Self-Compacting Concrete
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Edited by
Ahmed Loukili
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Introduction

Self-compacting concretes (SCCs), highly fluid concretes placed without vibration, were introduced into French construction works towards the end of the 1990s. The concept came into being a decade earlier in Prof. Okumara’s laboratory [OKA 00] in Japan. The high seismicity of this geographical region requires the use of high levels of steel reinforcement in construction. The use of “self-compacting” concretes appeared as a solution to improve the filling up of zones which are not very accessible to conventional methods of concrete compaction. This solution also has the advantage of overcoming the gradual decline in the number of workers qualified to handle and place concrete.

In France, SCC was initially of interest to the precast concrete and ready mix concrete industries, and in the construction industry, well before project managers and contracting authorities became interested in it [CIM 03]. The use of SCC enables improvements in productivity through reductions in manpower and placing delays. It also improves quality through a better filling of the formwork, better coating of the steel reinforcement, even a better facing. Finally, and undeniably their best asset, SCCs reduce the difficulty of the work. By preventing vibration, the health effects of concrete construction disappear (white hand syndrome, hearing loss, noise disturbances for the
neighbors). Little by little, SCCs have also won over architects by offering them the possibility of playing with complex volumes.

Even though SCCs have established their position in the prefabrication industry (around half of the volume produced), SCCs used in situ are struggling to make an impact on construction sites, in France as well as in other countries [SHA 07]. Despite their numerous advantages, SCCs represent less than 3% of ready mix concrete produced in France [BTP 07]. Several factors lend themselves to explaining this slow expansion of SCCs [CUS 07]. Firstly, making SCCs is somewhat difficult, since the components must be of a good quality and have little variation in their properties. While the properties of fresh vibrated concretes are affected relatively little by normal variations in the components (size distribution, water content, etc.), SCCs, on the other hand, are much more sensitive. Secondly, the production tool is not always precise enough for making concretes which are strongly affected by errors in the mixture proportions. Thirdly, the formworks must be well prepared, properly waterproofed and must, above all, be able to withstand pressures that are a priori higher than those involved in handling vibrated concretes.

However, SCCs have the potential of continuing to expand. To begin with, the standardizing framework, which had previously been vague in Europe, was enforced in June 2010 with the release of the EN 206-9 standard which brought in rules for production, handling, and specific controls for SCC, complementing EN 206-1. SCCs are becoming widespread elsewhere by strengthening the dialog – which is truly indispensable – between construction agents, owners, project managers, architects, businesses and suppliers, and also research laboratories. SCCs, complex and innovating materials, have been the object of a real infatuation by researchers the world over. As a witness to
this success, international conferences have been dedicated to SCCs since 1999 [SCC 99]. Today the extent of the research allows us to have a better understanding of the behavior of these concretes.

The objective of this book is therefore to disseminate knowledge acquired by recent research in order to enable the student, the technician, or the engineer who reads it, to develop an understanding of the formulation of these materials. The composition of SCCs must satisfy several criteria. In addition, different authors have endeavored to reply to each of the questions posed in the following chapters, without losing sight of the global objective of techno-economical optimization.

Chapter 1 is dedicated to rheology and concrete casting. Theoretical concepts are presented and useful experimental tools for characterizing the behavior of these complex mixtures are described. Experimental data also shows the range of variability and the influence of the principal formulation parameters.

Chapter 2 enables the reader to understand the specifics of the behavior of SCCs at early ages. This behavior, which is strongly influenced by the particular formulations of SCCs, is characterized by vulnerability to desiccation and the resultant strains.

Chapter 3 focuses on the mechanical and delayed behaviors of SCCs in comparison with ordinary derivative concretes. This aspect is crucial for designing self-compacting concrete pieces.

In Chapter 4, the question of durability is examined. Degradation phenomena linked to environmental events are described, and experimental data on SCC and vibrated
concretes are brought together to show which parameters are influential from the point of view of potential durability.

Finally Chapter 5 is dedicated to the thermal stability and fire resistance of self-compacting concretes.

Bibliography


1.1. Towards a fluid concrete

Recent decades have witnessed a remarkable evolution in concrete performance, as much in the field of their rheological behavior in the fresh state as in their mechanical behavior in their hardened state. These technical advances are the results of coupling between the formulation principles, coming from a long period of learning by experience and the mastering of physico-chemical principles which govern the behavior of cement-based materials.

Initially made using a simple recipe of water, cement and aggregates (sand and gravel), concrete has since seen its formulation enriched by the inclusion of high quality components such as mineral additives (limestone fillers,
silica fumes, etc.), chemical additives such as superplasticizers and reinforcing materials such as fibers.

The complex formulations thus obtained must satisfy the production specifications in which the obligations often go beyond the conventional output requirements in terms of fluidity during casting, and strength of the hardened concrete. Concrete design can thus be adjusted to suit the working conditions (pumping, vibration, transport time and casting time), hardening (time at which the concrete is removed from the mold, required short-term strength) and service (developing strength, durability, etc.).

Self-compacting concrete (SCC) is an illustration of research in mastering such complex mixtures. The origin of SCCs is associated with the development, at the beginning of the 1980s in Japan, of a design method for fluid concretes. The high seismicity of this geographical region necessitates that structures are highly reinforced with steel. In these much more difficult pouring conditions, compacting the resultant concrete using conventional methods (internal or external vibration) is at risk of being insufficient, thereby compromising the buildings' quality assurance.

The SCC concept was therefore born from the desire to make the concrete compacting completely independent of the production context, whether in the technical plan or in manpower, knowing that the number of qualified workers is noticeably declining in Japan, which is also the case in numerous other countries.

SCC is therefore a mixture which is both fluid and homogenous, which fills formworks perfectly by flowing under the effect of gravity alone, and which completely wraps around all the reinforcing bars without causing blockages or grain separation in their vicinity (Figures 1.1 and 1.2). These properties appeal to the structure designer
for the work, who can envision more complicated shapes using these materials; and to the production team who is interested in simplifying the work involved in creating the structures and reducing construction delays. This is why the use of SCCs tends to increase on a large scale.

![Figure 1.1. Filling capability of SCC (top) and conventional concrete (bottom) [CAS 05]. SCC, moving under its own weight, flows around obstacles and ensures good coverage. Without an external energy supply, such as vibration, conventional concrete cannot achieve the same result](image)

On the construction site, the use of SCC results in the interruption of vibration techniques leading to significant reductions in noise and occupational illnesses such as white hand syndrome – Raynaud’s syndrome – improvements in safety during casting and reduction in the workforce required for casting. It also improves the conditions for
filling formworks by increasing the concreting speed, allowing concreting in highly reinforced zones, faster formwork rotation. Finally, the use of SCCs results in a better facing quality (Figure 1.2).

Figure 1.2. Improvements in facing quality with SCC [CAS 05]. Casting is made easier with SCC which reduces the formation of air bubbles and pebble clusters at the faces of the formwork, including frames with complex geometrical shapes. In the case of conventional concrete, such defects can be eliminated using vibration which is always difficult to implement.

This collection of properties affects construction as much as project managers do, since they are also involved in
improving productivity during the construction phase, in the quality of constructions and in their durability.

The transition to SCCs cannot be envisaged without reconsidering and adapting the fabrication and casting methods. Numerous works have therefore been committed to the problems of mixing, transport, pumpability, formworks (waterproofing and controlling pressure on the inner surfaces), facing quality, etc., according to the workable nature of SCCs. Controlling the production of SCCs, relying on simple and rudimentary tests in construction sites also constitutes a theme for collective consideration which has led to the publication of a reference document in France.

Recommandations pour l’emploi des bétons auto-plaçants [AFG 08], classifies SCCs, specifies the required properties as well as their corresponding tests, and describes the conditions of use and the characteristics of these concretes. However, operators confronted with formulating, producing or casting SCC have systematically noticed that this type of mixture is characterized by a fluidity which is strongly affected by all deviations in composition. To understand the reasons behind this, the design basics are initially discussed.

The various arguments dedicated to developing an understanding of a mixture’s flow properties with respect to quantifiable and representative rheological parameters are then introduced. Next, the most suitable test methods for estimating these rheological parameters are presented. The influence of design parameters on the values of the rheological parameters is also studied. The different arguments make it possible to make judgments of a formulation’s robustness in light of measurement differences which are often the origin of a lack of reproducability. Armed with this knowledge of design principles and rheological parameters to consider, industrial practices regarding mixing, transport and pumping are developed. Finally the
pressure exerted by SCCs, once in place, on formwork is described in the results from recent works.

1.1.1. Area of application

At the time of writing, SCCs represent 2-3% of the volume of ready mix concrete produced in France, with a tendency towards horizontal applications (80%) by comparison with vertical applications (20%). A 40-50% proportion of SCC is intended to precast products with delayed demolding [MAG 07].

Whether we are concerned with horizontal structures (floors, raft foundations, paving, screed, etc.) or with vertical structures (columns, walls, bridge piers, etc.), the function of SCCs in their fresh and hardened states are singularly different.

For horizontal structures, the term self-leveling concrete (SLC) is sometimes used. In their fresh state, finishing quality and leveling is crucial. This is obtained by putting concrete in place without recourse to mechanical work, especially for the surface. Neither segregation nor excessive bleeding is tolerated. For this type of application, the current method combines thickening agents (starches, Welan gum, etc.) with super-plasticizers to achieve the ideal fluidity/stability coupling. In the hardened state, the strength is of the order of 40 MPa.

For vertical structures, the generic term self-compacting concrete (SCC) is used. Vertical elements are often load-bearing, which requires a high level of steel-reinforcement and a high concrete strength to reduce the section of pieces installed. Targeted strengths can reach the limits of Eurocode 2, i.e. 90 MPa. The difficulty in formulating an SCC with high mechanical performance stems from the conflict between the mechanical performance objective and
that of fluidity and stability. The first objective is linked to optimizing the cement hydration reaction for a water/cement mass ratio of 0.23 (stochiometric optimum). The second objective leads straightforwardly to a water/cement mass ratio of 0.6. In order to guarantee high strength, reactive mineral additives and super-plasticizers which effectively reduce the water requirements must be used.

Whatever the intended application may be, the use of specific chemical additives and large proportions of mineral admixtures must be understood, in a different way to conventional approaches to concrete composition [BAR 97], formulating cement + mineral additive pairs and determining the amount of aggregate in the concrete.

1.2. SCC formulation basics

1.2.1. Overview

Formulating SCCs is a compromise between sufficiently high fluidity to ensure good casting and an adequate consistency to avoid phase separation problems (segregation or bleeding).

The principal idea in designing a SCC involves considering the mixture as a concentrated suspension in which the suspending phase is viscous and dense enough and in which the dispersed phase is at a low enough concentration to prevent too much interaction. The suspending phase is often called “the paste”. It comprises finely-sized components, chemical additives and water. The dispersed phase includes larger-sized components (aggregates). According to this simplistic explanation, the separation risk is therefore directly linked to the difference in densities between the aggregates and the paste. The volumetric proportion of the paste in the mixture must be high enough to limit interactions and thereby reduce the risk
of blockages during pouring. Consequently, the overall fluidity of the mixture turns out to be strongly linked to the quantity and fluidity of the paste.

The definition of a clear boundary between the paste and occlusions in terms of particle size is, however, difficult and arbitrary. Conventional methods of formulating vibrated concretes generally consider that fine particles are particles with a diameter of less than 63 µm, or 80 µm according to the authors. This boundary reflects a change in the type of interaction between the particles. The largest particles interact mainly by contact and friction between the grains. The interactions of the finest particles are modified by colloidal effects, for example, these effects are particularly affected by introducing additives. In the case of SCCs, it is important to consider that this boundary can be modified as a function of the flow conditions. In static phases, the distinction between the paste and aggregate goes back to a small particle size whereas during a significant shearing of the concrete, the boundary is moved back towards the largest size of aggregates.

Moving these basic SCC formulations back in the form of ratios between the components therefore turns out to be complicated. It is possible, however, to resolve this problem by referring to the basic formulations of conventional vibrated concretes. Figure 1.3 shows schematically how the formulation of an SCC differs from that of a conventional vibrated concrete [TUR 04]. At similar levels of cement, sand and water, SCC yields a greater quantity of paste through the addition of mineral admixtures and a lower quantity of gravel. The volumetric increase in the paste, associated with a reduction in the quantity of gravel used, limits intergranular contact and prevents the risk of blockages in highly reinforced situations.
Obtaining adequate paste fluidity when the paste has an increased concentration of fine particles requires the introduction of fluidizing chemical additives. Superplasticizers, which act like defloculating agents for the finest particles, are regularly made use of.

In order to limit the risk of the largest aggregates in suspension in the paste separating out, the paste viscosity must be adjusted to slow the phenomenon down, or even suppress it. Thickening agent additives are therefore used.

Note that the principles for formulations summarized above do not contradict the requirement for a compact grain size spectrum. The component concentrations in a SCC can, in effect, be determined in order to optimize the packing density of the granular mixture. The optimization method developed by de Larrard [LAR 00], can be used to this end.

SCC formulations must also include an objective in terms of target strength, denoted \( f_c \), for the hardened mixture. Since SCC components are the same type as those for conventional concrete, it is logical to make use of the usual
relations which link the target strength to the component concentrations.

The Bolomey equation [BOL 35]:

$$f_c = k_b R_c \left( \frac{C'}{E + V} - 0.5 \right)$$  \[1.1\]

where $R_c$ is the true class of the binder, $k_b$ is a characteristic coefficient of the aggregates, $C'$ is the mass of equivalent binder, $E$ is the mass of water and $V$ is the mass of water which occupies the volume of the entrapped air void. This equation is currently used for conventional concretes.

The Feret equation [FER 1892] generalized by [LAR 00]:

$$f_c = k_g R_c \left( \frac{V_c}{V_c + V_e + V_a} \right)^2 \text{EMP}^{-0.13}$$  \[1.2\]

where $k_g$ is a characteristic coefficient of the aggregates, $V_c$ the volume of the binder, $V_e$ the volume of water and $V_a$ the volume of the entrapped air void. EMP is the maximum paste thickness (maximum distance between two large grains in the mixture) [LAR 00].

This type of equation is preferred for concretes which have fine aggregates such as sand concretes [ENP 94] and mortars. Nevertheless, in the case of SCCs, the Bolomey equation is still in current usage. The equivalent binder concepts can also be used to take into account the effect on strength of introducing mineral additives. The amount of entrapped air voids is an important parameter for SCCs. In a few cases, the introduction of an air-entraining agent in the formulation is foreseen. This development has a double role. On the one hand, creating air bubbles within the paste modifies its viscosity. On the other hand, the presence of air
bubbles can lead to a change in the size distribution of occlusions, which affect the conditions of grain arrangement.

<table>
<thead>
<tr>
<th>Component</th>
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<th>Volumetric quantities range (liter per cubic meter of concrete)</th>
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<tbody>
<tr>
<td>Powder (cement, etc.)</td>
<td>380-600</td>
<td></td>
</tr>
<tr>
<td>Paste</td>
<td></td>
<td>300 – 380</td>
</tr>
<tr>
<td>Water</td>
<td>150/210</td>
<td>150/210</td>
</tr>
<tr>
<td>Gravel</td>
<td>750/1,000</td>
<td>210 – 360</td>
</tr>
<tr>
<td>Sand</td>
<td>Typically 48-55% of the total aggregates</td>
<td></td>
</tr>
<tr>
<td>Water/binder</td>
<td></td>
<td>0.85/1.1</td>
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**Table 1.1. Range of typical mixture proportions for SCCs [EFN 05]**

1.2.2. **Specificity of SCC formulation**

As has been previously hinted at, formulating SCC involves increasing the proportion of fine particles in the mixture. Increasing the proportion of cement in the mixture is a satisfactory solution from a technical point of view, but often penalized, economically speaking, and detrimental to the environment (energy consumed and greenhouse gas
emissions). Using additives is therefore often the preferred route. The introduction of chemical additives is generally required to ensure the fluidity of the mixture. Each component plays a different role with regard to the rheological behavior of the concrete, and some components interact with one another.

1.2.2.1. Effects of chemical additives (super-plasticizer and thickening agents)

Super-plasticizers work by dispersing particles of cement and mineral admixture. They effect this dispersion in two modes, the dominant mode depends on the nature of the basic polymer. An electrostatic equilibrium is achieved by neutralizing the positive electric charges which exist on the surfaces of cement grains, and sometimes mineral additives. A steric repulsion is induced by the presence of macromolecules coating the particles of cement and mineral admixture.

Certain polymers are branched (for example polyoxyethylene) which are not adsorbed and which persist in the water surrounding the particles. These molecules disturb the flow of fluid between the particles. Contact between particles is almost impossible and the film coating the particles modifies the lubrication between particles. The result of these two modes of action is a fluidizing of the mixture without water addition, or accompanied with a reduction in the water proportion required in the mixture.

Thickeners present a cohesive action in the same manner as the addition of fine particles in a paste. The AFGC recommendations require the use of these additives as soon as the water/binder ratio is too high and may induce segregation or bleeding [AFG 08]. By adding a thickener to a mixture, the mixture becomes more “sticky” which relates to an increase in the viscosity. In general, three principal action
mechanisms are used to explain the increase in viscosity: adsorption, association and interlacing [KHA 98].

![Diagram](image_url)

**Figure 1.4.** Dispersion combining electrostatic and steric effects between two particles (cement and/or additive) [CAL 98]

The first mechanism operates when the thickening agents have long chains (hydrophilic) which adsorb and fix molecules of water in the suspension, and extend throughout the mixture. From this an increase in the viscosity of the fluid arises, and therefore in that of the paste too. The second mechanism appears when adjacent thickener chains develop forces attractive to one another, thereby blocking the flow of water in the suspension. As a consequence, the suspension gels and flowing becomes more difficult.

Making this gel flow requires a shear stress level which is sufficient to break bonds. This is known as the static yield point. This mode of action therefore relates to a yield point
value and an increase in the viscosity. Polymer interlacing generally occurs at a low shear rate and especially when the thickener concentration in the mixture is high. The chains interlace and tangle, causing the viscosity of the mixture to increase. Interlacing can be reduced at high shear rate by the alignment of polymer chains in the direction of shearing.

In a practical sense, the combination of the superplasticizer’s fluidizing action and the stabilizing action of the thickener show the fundamental characteristics of SCCs: fluidity and homogeneity. This combination is discussed in section 1.3.3.2.

However, the use of super-plasticizers and thickeners necessitates a test of their compatibility with the cement being used. This is carried out with laboratory tests [SCH 00, LAR 96]. As for the formulation of a conventional concrete, the cement used in SCC formulations does not require any particular specification. It must simply conform to the NF EN 197-1 standard, adapted to the target strength range and environmental class (NF EN 206-1).

The paste volume can be increased by adding a mineral additive. The mineral additive also contributes to avoiding an increase in the exothermic heat during the concrete’s hardening phase if the concrete contains nothing but cement. Furthermore, an increase in the mixture proportion of Portland cement can induce increased shrinkage which may lead to cracking in the SCC.

At present in France, limestone filler tends to be the most widely used additive in SCC designs since it is not very costly and is available in large quantities, even though there is a reduction in the production of fly ash due to the progressive closures of coal-fired power stations.