1977; Drewin 1982). The process comprises:

1. Selection of work to be measured (A.1): clarification of exactly what is to be measured. Here, to compare SCC with conventional concrete, in the construction of single family homes.
2. Defining the method (A.2): selection of the optimised construction process. In this case, traditional slab construction with conventional concrete and SCC construction methods.
3. Establish work elements (A.3): breaking down the methods into elements which are easily measured, identifiable and transferable between construction options. Final quantification can only be confirmed when observations are complete.
4. Measurement of elements (A.4): direct timing of an element of work. Success depends on clearly defined work elements with distinct start and finish points

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incorporating a defined and detailed method of data capture. Standard rate of working and rest time are factored in.

5. Obtaining a standard time (A.6): determining an overall time for the construction processes combining all measured elements and adjustments.

Rationalisation of time measurements was on a unit area and volume basis.

2.2. Selection of project cases and method used

The study element must be built regularly with very similar or standardised methods; ground floor residential slabs satisfied these criteria providing directly comparable, robust results that could compare the claimed benefits of SCC with conventional concrete. There are two distinct slab construction methods for UK houses ground floors: ground bearing insitu (GB); or suspended (SS). SS typically use precast beam and blocks with an insitu topping and use SCC more often than GB slabs. The management structure for such projects is simpler than structural frame projects, leading to easier permissions for site observations. While a number of parties are involved, it is only the contractor responsible for the placement of concrete that experiences any changes to methods of working through SCC. The contractor's primary concern is the strength and finish specifications (British and Eurocode standards along with National House-Builders Council (NHBC 2011) standards), it is therefore only this contractor's work that needs to be observed and considered. A total of 14 separate slabs were investigated, six using conventional concrete mixes (ranging from C16/20 to C28/35) and eight using SCC over a three month summer period in 2010. The sites were within reasonable travelling distance from base, were comparable in size and design and all had experienced contractors. The processes were filmed to record the movement of materials, labour and plant. For each pour,

records were made of total pour time, time from initial material discharge to curing, activity times, time for each individual construction activity to be completed, along with labour times, time on the pour and time actively working. To identify significant differences in construction protocols so that any anomalies through the analysis of times may be interrogated to determine the drivers, several additional observations were made, including slab dimensions and construction details, material design, labour, plant and ambient conditions.

2.3. Developing cost model scenarios

The cost differences between the two methods were determined, using both the timings and labour/plant movement data captured on film along with additional cost data, facilitating a more holistic understanding. Cost modelling was an appropriate method enabling rationalised comparisons based on realistic scenarios. Two conventional concrete scenarios illustrated variability in the power floating operation, where completion is dependent on the rate of curing (dictated partly by ambient conditions). Only one scenario was needed for SCC as it does not require any break point once pouring has commenced. Each scenario was based on slabs of a similar type to those used in obtaining the time data. The slab design was an idealised suspended ground floor residential slab, common to the UK housebuilding, constructed using an insulated block and beam system with a concrete topping layer (to a size of $9\text{m} \times 5\text{m} \times 0.075\text{m} = 45\text{m}^3$), finished smooth to suit final finishes (Figure 2).

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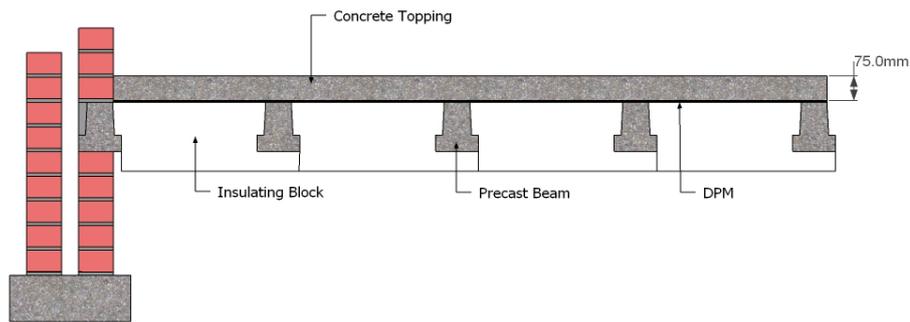


Figure 2. Representation of suspended slabs (SS) design.

As-built cost data was developed from construction time data to describe the construction process. The study was extended by further and more detailed observations of the construction process, with an understanding of each step in the construction process and its requirements with respect to auxiliary items such as plant, labour, materials etc. This was where additional site observations provided deeper understanding of each construction activity. For each process the cost to construct was developed considering material price (concrete and supplementary (curing agent, form release agents etc)), operative pay rates, volume of labour, plant and equipment costs (hire or purchase), site overheads, out of hours working and regional cost variations. Data was collected from material suppliers, contractors and pricing books, and was current at first quarter 2011. Currency of the data, the units of measurement and outlying factors that might influence the costs on a live project were verified. The eventual costs of each element were collated into a single cost to determine the difference between conventional and SCC methods.

4. Results

4.1. Time study

These results are based on direct observations of the construction of 14 residential slabs similar to Figure 3. In the majority of cases, the SS structures incorporated inverted T precast beams, with either concrete or insulated polystyrene infill blocks. Brick or block work was initially constructed from foundation level to two brick courses below damp proof course (DPC) level. Precast beams were laid typically spanning between perimeter foundation walls to intermediate supporting columns or walls. Brickwork was laid to final finished slab level, and the infill blocks installed. A damp proof membrane (DPM) was placed onto the block and beam structure overlapping onto the brickwork at DPC level. In both approaches, concrete was discharged to the slab from the bucket of a 360° excavator with no significant variation in discharge rate. Compaction of conventional concrete typically used mechanical poker vibrators or vibrating tamping rails.



Figure 3. One of the residential sites used in the time study.

The Total Construction Time (TCT) for each slab was determined from the film analysis, from initial discharge to the final application of curing protocol, along with

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intermediate breakdowns of each distinct phase; placement, tamping, screeding, floating, power floating, dappling and curing. This provides a descriptive account, but does not enable direct comparisons to be made, due to the varying slab areas and depths, so the data has been rationalised. First, from a total time to an average time per unit area (m^2) and per unit volume (m^3) for each slab (the lower two rows in Tables 2 and 3) and secondly, the Average Construction Time (ACT), taken across all instances of SCC slabs and conventional slabs, can be seen at the far right hand columns in Tables 2 and 3.

Slab code number	Pour Time (mins:secs)	Area (m^2)	Volume (m^3)	Rationalised construction time (mins:secs)/m^2	Rationalised construction time (mins:secs)/m^3
CON1	82:54	41.83	3.14	01:59	26:24
CON2	86:05	37.80	2.84	02:17	30:19
CON3	80:15	37.80	2.84	02:07	28:16
CON4	47:57	16.50	1.24	02:54	38:45
CON5	47:07	16.50	1.24	02:51	38:04
CON6	84:15	56.77	4.26	01:29	19:47
ACT (Average Construction Time) for all 6 slabs				02:16	30:16

Table 2. Rationalised construction times for slabs using conventional concrete.

Slab code number	Pour Time (mins:secs)	Area (m ²)	Volume (m ³)	Rationalised construction time (min:secs)/m ²	Rationalised construction time (min:secs)/m ³
SCC1	28:40	36.73	3.67	00:47	07:49
SCC2	23:15	49.49	4.95	00:28	04:42
SCC3	45:40	69:31	5.20	00:40	08:47
SCC4	23:15	42.80	3.21	00:33	07:15
SCC5	30:50	42.85	3.21	00:43	09:36
SCC6	22:15	46.33	3.47	00:29	06:25
SCC7	23:30	41.46	3.11	00:34	07:33
SCC8	40:50	63.70	4.78	00:38	08:33
ACT (Average Construction Time) for all 8 slabs				00:36	07:35

Table 3. Rationalised construction times for slabs using SCC.

Direct comparison of the ACTs show that SCC produces a significant overall time saving over that of conventional concrete (36 seconds /unit area (SCC) compared to 2 minutes 26 seconds (conventional); and 7 minutes 35 seconds /unit volume (SCC), compared to 30 minutes 16 seconds (conventional)). Figure 4 illustrates pour time ($T_{PT2} = \text{Total pour time/m}^2$) and labour time ($T_{PL2} = \text{Total labour time/m}^2$) differences. SCC is 73% quicker and uses 70% less labour.

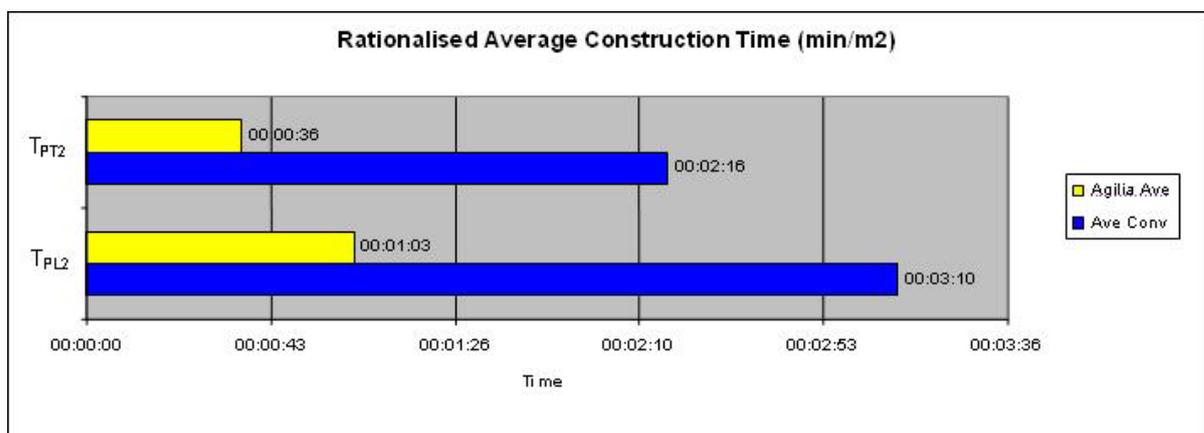


Figure 4. Comparison of ACT for conventional and SCC methods, including power floating operation.

4.2. Understanding the influence of material, plant and labour costs

It was stated earlier that the high material cost of SCC is a barrier to adoption, so the time study data has been extended to include cost information. Three scenarios were developed from observations as described in the research approach section (Figure 5 which includes both time and labour requirements):

- ‘Best case’ conventional concrete slab
- ‘Worst case’ conventional concrete slab
- SCC slab

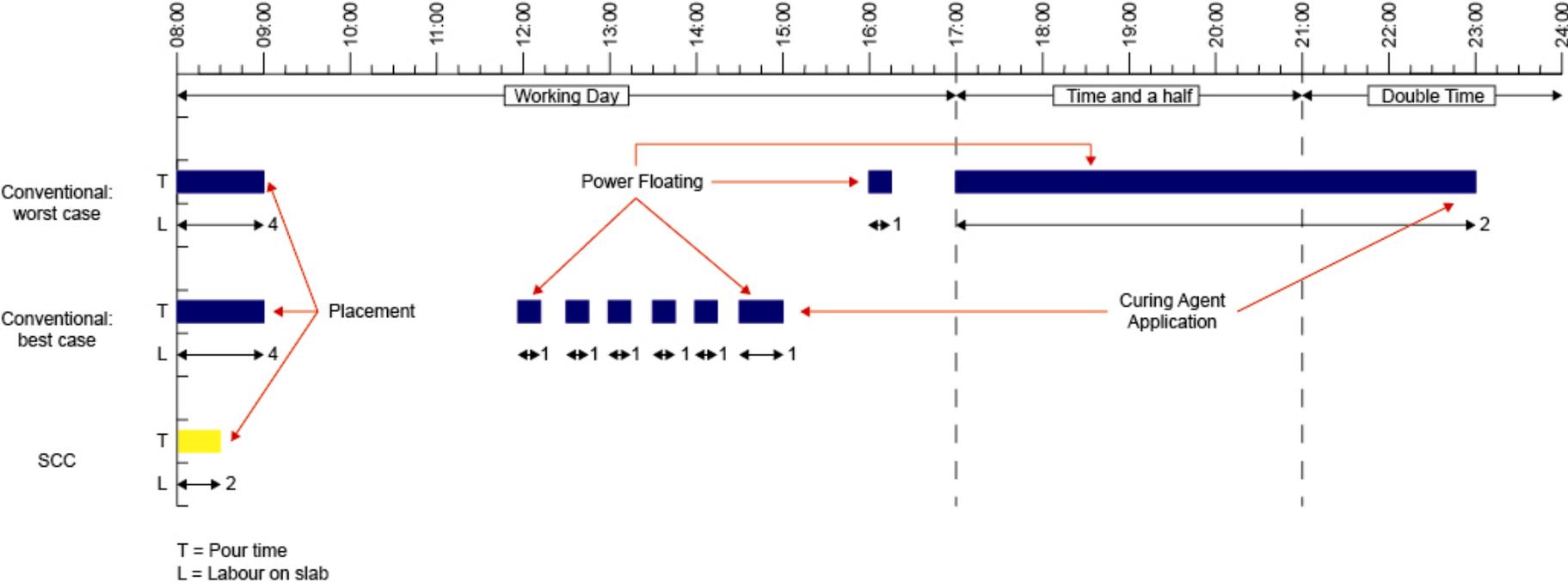


Figure 5. Gantt chart of idealised construction scenarios, with time and labour requirements

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Construction with conventional concrete is susceptible to significant variation in the cost to construct, mainly due to the powerfloating operation. In the worst case scenario costs are raised by 72% which, if encountered on a number of slabs, would significantly increase total project costs. SCC provides a substantial saving, £291.45 for completed construction, over the worst case scenario of conventional concrete. However, in the best case scenario, SCC is more expensive by £28.63 (Table 4). All costs were current at first quarter 2011.

Table 4 Costs for the three slab scenarios

Costs (£)	SCC	Conventional			
		Worst case		Best case	
Overheads	2.00	43.33		43.33	
Placement labor	15.22	57.02		57.02	
Power float labor	N/A	2.37		14.20	
Out of hours labour premium	N/A	334.00		N/A	
Material	380.63	252.59		252.59	
Curing labor	(included in placement)	(included in overheads)		2.09	
Curing agent	6.75	6.75		6.75	
Total	404.60	696.05		375.97	
Saving from using SCC compared with conventional concrete	n/a	+	+72%	- 28.63	-7%
		291.45			

Note: Overheads were developed from site observations and based upon nationally operating hire company rates. Placement costs are a function of Labour time illustrated in Figure 5 and labour rates. Out of hours working is based on the presence of two operatives for health and safety requirements. Material price has been derived from average UK national rates per m³, SCC £112.78 and Conventional £74.84. Labour rate of pay has been set at £8.35 per hour the minimum rate for concrete operatives as set by the Construction Joint Industry Council. All costs are UK-based and current as of 1st quarter 2011.

This comparison enables prevalent factors in method choice to be determined. SCC reduces construction overheads and placement labour through the simplified construction process; however they are not significant in the balance between options.

Material price is the most significant factor for SCC, which reflects existing literature which considers price as a major barrier to uptake (Holton 2003; The Concrete Society and BRE 2005; Rich et al 2012). The determining factor for conventional concrete is labour, where out of hours working is most influential. However, the relationship between out-of-hours working on conventional projects and the material price for SCC determines the tipping point between each method.

4.3. The importance of P_{\max}

It has been possible to establish the maximum permissible premium (P_{\max}) per unit volume (m^3) that can be applied to SCC by the supplier, such that the contractor can achieve parity between the as-built costs for both conventional and SCC methods (and therefore be at no overall disadvantage from using SCC). Here, P_{\max} is determined with respect to slab size and labour rate, based on the construction of a 75mm deep topping on block and beam construction (Figure 6).

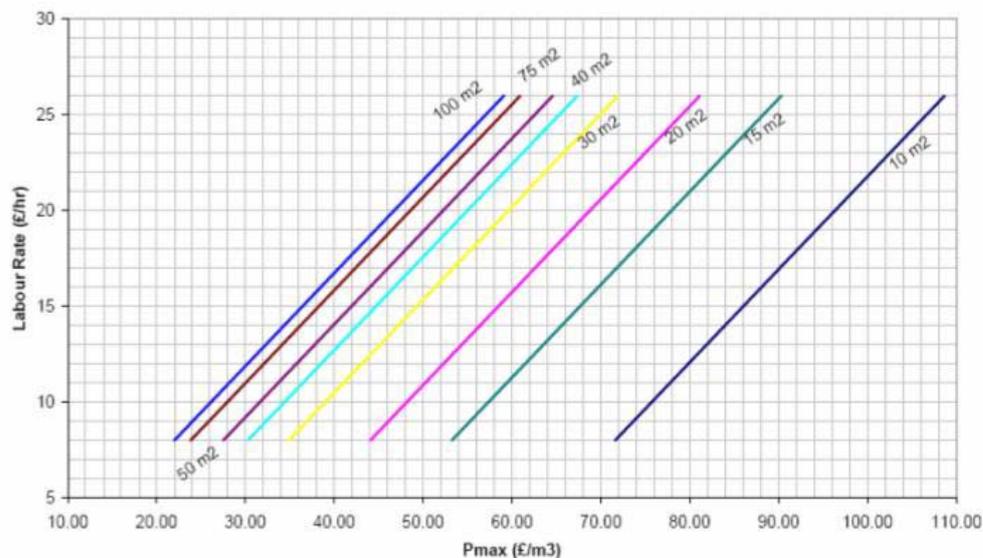


Figure 6. Graph of P_{\max} for varying slab size and labour rate (slab depth = 0.075m).

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In the 'best case' scenario for conventional concrete, parity can be achieved by providing SCC at a P_{\max} of £29.46 per m^3 above the price of conventional concrete. Figure 6 shows the relationship between slab size and P_{\max} , as slab size increases P_{\max} decreases, effectively reducing the cost benefit of the SCC method. However, at low labour rates P_{\max} is small because of the relationship that exists between material and labour cost, material price is the significant variable with SCC and labour with conventional respectively. When labour rate is low the difference between material and labour is at its greatest, which reduces P_{\max} as this is a function of the difference in as-built construction costs determined by material and labour costs. As labour costs increase for the same sized slab, material costs remain constant. This in turn reduces the as-built cost difference between methods and enables P_{\max} to be maintained at a higher value.

As slab size increases, P_{\max} decreases. However, for the same slab, there can be two different timings and costs from extended working hours due to varying ambient conditions. Therefore, the relationship between P_{\max} and slab size in these circumstances may vary. If out of hours working is incurred when constructing with conventional concrete (Table 4) the relationship between material cost and labour rate varies, where initially the difference in constructed costs will reduce to a point where conventional construction costs will exceed SCC, the worst case scenario. The amount of out of hours working is determined by two factors: ambient conditions and slab size. If ambient conditions remain constant for slabs of increasing size, the increase in out of hours working would be proportional to slab size. P_{\max} is directly related to these factors and would see a change in the relationship to slab size,

increasing rather than decreasing (Figure 7), improving the as-built cost benefit of SCC once out of hours working is required.

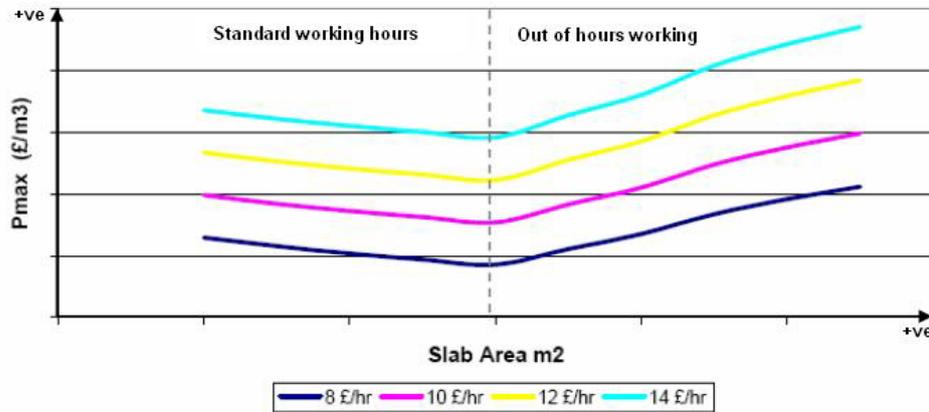


Figure 7. Variation of P_{\max} resulting from out of hours working, with respect to increasing slab area, for a range of operative pay scales.

The maximum permissible premium, P_{\max} , can now be calculated for residential suspended slab construction to find the tipping point between extra material cost of SCC and the extra labour costs by using conventional concrete. P_{\max} can determine when SCC would become a viable selection.

For single-family homes, where the slab areas do not exceed 65-75 m² with a depth of approximately 300mm, the P_{\max} relationship can be described mathematically based upon the total cost to place concrete into the slab, T (£), shown in Eq.(1) .

$$T = O_v + L + M \quad (1)$$

Where O_v = Overhead Costs (£), L = Labour Cost (£) and M = Material Cost (£)

Considering each term in detail, O_v = construction overhead costs (£), derived from onsite observations representing cost of plant and equipment. L = Labour Cost (£), a

On-site use of self-compacting concrete

product of the size of the slab and the time taken to place 1m^2 , labour operatives rate of pay and the cost to employ, therefore Eq.(2):

$$L = t \times a \times e \times r \quad (2)$$

t = time to place 1m^2 of slab (rationalised to a min/m^2 rate), a = slab area (m^2), r = rate of worker pay ($\text{£}/\text{min}$) and e = administrative costs to employ labour.

Material cost (M) is a factor of slab area, slab depth and the retail price of concrete Eq.(3):

$$M = a \times d \times p \quad (3)$$

a = slab area (m^2), d = slab depth (m) and p = concrete price ($\text{£}/\text{m}^3$). The overarching formula for calculating total placement cost remains constant but the contributing times and costs between conventional and SCC methods vary, therefore;

For conventional construction Eq.(4):

$$T = O_v^c + L^c + M^c \quad (4)$$

For SCC construction Eq.(5):

$$T = O_v^s + L^s + M^s \quad (5)$$

Parity between construction methods, when it is possible to derive P_{max} , is achieved when the total placement costs for both conventional and SCC are equal, therefore when Eq.(4) is equal to Eq.(5) shown in Eq.(6);

$$T^C = T^S \quad (6)$$

Rearranging equation (6) produces equation (7) used to attain the value of P_{\max} , Eq.(7);

$$p^S - p^C = \frac{O_V^C - O_V^S}{ad} + \frac{er(t^C - t^S)}{d} \quad (7)$$

Where $p^S - p^C = P_{\max}$, the maximum permissible premium to maintain parity between both construction methods. Respectively t^C and t^S can be replaced by the values of 340/60 and 72/60 respectively, which have been determined through detailed analysis of observations of suspended block and beam slabs construction.

By not exceeding P_{\max} , the supplier helps the contractor exploit the benefits of SCC to deliver a faster, higher quality slab at the same overall cost as conventional concrete. The existence and importance of this calculation has not been acknowledged in previous SCC research.

5. Discussion

Using time study of 14 residential slabs and cost modelling of three scenarios, SCC has been shown to improve construction times significantly as first proposed by Henderson (2000), Goodier (2003) and Holton (2003). In this research, SCC reduces time by up to 70%, compared to conventional concrete, due to its ease of placement and simplified construction process. Conventional methods combine compaction and leveling processes through tamping and screeding, a highly intensive and physically demanding activity; this intensity was apparent in the manipulation of the concrete – it requires more physical effort to manually level and powerfloat the slab, whereas

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SCC's fluid nature requires minimum work (dappling) to achieve a similar result. Literature also claims that material cost was a prohibitive factor in SCC's further adoption (Concrete Society and BRE 2005; Rich et al, 2012). The three cost modeling scenarios have demonstrated that financial savings can be realised through SCC, subject to several conditions. The 'best case' scenario for conventional construction was marginally cheaper than SCC considering all factors (i.e. material, plant and labour costs), but when out of hours working was required to complete the conventional concrete placement, SCC would result in significant savings. This offers new and insightful findings to a research field previously dominated by physical and structural testing. This research has also identified an important new variable, P_{max} , describing the relationship between labour and material costs, such that the potential cost saving per m^3 from using SCC can now be identified and understood.

There is also a wider implication: the combination of SCC's time and potential cost savings, alongside its reliability and predictability mean that construction variations and associated risks can also be reduced. The inherent variability of conventional, insitu concrete construction justifies the use of the more predictable and reliable SCC method. SCC could increase project team confidence in pre-project planning and cost estimation, thereby avoiding expensive out of hours working. Considering the wider consequences of delays there is potential for delays to follow-on trades which may impact on the project's critical path. Such delays potentially incur costs which would far outweigh the additional material cost of SCC (e.g. total site running costs and potential penalties for late completion). SCC can shorten the critical path; it is faster with fewer operatives.

Limitations of the study

The main limitation is that the cases were all based in the UK, so caution should be exercised before extrapolating the results to other countries. Furthermore, work measurement typically has limitations relating to process, subject of the study and generalisation as explained further as follows:

- The study observed operatives with the potential for work rates to increase from constant observation. In mitigation, instances of obvious enhanced speed were noted and negated during analysis.
- Site observations, data capture and analysis and interpretation of results were all by the same person to provide continuity. Although checking procedures were in place, additional observers could have been used to verify the data.
- Activity timings were based on observations of when each activity started and finished, with times being recorded to the nearest five seconds relying on the observer to identify the end points.
- A sample size of 14 slabs, while modest, has provided sufficient data to address concerns of unrepresentative sampling. The selection of a generic building type responded to gaps in the literature. While this has produced robust findings, any further generalisation of results would require additional analysis.
- The time study required the breakdown of the operation into individual elements or activities; these were individually timed and combined to establish total construction time. However, there was always more than one operative and often a number of concurrent activities, so construction was filmed and timings noted when reviewing the films.

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- Construction is inherently complex, involving numerous elements and the input of many parties, even for simple projects. While the optimum situation would have been the evaluation of a whole project from inception to completion, this was not practicable.

6. Conclusion

This research aimed to identify whether or not SCC had a quantifiable effect on construction, ostensibly because there was a lack of robust evidence in literature to establish if this was the case. Using data from 14 residential concrete slabs, SCC has been shown to present significant time savings and even if these may not always result in actual cost savings, then SCC can be priced to closely match conventional concrete project costs overall. The relationship between costs for SCC and conventional concrete for slabs has been clarified and a new mechanism for understanding profitability and viability of SCC (P_{\max}) has been presented.

The results also reinforce the case for considering SCC as a method rather than a material (Rich et al, 2012). Where operations are adapted to make the most of SCC's benefits, it can have a positive effect on construction time and cost. This was evident from the residential projects selected; the market for SCC for such slabs in the UK has been growing steadily, albeit the reasons for this were previously not well understood. Further research to examine the effects of SCC on flat slab construction is underway, where risk reduction may have a more significant effect and the larger slab sizes may prove more competitive for SCC. While extending the work to different slab types and other construction elements such as walls and footings would also be worthwhile, the development of an ideal or best practice model for design and planning of SCC

and how to adapt construction practices would also be a useful contribution to knowledge and practice.

Acknowledgement

The authors would like to acknowledge contribution from Lafarge Aggregates Ltd (now Lafarge-Tarmac) and all the project staff. This work is part of an Engineering Doctorate, funded by the UK Research Council (EPSRC), via Loughborough University's Centre for Innovative and Collaborative Construction Engineering.

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APPENDIX F

SCC mix design (extract from Domone, 2006)

Extract from Domone, P. (2006). Self-compacting concrete: An analysis of 11 years of case studies. *Cement and Concrete Composites*, 28 (2), 197-208.

Ref. no.	Date	Country	Application	Volume, m ³	Placing	Reinforcing	Coarse Aggregate			Powder		w/p, by wt	Paste vol %	vf/vm, vol%	Admixture		Sl. Flow mm	T ₅₀₀ , s	Other	Strength, MPa @ 28 days
							Max size (mm)	Type	Vol %	Composition	kg/m ³				Splast+	VMA				
[9]	1994	Japan	lw concrete structural panels		Pre-cast	Heavy	15	Ltweigh	34.9	pbfc	607	0.26	36.0	40.3		y	650			65
[10]	1996	Japan	Bridge pier caps	1000	In situ	Heavy	20	Crushed	31.2	pbfc	470	0.35	34.0	48.4	ae		620		V-funnel 3 s	50-60
[11]	1995	Japan	Port Structures	760	In situ	Heavy	20	Crushed	30.9	pbfc + pfa	385	0.48	31.2	51.8	ae	y	645	11	V-funnel 15 s	41
[24]	2000	Japan	Caisson shell	4800	In situ	Light	20	Crushed	33.4	pc + lsp	635	0.26	39.0	40.6		y	700			24

APPENDIX G

CONSTRUCT interview request letter

On-site use of self-compacting concrete

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07972 533581

04/02/2009

Title First Surname

REQUEST FOR INTERVIEW: RESEARCH ON SELF-COMPACTING CONCRETE

Dear Title First Surname

Based at Loughborough University, I am currently undertaking an Engineering Doctorate with the Centre for Innovative and Collaborative Engineering, focusing on '**Measuring the performance and sustainability benefits of self-compacting concrete (SCC)**'. The research programme is directed at clarifying the role that SCC can have on the performance of the construction industry, as a relatively new and widely unused material. Now more than a year into the research, it is becoming clear that decision-making, project planning and other pragmatic issues are highly relevant. To date I have considered the use of the material as a direct replacement for conventional concrete in a large high rise mixed used development within a major UK city; while this has provided information on the use of the material in a purely practical context it did not consider the issues and procedures that surround decisions regarding selection of materials.

As a result, for the next stage of the work, a series of interviews is planned with decision makers in large concrete construction organisations, and specifically with CONSTRUCT members. I would like to meet with you and/or your colleagues to discuss a number of issues (please see appended Question Sheet). Specifically, I will ask about your previous experience and current perceptions of SCC. I would also like to understand the procedures that affect material choice, how a material like SCC is influenced by and influences construction throughout the construction life cycle and, finally, how SCC is viewed in terms of sustainability. We hope that you will be able to assist in this programme of interviews and will be in touch by telephone shortly to make arrangements.

If you have any queries in the meantime, please do not hesitate to contact me.

Yours sincerely,

David Rich
Research Engineer

This research is being carried out in collaboration with a global construction materials supplier which offers a range of concretes, including self-compacting concrete products. All personal details and information will be stored and used in accordance with the Data Protection Act. No details from this research will be passed on to the sponsor or any other party, without explicit, prior written permission being granted. Participants are free to withdraw from this research at any time.

APPENDIX H

CONSTRUCT interview question guide

On-site use of self-compacting concrete



Survey of concrete frame constructors: identifying successful construction procedures and practices for self- compacting concrete

1. INTRODUCTION

As part of a broader, four year programme of research on self-compacting concrete (see attached letter), this particular research stage is targeted primarily at surveying the views of concrete frame constructors who are members of CONSTRUCT's SpecCC scheme.

The aim of the interview programme is to identify views held on self-compacting concrete (SCC) within the concrete frame construction community. It will also explore the procedures that surround decisions and planning of concrete construction projects. The findings will be used to help define the future direction of the research and it is hoped that practical guidelines for the use of SCC will be made available in due course.

This research is being carried out in collaboration with a global construction materials supplier which offers a range of concretes, including self-compacting concrete products. All personal details and information will be stored and used in accordance with the Data Protection Act. No details from this research will be passed on to the sponsor or any other party, without explicit, prior written permission being granted. Participants are free to withdraw from this research at any time.

Please note, there is no requirement for you or your company to have prior experience of using SCC, but we might envisage that those in senior/technical or site management positions might be best able to respond. In all cases, the survey will take the form of 45-60 minute personal or telephone interviews which will be arranged at your convenience; I will be in touch by phone to make an appointment.

An indicative set of questions that will be used is provided below.

2. INTERVIEW QUESTIONS

Section A – Past experience of the material

- 1) How much experience do you or your organisation have of using self-compacting concrete (SCC)?
 - a. In what type of application/s have you employed SCC?
 - b. What were the drivers for its use?
- 2) How is SCC perceived within your organisation (e.g. with regard to its viability as a regular construction material replacing conventional concrete)?
- 3) What would you define as the strengths and weaknesses of SCC?

Continues

overleaf...

On-site use of self-compacting concrete

Section B – Decision-making process

- 1) Who is responsible for the decision making on materials that are to be used and when typically are such decisions made?
- 2) What is the rationale regarding the choice of material to be used in construction?
 - a. Who influences this decision and what criteria are used?
- 3) How does material selection affect the overarching design of a structure?
 - a. Is material choice secondary to design and selected to fit a purpose?
 - b. Is there any history or precedents where a structure has been adapted to utilise a specific material (such as recycled concrete aggregates)?

Section C – Project planning

- 1) To what extent do you find that planning and resource allocation methods need to be adapted when adopting new construction materials and techniques?
- 2) Do you carry out any form of post project appraisal?
 - a. Does it ask about the effectiveness of the decisions made during the planning phases of a project?
 - b. Does it re-evaluate of projects considering new developments and changes in construction practices?

Section D – Sustainability

- 1) How does your organisation view sustainability? How is it addressing this?
- 2) In what way/s do you see concrete products developing with current moves towards more sustainable construction?
- 3) How are concrete products viewed in regards to their sustainable credentials?
 - a. Compared against other construction options?
 - b. Is SCC viewed as being different to conventional concrete in respect to sustainable credentials?
 - c. Does it present any areas of concern?

3. CONTACT DETAILS

For further details on either the interviews or the research programme please do not hesitate to contact:

David Rich

Email: D.Rich@lboro.ac.uk

Phone: 07972 533581

Project website: http://www.lboro.ac.uk/cice/prospective/abstracts/82_project.htm

APPENDIX I

Agilia™ user interview question guide



Agilia™ Users Interview Questions

- 1) What is your core area of business and what type of works do you undertake?
- 2) In what type of applications have you used SCC? What were the key reasons for employing SCC in these applications?
- 3) Do you have any experience of other forms of SCC other than Agilia™? How has your experience of these compared with Agilia™ in regard to material performance and service provision?
- 4) Dependent on order history, occasional or reduced/no longer use Agilia™ reasons why?
- 5) Your order history shows that you have reduced/no longer use/or are an occasional user of Agilia™ for what reason is this?
- 6) How has the use of Agilia™ affected the projects in which it has been used and has it changed the way in which work is carried out? Have there been any negative effects of using Agilia™ in projects or issues that have arisen with the product itself?
- 7) Given your experience of Agilia™ and SCC's, how do you envisage your future of the material and your use of it?
- 8) Through the use of Agilia™ have there been any changes brought about to the way in which you operate?
- 9) In respect to Agilia™ and other SCC's are there any changes or developments that need to be made in order to improve the material itself or viability of its use, other than material cost?

David Rich

January 2009

On-site use of self-compacting concrete

APPENDIX J

Table of interview participants

On-site use of self-compacting concrete

Interview	Company Type	Participant Role	Company Experience	Company Specialism
1	Concrete Frame Sub Contractor	Director	No previous experience of SCC	Reinforced concrete structures
2	Concrete Frame Sub Contractor	Managing Director	Experience and use of SCC on a few projects	In-situ concrete structures
3	Concrete Frame Sub Contractor	Commercial Manager	SCC used once or twice	Reinforced concrete sub and superstructure works, alongside civil engineering
4	Concrete Frame Sub Contractor	Commercial Director	Previous use in vertical applications	Complete concrete frame construction services
5	Concrete Frame Sub Contractor		Limited experience, one major project	Complete reinforced concrete service
6	Concrete Sub Contractor	Operations Director	Single use of SCC	Primarily a flooring contractor
7	Concrete Sub Contractor	Commercial Manager	Single use of SCC	Formwork provider and reinforced concrete frame constructor
8	Concrete Frame Sub Contractor	Contracts Manager	No previous experience	Complete reinforced concrete service
9	Concrete Frame Sub Contractor	Director	Extensive previous use	High rise concrete structures
10	Concrete Frame Sub Contractor	Contract Manager	Minimal experience, one or two applications	Reinforced concrete structures and groundworks
11	General Builder	Foreman	Regularly utilised	All types of small scale construction works
12	General Builder	Owner	Previous experience but on selective basis	Renovation works
13	Groundworker	Ganger	Minimal experience	All forms of small scale groundworks
14	Housebuilder	Site Manager	One previous application	One off specialist houses
15	Housebuilder	Foreman	Minimal experience	General Housebuilder

On-site use of self-compacting concrete

16	Generalbuilder	Owner	No previous experience	All types of small scale construction works
17	Housebuilder	Site Manager	Regularly utilised	General Housebuilder
18	Generalbuilder	Foreman	One off previous use	All types of small scale construction works
19	Housebuilder	Works Manager	Regular user	Medium scale house developments
20	Groundworker	Foreman	Regular user	Typically ground works for housing schemes
21	House Builder	Site Manager	Occasion user 2 to 3 uses	One off high quality houses
22	Precaster	Factory Supervisor	Used in the majority of products	Structural elements
23	Groundworker	Ganger	Occasional use	All forms of small scale groundworks
24	Housebuilder	Owner	Regular utilisation of SCC	Small scale housing sites
25	Groundworker	Foreman	Regular application	Housing oversites
26	Groundworker	Foreman	Regular user	Housing slabs
27	Precaster	Owner	One off use	Structural housing elements
28	Concrete Contractor	Owner	Occasional user	All forms of concrete construction
29	Concrete Frame Contractor	Works Manager	No previous experience	Reinforced concrete structural frames
30	General Contractor	Owner	Previous user	All forms of construction work
31	Housebuilder	Site Manager	Regular user	Housing developments
32	Housebuilder	Owner	Occasional use	Small scale housing developments
33	Housebuilder	Site Manager	Occasional use	Bespoke one off housing

34	Housebuilder	Ganger	Regular application	Housing oversites
35	Groundworker	Foreman	Single previous use	General groundworks
36	Precaster	Owner	Regular user	Wide range and variety of precast elements
37	Pumping contractor	Owner	Regular user	Concrete pumping services acting as material supplier
38	Housebuilder	Foreman	Occasional applications	General house building
39	Groundworker	Site Manager	Regular user	Primarily housing oversites
40	General builder	Owner	Sporadic use	All forms of general building
41	Housebuilder	Ganger	Regularly used to replace conventional concrete	General house building
42	General builder	Ganger	Regular use	Primarily housing oversites, but all forms of general construction
43	Groundworker	Operative	Occasional use when required	Housing oversites and floor slabs
44	Housebuilder	Owner	One previous use	Small housing developments and occasional renovations
45	General builder	Site Manager	Occasional use	All forms of general building
46	Housebuilder	Site Manager	Regular application in homes	General housing developer
47	General Concrete Contractor	Owner	No longer used	Formerly only housing now public sector works
48	General Concrete Contractor	Works Manager	Occasional use	Reinforced concrete frames

On-site use of self-compacting concrete

APPENDIX K

Work Study site observation data capture form

Work Study Site Checklist

6 - PRODUCT

A. Horizontal
A. Force
Conv.

7 - OVERALL POUR SCHEDULING

Scheduled Start	
Actual Start	
Finish	

9 - TRUCKING

TRUCK	BATCH TIME	ON SITE	OFF SITE	DISCHARGE		WAITING
				START	FINISH	
1						
2						
3						
4						
5						

8 - MIX DESIGN

STRENGTH	N/mm ²		
FIBRES	None	Steel	Poly
SLUMP	mm	S Flow	mm

8 - TEST RESULTS

PLANT	S Flow	mm	O Funnel	sec
SITE	S Flow	mm	O Funnel	sec
	Slump	mm		

10 - BREAKS IN POUR

DELAYS/BREAKS	DURATION	PLANNED/OPTIMAL/ACCIDENTAL/ENFORCED
1		
2		
3		
4		
5		

VISUAL ASSESSMENT	segregation/dispersion/coverage/bleed
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11 - NOTES

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On-site use of self-compacting concrete

APPENDIX L

Lafarge Self-Compacting Concrete Data Sheet

DATA SHEET

CONCRETE








Agilia™ Horizontal's finishing characteristics and high quality surface finish eliminate the need to power float concrete on site.

Applications

- Slabs
- Residential dwelling over site / slabs
- Structural toppings
- Domestic floors
- Commercial slabs such as composite deck construction (rib metal decking)
- Low traffic industrial floor slabs
- Mezzanine & office areas within industrial units

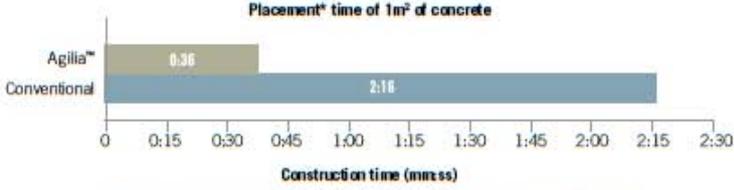
Characteristics

- Agilia™ Horizontal enables the rapid and effortless fabrication of slabs and floors.
- Lafarge **RHEOLOGIK** technology means that surface finish is of high quality.
- This can eliminate power-floating on site.
- Floor finish tolerance to BS 8204 – 1 SR2.

Agilia™ is proven to improve your construction processes, after extensive research with Loughborough University^{1, 2}.

- Research focused on determining and clarifying the exact benefits that Agilia™ can bring to the construction process.
- The research made it clear that Agilia™ is not just a material for construction but it is in fact a method of construction. By adhering to the Agilia™ method significant savings were shown to be achievable.

Placement* time of 1m² of concrete



Method	Construction time (minutes)
Agilia™	0.36
Conventional	2.16

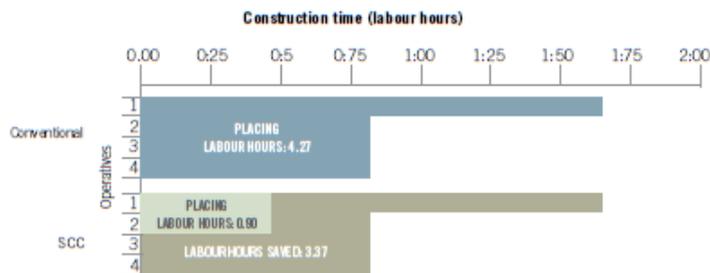
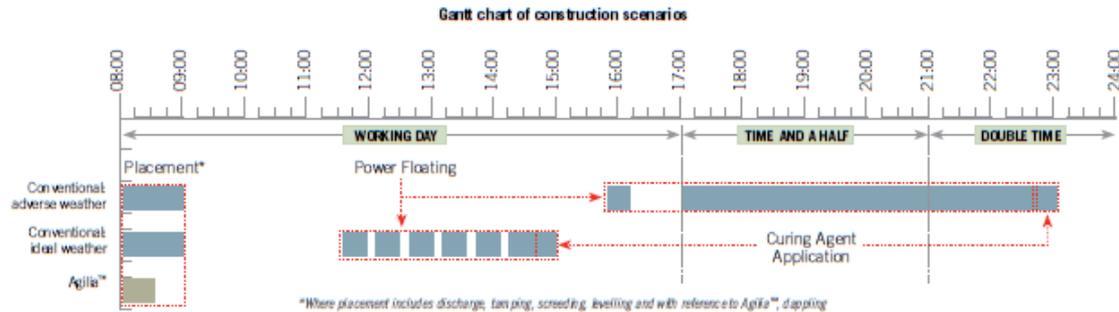
*Where placement includes discharge, ramming, screeding, levelling and with reference to Agilia™, applying.

- Placement with Agilia™ can reduce slab construction time by nearly 75%.
- Whilst also reducing the gang size from four operatives to two.

¹ Research undertaken by the Centre for Innovative and Collaborative Construction Engineering at Loughborough University to explore and quantify the effects of SCC in construction.

Agilia™ Construction Method

- Removal of the power floating operation reduces an aspect of the variability and unpredictability with concrete slab construction.
- Agilia™ increases the predictability of construction projects with respect to project time and costs, reducing the risk of unforeseen expenses and delays.



- In an example case study of a suspended 45m² house slab, priced on average UK material costs, Agilia™ was seen to save £291.45 on total as-built costs when power floating could not start promptly.
- Agilia™ removes issues observed with conventional concrete practice of water addition, insufficient compaction and curing. Complying with requirements of NHBC standard 2.1 – S10 parts c, f and g.

¹ The research described in this data sheet can be found in the following: Rich, D., Glass, J., Gibb, A.G.F. and Goodier, C.I., UK Contractors' views on self-compacting concrete in construction. Proceeding of the ICE – Construction Materials, In press. And From reactive to proactive: quantifying the onsite benefits of self-compacting concrete http://www.lboro.ac.uk/civil/people/alumni_theses.html

Installation

- Agilia™ Horizontal can be laid over any stable substrate.

Bond to substrate

- When the concrete is laid unbonded to the substrate, a polythene membrane of suitable thickness will be required.
- When the concrete is to be laid bonded, steel reinforcement mesh will be required. Bonding compound (such as an SBR type product) to be applied.

Perimeter isolation

- A compressible strip with a minimum thickness of 5mm and maximum of 15mm should be fixed around the walls.
- The isolation strip is required to be fixed around vertical features such as columns and pipe ducts.
- Particular attention must be taken at re-entrant angles such as doorways, bays and alcoves.
- Ensure the perimeter isolation is placed at right angles into all corners of the room.
- On exterior angles it may be necessary to double up the isolation to ensure that the minimum thickness is maintained around the angle.
- The most suitable material for this is a self adhesive ethafoam strip; a small amount of steel mesh should also be placed around any internal corner or extrusion through the slab.

Substrate preparation

- In all cases, a polythene membrane of 150µm minimum thickness and 350µm maximum thickness must be laid on the substrate.
- Agilia™ Horizontal is highly fluid and this requires the membrane to be substantially watertight to prevent loss of material.
- The sheet should be laid with a 300mm overlap, adhesive tape at least 50mm wide should be applied along overlapping joints of the sheets to seal them.
- Care should be taken to ensure the membrane is folded, or cut and sealed, into a corner.
- Around the perimeter of the room, the edges of the polythene membrane should extend well above the intended level of topping or should be taped to the ethafoam strip.

SPECIFICATION

Maintenance of fluidity = two hours	Minimum thickness = 75mm
Compressive strength at 28 days = 35N/mm ²	If a greater strength at 28 days is required Lafarge will work to customer specification.

