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Self-consolidating Mortars using Various Secondary Raw Materials

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ABSTRACT: Secondary Raw Material (SRM) particle characterisation and the flow behaviour, strength development, microstructure and early volume of stability of SCMs are reported. A simple procedure has been suggested for strength quantification of SCMs using various Secondary Raw Materials (SRMs). The study demonstrates that shape, size and surface morphology and porosity of SRMs lay a significant role in determining the water and high-range water-reducing admixture (HRWRA) demands of SCMs. SRM characterisation also helps to understand various test results routinely performed on SCM systems. Based on the comparative tests, limestone powder (LSP) alone is not the best SRM for self-consolidation cementitious systems (SCCS). Suitable blends of fly ash (FA) and silica fume (SF) or LSP can be good SRMs for an overall response of SCMs using well-graded aggregates.

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Self-compacting concrete

The SCC Overview technical paper, by Petrus Jooste, was presented at SCC Seminars around the country.

Fig. 1: Bridge 2235

Abstract

Self-compacting concrete (SCC) is becoming a popular form of concrete usage in a range of applications throughout the world. This new concrete type has also found application in South Africa with great success in contracts such as the Nelson Mandela Bridge. The first formal application of self-compacting concrete occurred in Japan in 1988, and was driven by a shortage of skilled workers to place concrete at the job site and the resultant inadequate compaction and finishing of the concrete.

The response was to develop a concrete that flowed easily around obstacles into all the corners of the formwork without the need for compaction. This, together with the need for fewer skilled construction workers, made the construction of concrete structures much quicker.

This article considers the development of the technology and use of self-compacting concrete, addressing the benefits as well as the disadvantages. Importantly, the article aims to highlight the opportunities for using self-compacting concrete in South Africa.

SCC characteristics

SCC is a specialised concrete designed to flow freely around obstacles, completely fill formwork and enclose all reinforcing bars without segregation or bleeding.[1] The three key properties of SCC are filling ability (highly fluid to ensure flow under self weight), passing ability (passing around obstacles without blocking) and resistance to segregation (no separation of phases during flow or at rest after placing). As the name indicates, this concrete type requires no external consolidation effort while still fulfilling all the requirements of conventional concrete.

Mixture design requirements

Various mixture design methods have been developed throughout the world to design SCC mixtures. Unfortunately no universal SCC mixture design method can be produced, because of regional variability and availability of concrete materials. The main criterion for a SCC mixture is the self-compactability, i.e. good filling ability and passing ability without segregation or bleeding. These properties are only possible when a new generation super plasticiser is used. SCC is very sensitive to both the water content and the super plasticiser dosage. This creates a fine line between a mixture with the required properties and a mixture that segregates. A viscosity modifier can be used to assist with this problem but then the cost is increased and workability retention is shorter.

Domone[2] undertook a study on the commonly available mixture design methods and concluded that there is a wide range of mixture proportions that can be used to produce SCC. The key factors, expressed in volumetric terms are as follows:

- 30-34 % of the concrete volume to be coarse aggregate
- 0.25-0.5 as the water to powder ratio and mixtures with values at the upper end of this range require a viscosity modifier to enhance the viscosity
- 155-175 l/m^3 water if no viscosity modifier is used and up to 200 l/m^3 with a viscosity modifier
- 34-40 % of the concrete volume to be paste
- 40-50 % of the mortar volume to be fine aggregate

These volumes can be expressed

Constituent	Typical range by mass (kg/m^3)	Typical range by volume ($litres/m^3$)
Powder	380-600	
Paste		300-380
Water	150-210	150-210
Coarse aggregate	750-1000	270-360
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48 - 55% of total aggregate weight.	
Water/Powder ratio by Vol		0.85 - 1.10

Table 1: EFNARC typical range of SCC mix composition[3]

as approximate proportions by weight as follows:

Coarse aggregate	750 - 920 kg/m³
Fine aggregate	710 - 900 kg/m³
Powder	450 - 600 kg/m³
Water	150 - 200 kg/m³

The European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) suggests a typical range of constituents in The European Guidelines for Self-Compacting Concrete.[3] These proportions, which are in no way restrictive, are given in Table 1. The EFNARC guidelines also recommend a maximum aggregate size of 12-20mm[3].

Benefits of using SCC

The most valuable benefit when using SCC is that no compaction of the fresh concrete is required. This leads to reduced energy requirement in the placing and finishing of the concrete. Placing is quicker and easier, the construction time is reduced and workers can be used more effectively. This was evident in the construction of the anchorage of the Akashi-Kaikyo Bridge, where the use of SCC reduced the total construction time from 30 to 24 months. Another project where the use of SCC reduced the construction time from 22 to 18 months was the wall of the liquid natural gas tank for the Osaka Gas Company[1].

Fig. 2: The Nelson Mandela Bridge

The high flowability of SCC makes alternative placing methods possible, like pumping the concrete continuously from the bottom of the structure. This method was used in the filling of the pylons of the Nelson Mandela Bridge.

The high flowability and elimination of the need for compaction make the use of special designs and shapes possible. With conventional concrete, designs were restricted to shapes where concrete could be placed manually and where compaction equipment could reach. The Science Centre in Wolfsburg, Germany[4], the façade of the National Theatre in The Hague[5] and the pylons of the Nelson Mandela bridge are examples where the use of conventional concrete would not have been possible. SCC lends itself to creative shapes and innovative construction systems. Designs with very congested reinforcing are also acceptable, since SCC can flow around these and external compaction is not required.

With the reduction of the noise levels (about 93 dB when compacting conventional concrete) the working environment is safer and the noise is reduced in built-up areas. When using SCC the noise level can be brought well below 80 dB. Intensities higher than 80 dB can cause deafness, stress and fatigue[5]. With lower noise, no ear protection is needed and communication on site is easier. Vibration above 0,25 m/s^2 causes pain and stiffness in limbs, back and neck[5]. A more serious ailment caused by continuously using the poker vibrator (vibration levels from 0,75 to 4 m/s^2) is known as 'white fingers' which affects the blood circulation of the vibrator operator[4].

With well compacted concrete, the possibility of air voids is reduced, which increases the strength and density of the concrete. The bond between the concrete and the reinforcing steel is improved and there is a reduced chance of bleed water lenses beneath reinforcing and aggregate.

The off-shutter finish when using SCC is also very good. The chances of honeycombing and blow holes are very slim. The use of admixtures assures thorough mixing since all the cement particles are better dispersed throughout the mixture, resulting in a more homogeneous concrete. This was evident in the concrete finish achieved with the construction of Bridge 2235.

The properties of SCC are well suited to produce good quality precast elements, reducing energy consumption in the production process. The energy required is not just the power to operate the plant, but also labour and equipment efficiency. Cycle time of the moulds is shorter because the admixtures used in the mixture can accelerate the hydration process which accelerates strength development. There is also less wear and maintenance on the mixing equipment.[6]

Disadvantages of using SCC

The biggest disadvantage of SCC is the cost involved in making this type of concrete. The material cost is higher since admixtures must be used. The aggregate also needs to be a smaller size, which can be more expensive and not readily available. The mixture requires a large percentage of fines and filler material to avoid segregation. SCC is sensitive to variation in the aggregate and this needs to be well controlled for consistent quality and grading.

The material sensitivity of SCC means that strict quality control is necessary at the batching and mixing operation. The material used in the mixture needs to conform to a very narrow specification. This necessitates careful grading and washing of sand to control the fines content of the mixture. If the fines content of the sand is not controlled, the water demand and admixture content will be affected and the end product can not be predicted. This could lead to a mixture that either segregates or does not flow satisfactorily. Mixer operators must be well trained and always aware of the sensitivity of this product.

Furthermore, special formwork is required when using SCC. The formwork must be stronger to support the concrete at early ages since form pressure is higher than with conventional concrete. Formwork needs to be near watertight to prevent loss of fines from the concrete mixture.

Development of SCC

SCC was first developed in 1988 by Okamura[7] at Tokyo University and its use has gradually increased. Okamura develops SCC to accomplish more durable and reliable concrete structures. The lack of skilled workers for compaction work and the misunderstandings between designers and construction engineers emphasised the need for SSC.

From Japan, the use of SCC spread through Asia and in 1993 it was also used in Europe. In North America the use of SCC grew from an insignificant amount in the year 2000 to more than a million cubic metres in total at the end of 2002. SCC was first used in South Africa in 2002. In Britain the Ready Mixed SCC usage show a 10% growth year on year and increased from near zero in 2000 to 400 000m^3 in 2008. Even though much research has been done across the world, further research is still required.[9]

Applications

Japan

One of the first big projects undertaken in Japan using SCC was the anchorage (83 m long, 63 m wide and approximately 45 m high) of the Akashi-Kaikyo Bridge. This project is a very good example of where the use of SCC reduced the total construction time from 30 to 24 months. Another project where the use of SCC reduced the construction time from 22 to 18 months was the 0.8 m thick wall of the liquid natural gas tank for the Osaka Gas Company[1]. More recent applications of SCC in Japan are lattice work (thin ribs), casting without a pump (discharging concrete from the truck and allowing it to flow freely to fill the formwork) and tunnel linings. SCC is used in lattice work because conventional concrete cannot be vibrated in this manufacturing process. To prevent cold joints in tunnel linings, SCC is used because it limits bleeding or laitance at joints.[7]

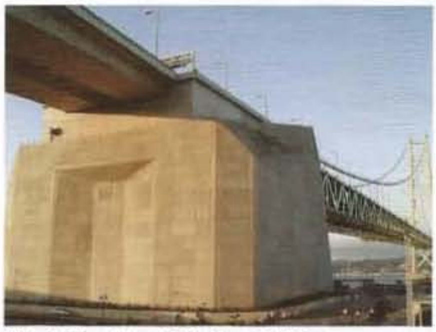

Fig. 3: The Akashi-Kaikyo Bridge

Fig. 4: Spiral staircase

Sweden

Sweden started to develop SCC in 1993 with a project where walls were cast using different materials as fillers in the mixture designs. In 1998 a monolithic frame bridge was constructed in Kjula using SCC. This was the first bridge outside Japan where SCC was used for the whole structure.[1] Since then, SCC has been used in bridges, box tunnel monoliths, rock lining monoliths (Sodra Lanken), tunnel entrances, headwalls, foundations and frame supports. The current use of SCC in Sweden's precast and ready mix concrete industry is about 10% of the total concrete usage.[8]

Netherlands

The development of SCC is particularly favoured in the precast concrete industry. Some precast concrete producers in the Netherlands only use SCC in the manufacture of their products.[5] Through this extensive use of SCC, much experience has been gained and SCC is now used in pre-cast slabs, beams, walls, columns, arches and bridge elements. SCC has also been used *in situ* but only in special cases. The first major project was the façade of the National Theatre in The Hague where only SCC could be used to fill the tiny ribs (8 mm deep). In some tunnel walls SCC was used because of the possibility of remote casting techniques. At the Rotterdam Zoo the heavily reinforced walls of a large fish pond were constructed with SCC to ensure a homogeneous watertight structure. The design and shape of the bridge piers for the 'South Tangent' traffic connection between Haarlem and Amsterdam was of such a nature that only SCC could be used. In this project 1800 m^3 of SCC was used. The most recent development in the Netherlands is self-compacting fibre reinforced concrete. This is used to produce floor elements that are thinner and lighter.[5]

America

Further examples of SCC applications are the steel form columns at Toronto International Airport and the outrigger columns at Wall Centre in Vancouver. A more interesting application is in the construction of houses in Houston where the exterior walls and slabs were cast monolithically out of SCC. The walls are textured and stained on the outside to resemble brick and have a polystyrene foam core for insulation. These houses are designed to withstand tornados and hurricane winds in excess of 218 km per hour.[10]

South Africa

The Nelson Mandela Bridge Project was the first project where SCC was used in the construction in 2002. This bridge (see Fig. 2) is the largest cable-stayed bridge in South Africa, connecting Braamfontein with Newtown and spanning the Braamfontein rail shunting yards. Newtown is the centre of the cultural precinct and the bridge provides access from the northern side of Johannesburg to this area.

A serious challenge during this project was the placing of the concrete inside the hollow steel pylons. The pylons were constructed from 20 mm (southern pylons) and 40 mm (northern pylons) thick steel plate, rolled to produce 1.35 m diameter steel pipes, which had to be filled with concrete to provide the required stiffness. The southern and northern pylons are respectively 31.1 m and 43.9 m high. This created difficulty with concrete lifting and placing, due to the free fall limits, access constraints (due to operating railway lines) and stressing chambers at the top of the pylons.[11] In addition, mechanical vibration was impossible due to limited access. External vibration was inappropriate because of the large amount of energy needed to overcome the pylon inertia. To overcome this it was decided to pump SCC into the pylons from the bottom. The concrete was pumped through a special pipe and valve arrangement at the bottom of each pylon.

Bridge 2235

Bridge 2235 forms part of an off-ramp from the Bakwena highway. The Bakwena highway, which extends from Pretoria to Botswana, is part of the east-west link across the southern part of Africa. The bridge deck is a post-tensioned two-cell box girder type structure, unlike the conventional metal drum void formers used in similar bridges. To save time and labour costs, it was decided to cast the deck of Bridge 2235 in one operation. Since compaction and placing was a problem in the reinforcing congested bottom slab, it was decided to use SCC.

When the first trial was poured, the concrete showed signs of segregation and too much mortar. Adjustments to admixture/binder proportions were made and the trial was repeated the following day. The second attempt was successful and the concrete stayed in suspension and flowed from the one upstand through the bottom slab shutter filling both upstands to their full height.[12] The bridge deck was then cast successfully with very little trapped air voids visible.

Fig. 5: Repaired culvert in Cape Town

Spiral Staircase

In 2003, a spiral staircase at an office building in Pretoria was constructed using SCC. The position and geometry of this staircase made vibration impossible. It also had to be cast in one operation since no joints were allowed. At first, the formwork was not strong enough to withstand the concrete pressure, and adjustments to the formwork were required. With the formwork problems solved, the construction of the staircase was successful and the appearance acceptable.[13]

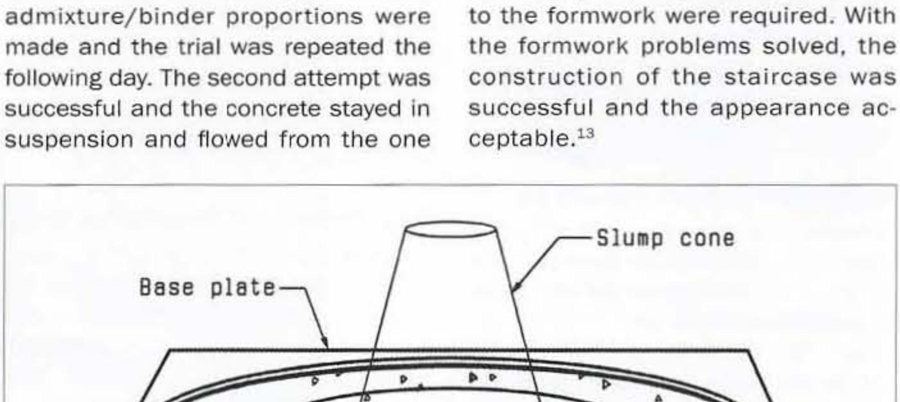

Fig. 6: The Slump flow test[1]

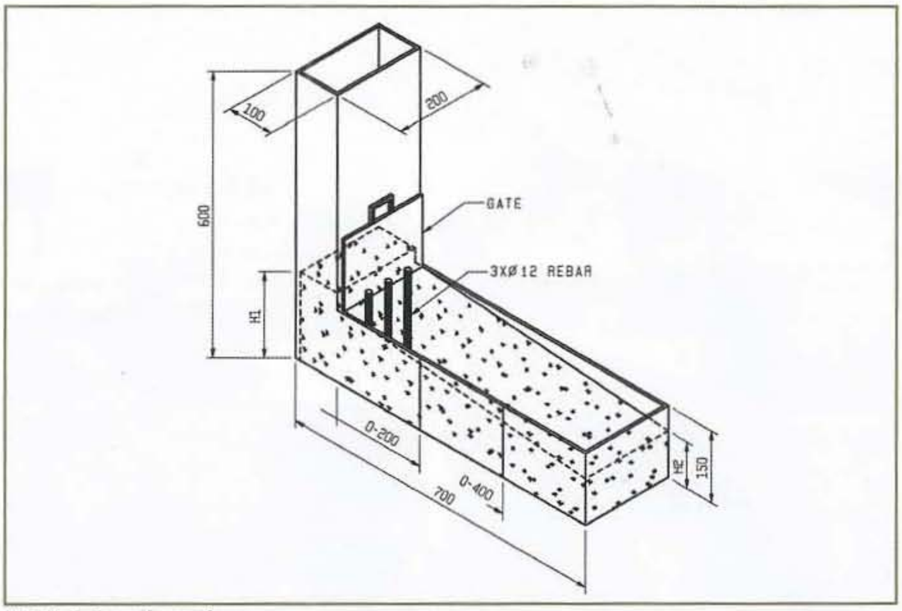

Fig. 7: L-box dimensions

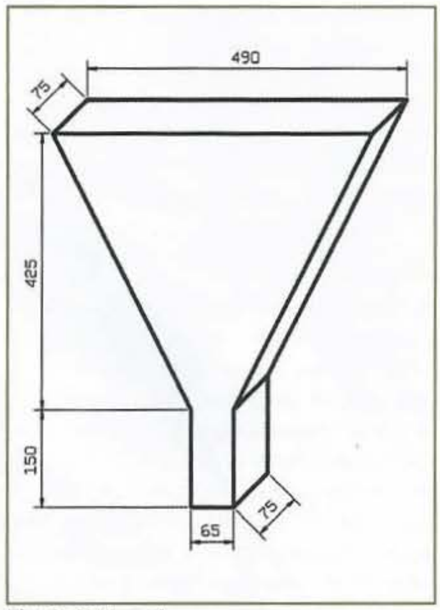

Fig. 8: V-Funnel

Culvert repair

In 2004 SCC was used on a project close to Cape Town for the repair of a culvert where the soffit had deteriorated to the extent that the reinforcing steel was exposed. To repair this, timber shuttering was placed below the soffit leaving enough room for extra reinforcing steel and concrete. SCC was placed through openings drilled from the top.

Inspection openings were also provided at the other end of the slab to check if the space had been filled completely. The operation was completed quickly and successfully. The only problem that was encountered was that rain affected the mixture on one of the days and the super plasticiser dosage had to be adapted. An alternative to using SCC in this case was to build a detour and rebuild the culvert. With the use of SCC the problem was solved in a shorter time and more cost effectively.[4]

Workability test methods

To determine the appropriate self-compacting properties, e.g. good passing ability, filling ability and resistance to segregation, various test methods are used. The three key properties cannot be described adequately with one method and a combination of tests is required. In 2001 a European project, Testing SCC, was started to investigate and establish suitable test methods to assess the three key properties of SCC.[14] The test methods selected in the European project include the slump flow, the L-box, the V-funnel, the U-test, The Oriment, the 'static sieving' test and the J-Ring. Individually, these tests cannot assess all three properties and the resistance to segregation simultaneously and therefore rheology is required to describe the properties of SCC fully. The European project did not only focus on the test methods but also related the results to fundamental rheological measurements. These rheological measurements will establish a scientific basis for the recommended properties.[14]

Rheology is the science that describes the flow and deformation of matter. The method used in South Africa to measure the rheology of concrete is the Tattersall Two Point Test. From the test methods selected in the European project, the slump flow, the L-box and the V-funnel are used to measure the workability of the concrete mixtures. These methods are used because of their stated suitability in other projects and, importantly, the availability of the equipment to perform these tests. All these methods are described in more detail below.

The Tattersall Two Point Test

This test is used to measure shear resistance at two shear deformation rates. The yield stress ($\square_0$) and plastic viscosity (μ) can therefore be calculated from the speed and torque measurements and used in the Bingham equation ($\square = \square_0 + \mu\gamma$) to determine the shear resistance of the concrete under investigation.

The Tattersall Two Point Tester measures the pressure in a variable hydraulic transmission when turning an impeller in concrete at different speeds. Measurements at seven speeds are sufficient to calculate the intercept and reciprocal slope of the torque against speed relationship.

The slump flow test

The slump flow test is used to evaluate the flowability, deformability and stability of SCC. Included in this test is the T50 value, which describes the viscosity. A conventional slump cone is used in this test. The test is performed on a 900 mm x 900 mm base plate with a 500 mm φ circle drawn on the surface for the measurement of the T50 time.

Testing procedure: [15]

- While pressing the cone down firmly, fill the cone continuously with SCC to the top, without consolidating the concrete and level off
- Remove the slump cone immediately and perpendicular to the base plate, starting the stopwatch as the lifting begins
- Record the time the concrete takes to reach the 500 mm φ circle (T50)
- Measure the final diameter of the concrete as soon as it stops flowing. Assess the concrete for segregation and bleeding

The V-funnel test

This test is used to evaluate the passing ability and segregation resistance of SCC.

Testing procedure:[15]

- Fill the V-funnel continuously with SCC to the top, without consolidating the concrete
- Wait one minute for the concrete to settle and observe for segregation and bleeding
- Open the gate and start the stopwatch simultaneously
- Record the time when the concrete

Slump flow	650 - 800 mm
T50 slump flow	2 - 5 sec
V Funnel	6 - 12 sec
L Box	H2 / H2 = 0.8 - 1.0

Table 2: EFNARC Specifications for SCC workability tests[3]

has flowed out of the V-funnel (flow time = t_0)

The L-box test.

The L-box test is based on the L-flow test developed in Japan for underwater concrete. Peterson[(15)] developed the L-box test to assess the through-flow ability and filling ability of SCC. The L-shaped box (as shown in Fig. 10) is 700 mm long and 600 mm high with reinforcing bars placed in front of the gate.

Testing procedure: [15]

- Fill the vertical section of the L-box continuously with SCC to the top, without consolidating the concrete
- Wait one minute for the concrete to settle and observe for segregation and bleeding
- Open the gate and start the stop-watch simultaneously, allowing the concrete to flow into the horizontal part
- Measure the time it takes the concrete to reach the 200 mm (T_{20}) as well as the 400 mm (T_{40}) markings
- Measure the H_1 and H_2 distances as soon as the concrete stops flowing

Table 2 provides a summary of the EFNARC[3] specifications for the workability tests described above.

Fig. 6: Tattersall Two Point Tester

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