

Final report of RILEM TC 188-CSC ‘Casting of self compacting concrete’

RILEM Technical Committee

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Abstract Increased productivity and improved working environment have had high priority in the development of concrete construction over the last decade. Development of a material not needing vibration for compaction—i.e. self-compacting concrete (SCC)—has successfully met the challenge and is now increasingly being used in routine practice. The key to the improvement of fresh concrete performance has been nanoscale tailoring of molecules for surface active admixtures, as well as improved understanding of particle packing and of the role of mineral surfaces in cementitious matrixes. Fundamental studies of rheological behaviour of cementitious particle suspensions were soon expanded to extensive innovation programmes incorporating applied research, site experiments, instrumented full scale applica-

tions, supporting technology, standards and guides, information efforts as well as training programmes. The major impact of the introduction of SCC is connected to the production process. The choice and handling of constituents are modified as well as mix design, batching, mixing and transporting. The productivity is drastically improved through elimination of vibration compaction and process reorganisation. The working environment is significantly enhanced through avoidance of vibration induced damages, reduced noise and improved safety. Additionally, the technology is improving performance in terms of hardened material properties like surface quality, strength and durability.

1 Introduction

The emerging development of self-compacting concrete (SCC) in the middle of the 1990s was observed in RILEM Technical Committee discussions on workability of fresh concrete. This discussion within that broad international forum rapidly led to the establishment in 1996 of a RILEM Technical Committee especially devoted to SCC. Members from ten countries covering four continents joined the work. Japanese ideas, research and early applications became an

TC Membership—*Chairperson*: Åke Skarendahl, Sweden; *Secretary*: Peter Billberg, Sweden; *Members*: Harald Beitzel, Germany; Emmanuel Dehousse, Belgium; Vinciane Dieryck, Belgium; Aïcha Fadéla Ghezal, Canada; Ian Gibb, England; John J. Gibbs, Scotland; Michael Khrapko, New Zealand; Andreas Leemann, Switzerland; Luis Fernández Luco, Spain; Thomas Österberg, Sweden; David Revuelta, Spain; Geert De Schutter, Belgium; Mohammed Sonebi North Ireland; Olafur Wallevik, Iceland.

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important starting point. The committee (TC 174-SCC) organised the first International RILEM symposium held in Stockholm in 1999 with approximately 70 papers from 13 countries [1]. Twenty of the papers described applications which show the rapid uptake of the research findings in the building industry. The technical committee (TC 174-SCC) concluded its work through producing a state-of-the-art report [2].

Based on the potential of the technology to give a breakthrough change in the production process of concrete, a second RILEM SCC committee was established in 2001, named TC 188-CSC (Casting of SCC). In 2001 the second international symposium on SCC was held in Tokyo, hosted by Tokyo University, with 74 papers presented from 20 countries [3]. It was generally agreed that the rapid development of SCC worldwide required a schedule for international symposia every second year and the third International RILEM symposium was arranged in Reykjavik, Iceland in 2003 with the involvement of TC 188-CSC. At the Reykjavik symposium 108 papers from 26 countries were presented [4].

In addition to the series of International RILEM Symposia, many regional and national meetings have been organised. In 2002 the first North-American Conference was held in Chicago (in North America SCC stands for Self Consolidating Concrete) In May 2005, the first Chinese International Symposium on SCC was arranged in Changsha, China [5] co-sponsored by RILEM.



Fig. 1 Casting of self-compacting concrete (SCC) in a one-man operation (Courtesy of NCC Sweden)



The fourth International RILEM Symposium on SCC, combined with the second North-American Conference on SCC, was held in Chicago in late October 2005 [6] with 140 papers presented by participants from 38 countries. The fifth International RILEM Symposium on SCC will be held in Ghent, Belgium, in September 2007.

The present report is discussing the various aspects on the concrete production process from the handling of raw materials up to finishing after casting. The report is based on the experience of the committee members and reflects the vast literature now present in proceedings and journal papers. Due to the substantial amount of papers published on the subject over the last years, the committee decided not to give specific references in the report but rather encourage the readers to search on the web for literature following the specific aspects of their interest.

RILEM Technical Committee work on the SCC technology is continued covering rheology aspects (TC RFC) as well as durability aspects (TC 205-DSC).

2 SCC—A breakthrough change in the concrete production process

The technique of casting fresh concrete has remained basically unchanged over decades. Transport equipment and compaction tools have gradually facilitated the process and admixtures have made it possible to use concrete requiring less compaction effort. However, the basic procedure of casting by using vibration energy to compact (consolidate) fresh concrete has remained the same. The need for a breakthrough improvement has been obvious from the point of view of productivity increase as well as for the improvement of the working environment.

The introduction of SCC has radically changed the way a formwork is filled. SCC is a particle suspension with an extreme great span in particle sizes (like vibrated concrete) from micrometre sized fines to aggregate in the centimetre range. The development has been made possible through application of nanotechnology in the tailoring of surface active molecules used in chemical admixtures. The introduction of new

developments of superplasticisers and viscosity modifying admixtures (VMA) leads to systems with controllable higher fluidity and moderate viscosity in the fresh state and with high density in the hardened state. The understanding of the behaviour of mineral surfaces of constituent inorganic particles has also been important and has applied knowledge on particle packing leading to an elaborated use of fillers.

The concrete construction process is changed resulting in an improved productivity and a possible automation. This leads to new modes of organising workplaces and business. At the same time the development gives distinct working environment advantages. However the full potential of using the technology will be achieved only through evaluating and optimising the whole production process.

SCC is an innovation in the sense that it is now successful on its own merits on competitive markets. In precasting there are numerous examples of factories having fully converted to the use of SCC. The lead time for the development has been very short by construction sector standards. The development is however still in its infancy and many interesting challenges are lying ahead for both research and business. Important for a rapid and wide spread of the technology is that much of the knowledge generated is in the open domain and that necessary constituents and machinery can be accessed on competitive conditions from several suppliers. SCC is now used in large quantities in many countries around the world and a strong future growth can be forecast.

3 Requirements on fresh SCC

The functional requirements on a fresh SCC are different from those on a vibrated fresh concrete. Filling of formwork with a liquid suspension requires workability performance which is recommended to be described as follows:

- *Filling ability*: Complete filling of formwork and encapsulation of reinforcement and inserts. Substantial horizontal and vertical flow of the concrete within the formwork with maintained homogeneity.

- *Passing ability*: Passing of obstacles such as narrow sections of the formwork, closely spaced reinforcement etc. without blocking caused by interlocking of aggregate particles.
- *Resistance to segregation*: Maintaining of homogeneity throughout mixing and during transportation and casting. The dynamic stability refers to the resistance to segregation during placement. The static stability refers to resistance to bleeding, segregation and surface settlement after casting.

Additional criteria on fresh concrete, both SCC and vibrated concrete, can be described as follows. Characteristics for SCC are commented:

- *Open time*: Has to be closely following specified time. New generations of admixtures offer increased possibilities of setting a specified target open time, e.g. very short for precast applications and very long for in situ castings with long transports.
- *Precision and accuracy*: More essential to keep target workability for SCC as the casting is fully relying on the material properties as no tools normally will be available for manual material transport and compaction.
- *Pumping ability*: SCC is generally easier to pump. Depending on the specific rheological properties of the fresh concrete the pumping pressure versus the feeding rate has to be optimised.
- *Finishing ability*: SCC normally has less bleeding tendency. In many cases the finishing will be made on a coarser and stickier surface. Appropriate materials on the finishing tools are thus to be recommended.



Fig. 2 Self-compacting concrete (SCC) fulfilling requirements on flowability, passing ability and stability

- *Working environment*: Drastic improvement when using SCC. Reduction of noise level and avoidance of blood circulation disturbance (white fingers) induced by handheld vibrators. Improved safety through more mechanisation and remote control. Substantial reduction of hazardous objects, e.g. elevated platforms, electrical cables, vibrators.
- *Hardened concrete*: The fresh concrete has to be composed to meet the target performance during hardening and in the hardened state. SCC has shown to give improved microstructural features leading to potential improvements of strength, durability and surface quality.
- *Cost*: Increased cost for additional constituents, improved knowledge of workforce and improved quality assurance. The higher material cost is overrun by reduced cost for casting as well as improved performance—as has been shown on competitive markets!

4 Mechanism of change

To simply increase the water content in a mix to achieve a SCC is obviously not a viable option. Instead, the challenge is to increase the flowability of the particle suspension (the fresh concrete) and at the same time avoid segregation of the phases. The main mechanisms controlling the balance between higher flowability and stability are related to surface chemistry. The development of SCC has thus been strongly dependent on surface active admixtures as well as on the increased specific surface area obtained through the used fillers. Evaluation of these mechanisms requires studies of the rheological behaviour.

The performance parameters of the fresh concrete being most vital in material design are the following:

- yield stress
- viscosity
- thixotropy
- dispersion
- water retention

In addition to these surface chemistry-related properties the physical property of particle packing is also central.



Fig. 3 Viscometer used for determining rheological material data and workability testing in practice (Courtesy of M. Sonebi)

To be able to understand, modify and characterise the material behaviour it is necessary to work on a molecular scale which implies studies on material nanostructures as well as microstructures. Fillers as well as chemical admixtures are decisive for the behaviour of the fresh concrete and consequently the research on SCC has been focused on these materials.

The interest for SCC has thus strongly increased the interest for rheology evaluation of fresh concrete. Rheology is increasingly used in

mapping of mechanisms, in optimisation of constituent materials, in understanding the relation between thixotropy and formwork pressure, in fluid mechanics approaches used in modelling of flow etc. rheological evaluation is not only used by research laboratories but also by laboratories of frontline suppliers of admixtures, fillers, cement and concrete. This technique is still primarily used for research and development and not yet in any significant way as a tool in quality assurance procedures. An extension into this area is requiring further test method development.

In material design in practice, as well as in quality assurance and acceptance control, fresh concrete behaviour is most often evaluated through method specific workability test methods, e.g. slump flow, L-box, J-ring, U-box, V-funnel.

5 Key constituents and their handling

5.1 Key constituents

The key to enable a concrete to be self-compacting, i.e. extremely flowable and at the same time homogeneous, lays within the properties of the constituents in general and in the micro- and nanoscale behaviour in particular. In the micro–nano metre size range, colloidal forces and surface chemistry are dominating. Most colloidal particles in concrete, i.e. cement, fillers and the smallest aggregate particles, flocculate to different degrees spontaneously when immersed into the mixing water. Thus, they have to be dispersed to free entrapped water and to break the solid structure to enable the suspension to flow, i.e. reducing the yield stress as described by the Bingham model. Normally this pronounced dispersion obtained through addition of superplasticisers results in so much released mixing water that the suspension becomes unstable and segregates. Therefore, instead of decreasing W/C, either additional filler material or a viscosity modifying admixture (VMA) is added to bind the surplus water and prevent segregation. Thus, the most important mechanisms related to SCC fresh properties are dispersion of flocculated particles and wetting/binding of water.

The most common superplasticisers used for SCC belong to the third generation of dispersing surfactants. These are specially designed to meet different demands from different fields of concrete production, e.g. precast elements and ready mixed concrete. Both the first and the second generations of superplasticisers are to different degrees made from by-products (e.g. lignin, melamine and naphthalene) while the present, third generation is often based on polycarboxylate ether (PCE). The latter type is developed by the chemical industry using the recent tools in nanotechnology.

Fillers are primarily used to bind excess water and to gain sufficient stability and viscosity but also to increase the volume of the continuous phase which in some cases is the key to gain passing ability.

Today, many types of VMA's are produced in liquid form and mostly consist of different types of polymers.

5.2 Handling of constituent materials

One of the most important advantages of SCC is that it can be successfully made using cement and aggregates used to produce other types of concrete. Materials for SCC can be stored in the same manner as they would be for production of vibrated concrete; in ground bins, plant overhead bins, silos, bags, and tanks for liquid admixtures, although consistency of raw materials needs to be controlled more frequently. It is recommended to apply the best practices on the maintenance of stockpiles of materials, i.e. moisture contents, free drainage, cleanness, and prevention of segregation. In this instance overhead bins may suit better, but the limited number of overhead bins at the most ready-mix plants may affect the flexibility of the plant operation.

In addition, concrete plants need to be able to store various filler materials and therefore needs additional silo capacity. Concrete ready-mix plants have a set of high-volume tanks for liquid admixtures to produce vibrated concrete. Since SCC always is produced by using superplasticisers and sometimes also VMA, it might be required to install extra storage tanks and dispersing systems. At this point of time no combined admixture, i.e.



Fig. 4 A modern concrete mixing plant with several silos (Courtesy of Swerock, Sweden)

SP and VMA, is recommended mainly because of the different dosage rate requirements of each admixture to achieve different properties of SCC.

5.3 Sensitivity to variations

During production SCC is more sensitive to fluctuations in the total water content than vibrated concrete. Fluctuations in raw material gradations and moisture contents can have dramatic influence on the stability and fluidity of the concrete mix. The total water content consists of mixing water and water from the surface moisture of aggregates. Thus, the surface moisture of aggregates is of a greatest concern in production of SCC. Moisture contents of fine aggregates normally are greater than those of coarse aggregates. There are at least two methods of measuring moisture parameters of aggregates, which can be successfully applied for production of SCC:

- moisture probes (sensors)
- manual drying tests.

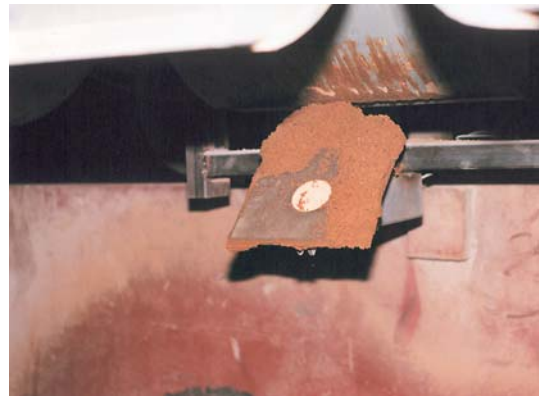


Fig. 5 Moisture sensor for continuous measurement of sand moisture in the batching process (Courtesy of Franz Ludwig GmbH, Germany)

Both methods have some advantages as well as disadvantages. Moisture probes can offer real-time result, although accuracy of the results may depend on the position of the probe in the production chain. However, the maintenance cost can be high and there is still a lack of comprehensive investigations of the performance of on-line moisture probes. Manual drying tests are very accurate, simple and reliable but these tests take time and consume labour and cannot offer real time results. Information obtained from these methods should be used to adjust the amount of mix water required by the mix design.

SCC is much more sensitive to significant deviations of material quantities. A concrete mixing plant with the sound history of producing concretes of consistent quality is able to successfully produce high quality SCC. Normal weighing tolerances regulated by national and international standards are in general acceptable for production of SCC. It should be noted, though, that larger load sizes of concrete lead to better consistency, so it would be recommended to avoid whenever possible batching of small loads of SCC. Accuracy of weighing equipment may affect the consistency of SCC and eventually on the cost to produce SCC, so the more accurate equipment will eventually produce more economical SCC.

Batching equipment should be regularly checked for the accuracy. A special attention should be paid to the accuracy of liquid admixture dispensing/dosing equipment. Depending on the

type of dosing equipment and its set-up (e.g. pulse metres, weighing, length of the pipe lines, free fall distance, etc.), accuracy may vary substantially. Hence equipment accuracy check and verification should be carried out more frequently. In countries with high seasonal temperature variations, viscosity of liquid admixtures may vary, which could influence on the accuracy of dosing of those admixtures.

5.4 Recycled water

Some measures to control quality and quantity of recycled water used in production of SCC should be taken into account. Solids from the slurry, as an extra source of ultra fine particles, can be beneficial for SCC, but the amount of solids in the slurry must be known and maintained constant. In such a case, the SCC mix design should be adjusted accordingly. Chemistry and age of recycled water and slurry may effect on the SCC workability life. Considering importance of potential influence of recycled water on fresh and hardened properties of SCC it would be wise to use a sample of such water when SCC laboratory development and full scale trials are conducted.

5.5 Overall recommendation

It should be emphasised that SCC can be successfully produced in a consistent and continuous way only at a properly equipped concrete mixing plant under an established and reliable quality assurance system. Experience shows that SCC does not forgive any short cuts.

6 Mix design

It is important to stress the fact that SCC is not a special category of concrete but instead a big family of different mixes having the least common property of self-compactability in the fresh state. Thus, any vibrated concrete used today aiming for certain properties such as; strength, durability, self desiccation etc. can be transformed to be self compacting. It has also been proven that SCC can be produced with local materials even though different actions regarding mix design must be taken.

Many different approaches have been made around the world to create a mix design model for SCC. Even though they differ in some respects many of them are based on the concept of SCC being a particle suspension. The coarse aggregate is regarded as the solid phase suspended in the continuous phase micro-or fine mortar. As already discussed in Sect. 4, the basic mechanisms behind SCC can be found in this continuous phase where all water, fine particles and admixtures are included.

If the basis for the SCC is a vibrated concrete mix design, optimisation often means to minimise the difference from the original. That is, finding the most cost-efficient type of filler material and the minimum amount necessary. This minimum amount will depend on the packing density of the coarse aggregate, on the characteristics of the cement and the fine aggregate. It must however always be investigated how the mix behaves during hydration and in the hardened state. In addition it is equally important to find the optimal combination of chemical admixtures, filler and cement.

Fibre reinforced concretes have proven to be possible to become self compacting. To achieve required filling ability when fibres are used shifting in amount of coarse to finer aggregate is necessary. There is also a threshold value of fibre amount depending on fibre characteristics and mix design respectively. Another important property is the passing ability which must be secured in appropriate applications.

Regardless of what mix design approach is utilised, the SCC properties shall be verified.

7 Mixing and transport

7.1 Mixing technique

For production of SCC, as is the case for vibrated concrete, the loading-and mixing sequences are very important. It is even more important for SCC as it contains a very high amount of fine particles needed to be efficiently dispersed in an optimal way. Suitable loading-and mixing sequences is to be determined for each plant individually by conducting some batching



experiments. SCC normally requires a more efficient mixing, e.g. longer mixing time, to make sure that all constituents have been mixed thoroughly. However, shorter mixing times are possible for the production of quality assured SCC by changing the mixing speeds in concrete mixers. Thus, economically favourable mixing times are also possible for the production of SCC with appropriate changes to the concrete mixer.

Admixture manufacturers recommend that superplasticiser should be diluted in water before added to the concrete. This permits a better distribution of relatively small quantity of admixtures within the mass of SCC. Practice in general confirms this.

Most stationary mixers have a steady mixing speed, while truck mixers have a variable speed. When mixing SCC in a truck mixer, it should be at 'mixing' speed, which is normally between 15 and 25 rpm.

For better consistency, the volume of the SCC mix should be as near to the maximum mixer capacity as possible. Mixer shall be clean but not dry. Mixing vibrated concrete before mixing SCC may create some inconsistency in properties of SCC, especially if some incompatible admixtures such as superplasticisers were used before mixing SCC. In such situation one should ensure that the mixer is clean before loading. From the practicality point of view, in order to prevent any potential hold-ups associated with production of SCC, daily production programme should be carefully scheduled to make sure that only compatible admixtures are used in between SCC loads.

7.2 Mixer types

Force type of mixers can normally be regarded as more efficient in mixing SCC than gravity mixers. Some studies indicate that larger mixers are more efficient than smaller, which in general means that longer mixing time may be required for "smaller" mixers.

7.3 Ready mix plants

SCC can be successfully manufactured by a concrete mixing plant of any configuration and bat-

ched either automatically or manually as long as it is able to produce different types of concretes with consistent properties and has a proven reliable history of doing so. It should be noted though, that if SCC is mixed in a truck mixer, quality and consistency of SCC might vary from truck to truck depending on the mixer configuration, mixing speed and the condition of the mixer of different trucks. In no way SCC should be mixed in a truck agitator.

7.4 Transportation

SCC can be delivered either by truck mixer or truck agitator. The mixing/agitating bowl should be free from remains of the previously delivered concrete and remains of wash-out water, and it should not be dry. Truck mixers should be distinguished from truck agitators. In simple words, truck mixers are able to adequately produce, deliver, and discharge concrete while truck agitators can not adequately produce concrete. Often properties of SCC need to be adjusted on the job site and for some SCC producers this is a part of production/delivery process. At such circumstances truck agitators shall not be used. Great care should be taken if SCC is to be delivered by tip trucks due to the risk of static segregation.

The limitations to the delivery load size would be only dictated by the road conditions, i.e. driving uphill. SCC can be safely transported over the reasonably hilly roads if the load size of SCC is not exceeding 80% of the full capacity.

8 Quality assurance

As SCC is designed to fill formwork and encapsulate reinforcement without any manual intervention it is important to keep these properties over the time needed for the process. As some of the requirements have to be judged qualitatively an experienced person has to be responsible for the quality assurance following the requirements (see Sect. 3).

Several methods are proposed as quality assurance tools for SCC. Most such methods are workability related, e.g. slump flow including

T500, V-funnel, L-box, sieve stability test and J-ring which all have been selected for European standardisation. Also more complex methods to evaluate “self-compactability” have been proposed. Measurement of rheological parameters as a quality assurance tool is seldom used as the rheometers generally are not suited for in situ routine testing. Observations on separation, bubbles on the surface, stickiness etc should be made by an experienced person.

The sampling of fresh concrete for testing is sensitive as well as time and labour consuming. To counteract this, an “all acceptance test” has

been proposed. A device placed in the discharge flow ahead of casting and all concrete is passing this device. Concrete not fulfilling the criteria given are automatically rejected. Also measurement tools for registration of workability parameters or rheological material data automatically in the transport trucks or pumps are likely to appear in the future.

Especially at the beginning of a casting, large fluctuations of workability might occur. This is often caused by the starting up of mixers, trucks, pumps etc and normally levels out over time. It is thus important to have tighter quality schemes in the start up phase of castings. The site quality control plan has to take account of unpredictable variations in workability, for example slump flow values. If there are any uncertainties with regard to the delivered concrete, sampling of every batch or truckload is recommended. This should be done until the stability and constant quality of the delivered concrete has been ensured.

9 Formwork design and performance

9.1 Formwork design to loads

Using SCC opens up a possibility for enhanced casting rates, as there are no longer any limitations due to the compaction work by the site staff. In fact, it is to a certain extent favourable to speed up the casting rate in order to shorten surface exposure time since this generally prevents inhomogeneity and folds in the border zones between the different concrete layers.

A possible negative side effect by speeding up the casting rate is the potentially high form pressure that might occur. The risk of high form pressures must be considered in the planning process and reflects documented knowledge in regard of the type of concrete going to be used (at actual temperature, batch age and casting rate). Alternatively, the form pressure can be monitored during casting in order to secure the integrity of the formwork. Monitoring form pressure is especially important for high walls, columns or other high structures. The formwork surveillance can check impressions and deformations in clamp



Fig. 6 Both factory mixing and truck mixing is viable for self-compacting concrete (SCC) (Courtesy of M. Khrapko)

ties. When there are such signs of high pressure on formwork a break should be made in the casting.

Reports on form pressure measurements using SCC are scarce but indicate that a pressure equal or nearly equal to hydrostatic values will develop at casting rates over 3–5 m per hour. However, absolute figures cannot be given and it should be noted that the formwork pressure is closely related to local conditions, i.e. mix design and admixture type, water to binder ratio, type of cement, temperature of mix and casting rate. In case of pumping SCC into the formwork from below, the exerted lateral pressure can be increased with pump overpressure, resulting in even higher pressures than hydrostatic. At low casting rates (below 1 m per hour), reported results indicate low form pressures, well below hydrostatic pressure. For those cases, the thixotropic behaviour and the low rising speed contribute to reduce the pressure. Vibrations on construction site, however, could counter this thixotropic build-up.

Unless preliminary measurements are available which clearly show lower formwork pressure for the intended SCC type and casting procedures, SCC should be considered as a liquid and design of formwork should be done by calculating according to a hydrostatic pressure.

9.2 Concrete surface quality

SCC generally leads to very nice concrete surfaces, with in most cases only minor defects. Extremely smooth surfaces can be obtained by means of steel and plywood formwork, while nicely patterned surfaces can be realised using rough timber formwork. Especially for prefabricated SCC elements, some remarkable patterns can be obtained using specially designed formwork. Very smooth and uniform surfaces are generally obtained, also in the case of on-site casting.

In order to obtain high-quality surfaces, some basic recommendations have to be followed:

- The amount of SCC needed for one panel should be accurately estimated, as some colour differences can be expected with different batches.



Fig. 7 Formwork pressure could be monitored using (small) pressure transducers, flush with the form panels (Courtesy of V. Dieryck)

- The formwork should be prepared thoroughly, as illustrated in Fig. 10: cleaning before use, and applying special form releasing agent in a constant dosage (thin layer!).
- The top of the formwork should be covered to protect from rain. Even a small amount of rain can yield discolouring and sand stripes on the SCC surface.

Sometimes, SCC surfaces show some deficiencies like blowholes. The origin of these blowholes is not clear at this moment. Explanations may be a prolonged setting time due to retarding effect from the SP added or due to low casting temperature. During this prolonged setting time, the concrete may segregate or bleed, allowing water to be transported to the mould surface, where it may produce blowholes or stream upwards along the mould. Other contributing factors could be the interaction with the form releasing agent: type and thickness applied to the moulds.



Fig. 8 With self-compacting concrete (SCC) at high casting rates, the formwork should be strengthened especially at the bottom (Courtesy of M Sonebi)

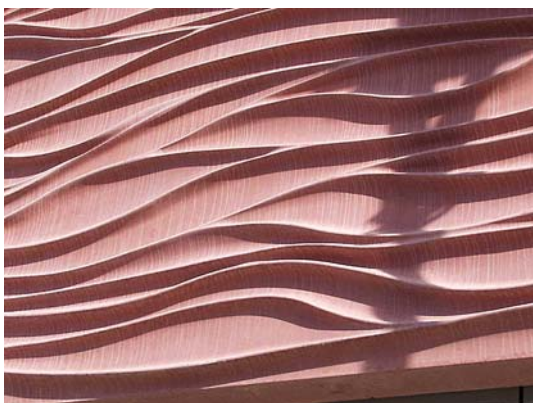


Fig. 9 Remarkable wave pattern in self-compacting concrete (SCC) precast elements, Nieu-Venep, the Netherlands (Courtesy of I. ter Borch)

During compaction, with hand held pokers or fixed vibrators, entrapped air in the concrete or in the border zone between the form and concrete, can relatively easily be “pushed” upwards and out by the induced vibrations. For SCC, entrapped air has to be forced out by the moving



Fig. 10 Properly prepared formwork is important for high surface quality (Courtesy of G. De Schutter)

concrete inside the formwork, with some help of gravitational forces. For this, SCC should always be given the possibility to flow for at least a certain distance. Casting all along the element should be avoided. Some entrapped air near the formwork may escape if the formwork is permeable enough. Tight formwork materials therefore often results in more porosity and blowholes compared to permeable form work materials. Badly cleaned or heavily worn surfaces have a tendency to induce more surface porosity compared to new smooth surfaces. This is probably due to the fact that small air bubbles stick easier to dirty, rugged or bad cleaned surfaces. A thin coating of form release agent seems to be favourable in comparison to a thick layer since air bubbles apparently sticks harder to a thick layer of release agent. The choice of form release agents have shown to be more critical in regard to the appearance of the finished structure, compared to vibrated concrete.

The amount of pores is partly also reflected by the casting rate. A high casting rate, with thick concrete layers, usually results in more blowholes compared to thinner layers and a lower casting rate. Low temperatures tend to give a higher porosity, especially if the form work itself is cool, presumably depending on water separation at the border zone between the concrete and form work.

In order to prevent SCC from leaking, the formwork should be made more carefully than that for vibrated concrete. A special consideration arises from the aesthetic requirements for the concrete surface. When the forms are made of

a material with no absorption capacity, permeable linings can be considered to prevent bug-holes from appearing.

It is recommended to ensure good formwork water-tightness so as to avoid leak of slurry from the SCC resulting in honey-combing. The use of foamed plastic sealing strip or moisture curing gunned silicone rubber provides effective means if sealing joints. Adhesive sealing tape is usually placed on panel joint with very good results.

In summary: SCC seems to be more sensitive with regard to surface finishing, due to the way it is cast, the nature of the formwork, the type and thickness of applied release agent, temperature of the formwork and weather conditions. However, SCC shows great potential to obtain good surfaces, in a way which is not possible with vibrated concrete.

10 Casting

10.1 Planning

The process of casting SCC can be mechanised to a great extent. Increased productivity, lower cost and improved working environment is achieved. A minimum of manual interaction in the process is however necessary. Based on formwork configuration, reinforcement, temperature, casting equipment, casting speed etc., the persons in charge of the concrete supply and the form filling respectively have to plan and jointly agree on SCC workability data, including accuracy, open time, casting speed etc. In more complex industrialised casting operations, the planning of flow of concrete can be computer modelled in order to optimise the rheological material data to the specific formwork, the reinforcement configuration and the sequence and methods of casting.

The planning also includes agreement on the quality assurance procedure, test methods, frequency of test as well as of actions taken as results of tests. The planning should also address the corrections of the mix that might be done at the casting site through extra dosage of plasticiser.

For more complex projects—and before adequate experience is gained by the actors—a mock-up test can be advisable. The test is an

excellent opportunity to educate untrained personnel, test workability data towards intended casting process, test form surface treatments for surface smoothness, air pore stability etc.

Even if there will always be options of buying SCC off the shelf as standard products, the strongest benefits and highest profits will come from optimising the fresh concrete as an integral approach in an industrialised process designed for the specific situation at hand. Even if there is a significant reduction in the needed skill for the actual casting when SCC is applied, the need for skills in planning, preparation and quality assurance is raised.

10.2 Filling of formwork

SCC is a liquid suspension following the rules of fluid mechanics while vibrated concrete is a granular mass requiring vibration to be compacted. SCC is well suited for pumping and can be fed through valves under pressure into vertical formwork. This technique is frequently used when casting complex enclosed volumes where release from above is not possible or no limited entrance to the interior of the form work is possible, nor vibrating it by hand tools. Pumping SCC into the form work from underneath has proven to be beneficial when high demands of aesthetics are of importance. The problem with pores and pot-holes also tends to be less when the concrete has been fed from underneath through valves. Experience from pressurised castings of 30+ vertical meters exists from practice. If the pipe-based feeding system used includes furcating, the concrete flow chooses the easiest way through the piping system. This may result in parts of the concrete not moving, thereby preventing the concrete to fill the form work uniform and symmetrically. A close watch is therefore recommended and the use of sensors and controlled valve openings can rectify the problems.

Vertical formwork can also be cast by dropping from above using pumps or crane skips. Experience from dropping heights of 8 m exists but 1–3 m will be more common. Flat and shallow formwork such as slab and decks are most often filled from above even if in certain situations, e.g. in industrial production, casting through valves by

pumping might be an attractive option. For flat and shallow structures the dropping height is about 0.5–0.8 m. High dropping heights require a stable mix to counteract the risk of segregation and damage of the air pore system.

To release the SCC from a pump hose submerged some decimetres under the concrete upper surface tends to reduce the coarser air pore structure. The results are not fully consistent depending probably on the fact that the specific workability features of used SCC have differed.

The layer thickness should be kept as thin as possible, in order to prevent larger air bubbles to get trapped in the concrete or at the form surface. It is also beneficial to let the concrete flow horizontally some distance (how long is depending on the mix and local circumstances as form work geometry, denseness of reinforcement etc.). On the other hand, the concrete has to be prevented to flow a very long distance in the form. If this is not taken care of, separation at the front might occur. This is the reason why the concrete should be released at fixed distances along the form work. These points of release should be at a maximum distance from each other of about 5–8 m depending on the geometry of the form and density of the reinforcement and other obstacles.

Due to the high amount of fines, SCC is suitable for pumping. The usually high viscosity of SCC may require a slower pumping rate, in order to avoid high pressure built up in the piping system. High pressure may cause aggregate separation and pump-stops. A possible negative effect of too high a feeding rate is a significant drop in slump flow (and mobility) after the pump. The reason for this is neither fully investigated nor understood, but the problem is probably related to the fact that high pump pressures result in shearing, causing paste separation at the interior surfaces of the pump system.

An alternative way of feeding the form work with concrete is the use of openings or holes in the form work. This is especially valuable at closed or inclined form works. The openings should be large enough to allow the pump hose to pass inside the form in an inclined position and when the concrete level has reached the opening (openings) the pump hose (hoses) is pulled out and moved to the next opening above. The lower



Fig. 11 Casting of wall with two methods (Gravity filling and pressure) (Courtesy of NCC, Sweden)

openings are thereafter closed. Horizontal distances of 4–6 m between the openings and correspondingly 2–3 m in vertical direction, have been proven successful.

Practical experiences have shown the importance of operating with several valves or pipes, in order to fill the formwork evenly and symmetrically, and to prevent the concrete from travelling a long horizontal distance in the formwork. The most common procedure is to pump the concrete through two or more valves or pipes simultaneously.

It is important to visually observe the flowing concrete in the formwork. Especially important is to notice its flow around obstacles, reinforcement bars and other objects in the form. Even in sections with dense reinforcement, the surface of the flowing concrete should be fairly even, without any significant differences between the levels of the upper surfaces that might indicate blocking. Coarse aggregate should be visible on the upper

surfaces. Foam on the upper surface is likely to indicate segregation.

It is important to plan the casting sequence. Layers of fresh SCC should be given some time for the release of air through the surface while on the other hand following layers should not come too late, which might make an integration of the layers difficult.

SCC is not necessarily self-levelling. SCC can be so designed that it can be built up in a slope of a few degrees from the release point. This is an important possibility when casting e.g. a bridge slab requiring a limited slope from the centre to the edges.

10.3 Finishing

Finishing operations can be more difficult for SCC due to the thixotropic, sometimes sticky behaviour. The absence of bleeding makes it even more difficult and the finishing operations should be related to the setting time of the mix in actual conditions. It is advisable to perform an appropriate field trial in advance to improve planning and timing of finishing. The characteristics of the SCC mix, and the skill and timing of the finishers during placement affect the quality of the surface of slab cast.

The general experience seems to be that conventional tools and ways to finish the upper surface can be used working with SCC but sometimes finishing tools with other surface materials are used. It is wise to expect this operation to take a little longer in comparison with the finishing of conventional vibrated concrete.

10.4 Curing

SCC mixes are characterised by a moderate to higher amount of fines in the formulation, including various combinations of powders such as Portland cement, limestone filler, fly-ash or ground granulated blast furnace slag. Thus, there might be very little or no bleeding and the concrete will sometimes be more sensitive to plastic shrinkage cracking. The tendency of plastic shrinkage increases with the increase in the volume of fines. This situation is sometimes more

complicated if the setting time is delayed because of the admixture effect, and the concrete remains many hours in the fresh state.

Curing to counteract longer term shrinkage is to be handled like what is done for vibrated concrete. It should be observed that due to a lower permeability of SCC, the drying rate and following from that also the shrinkage rate might be slower.

10.5 Working environment

The improvements in working environment when using SCC are substantial on the individual human level, on the society level as well as on the technical and economical level. The values are appreciated in a growing extent on the market and so are the economical savings that follow. The cost of the society for health care is reduced as well as the company costs for sick leave, early retirement etc. Another positive economical effect of the improved working environment is that legal limitation on time when persons are subjected to high noise will not be decisive for the length of a working day.

The most important aspects of the improved working environment are the elimination of blood circulation disturbance due to handheld vibrators and the strongly reduced noise level. Furthermore, the reduction of physical loading from lifting equipment and moving concrete is important as well as the increased safety due to elimination of cables, transformers, pokers on the workplace and possibility of verbal communication between workers.

An additional positive effect of the improved working environment is that the reduction of the overall noise from the workplace is creating fewer disturbances to building site neighbours.

11 Industrial production

Vibrated concrete and SCC behave in similar ways during mixing as well as in transport. The main difference appears in the filling of the material in the formwork and in the work of compaction. It is thus mainly in the precast production halls or on site that the difference is



Fig. 12 Good curing practice has to be applied also for self-compacting concrete (SCC) (Courtesy of M. Sonebi)

apparent and where the savings are made. However, most of the development work has been made in the field of material design and material performance involving material suppliers, while development of the concreting process involving those who are carrying out the casting has been less pronounced.

The uptake of the SCC technology seems at present to be strongest in precast concrete manufacturing. Several units in many countries have completely shifted to SCC being able to offer higher quality of their production and improved working environment under competitive terms. In on-site production, several excellent and interesting full-scale applications have been carried out in many countries. In many of the projects solutions to very specific situations have been created but several projects has also clearly been targeting industrialisation of in situ concrete construction.

In many of the production technologies now under development, it is evident that the new procedures are making full benefit from the flowability of SCC to the extent that they exclude the possible use of vibrated concrete.

12 Conclusions

12.1 Research and innovation

The SCC technology has a very large potential for refinement and further development and the need for further fundamental mechanism oriented research is significant. In addition there is a strong need for innovation processes. These adjustments and optimisations have to take into account local raw material supply, existing production and transport facilities as well as local market needs. Available constituents as well as production equipment and skill of personnel vary. Thus every mix design and production process have to be uniquely connected to the local conditions.

12.2 Rheology and workability

Understanding the behaviour of fresh concrete is the central requirement for successful use of SCC. An increased understanding of the rheology of pastes, mortars and fresh concrete is supporting improved material design as well as design of



Fig. 13 Walls being cast with self-compacting concrete (SCC) as an integrated part of the fully industrialised prefabricating house building system NCC complete (Courtesy of NCC, Sweden)



Fig. 14 From noise, vibration, ergonomic loading to high quality working environment using self-compacting concrete (SCC) in precasting (Courtesy of K. Juvas)

mixing and casting processes. Evaluation through workability measurements will be an important part of local mix optimisation and quality assurance in practice.

12.3 Constituent materials

SCC is relying on increased understanding and significant developments of surface active admixtures, viscosity agents as well as fillers and cementitious materials. These key drivers are likely to be further improved. In addition, cement development is likely to offer specific modifications of the cement material adjusting to requirements of the SCC technology.

12.4 Handling of constituents

SCC can be produced in most existing plants, but to be able to offer the market the variety of products that are now viable, improvements are relevant to consider. Mix designs are likely to include more than one admixture and more than one mineral additive. This will require additional installations as well as proper processes for batching. To further optimise the processing and the quality, an improved handling of the aggregate, e.g. in the form of split fractions will be common practice. A close control of the aggregate moisture is also enhancing quality and cost efficiency.

12.5 Batching and mixing

The sequence of feeding the constituents into the mixer is important as well as the use of a proper mixing time. Understanding of what is required will be improved and new equipment and procedures for batching and mixing are likely to be developed. In general, forced mixing is advantageous but gravity mixing of SCC is also usable but requires prolonged mixing time. Truck mixing of SCC has proven to be successful provided the quality and efficiency of the truck. Further development of truck mixers as well as site mixing systems is expected to be developed.

12.6 Pumping

SCC is well suited for pumping. Optimisation of pumping of mixes on the basis of fluid mechanics will give improved control of pump pressures and feeding rates. New pump generations are likely to consider the specifics of SCC. Also the remote controlled furcating of pump flows into several hoses and inlets to forms will be further developed.

12.7 Casting

Casting of SCC can be made both with pressure, i.e. pumping through valves and traditional filling from above. The elimination of manual compaction during casting makes very high casting rates possible which, in combination with the high

flowability, might cause high formwork pressures. If the concrete is so designed, thixotropic effects can significantly reduce the formwork pressure. New formwork concepts are likely to be developed further, e.g. using furcated flows through multiple inlets, thus facilitating larger pours and thus make more efficient use of the high casting rates possible.

12.8 Industrialisation

The development of SCC strongly supports an increased industrialisation of the concrete construction process. The fact that concrete can be handled as a fluid gives in itself drastic process improvement possibilities. The possibilities of utilising complex formwork systems has improved and an increased use of permanent formwork of high quality sheet materials are clearly in the direction of future development. Positive results from studies of fibre reinforcement of SCC are further enhancing the possibilities of industrialisation.

12.9 Knowledge and competence

SCC is a complex material with several sensitive interactions between the constituent materials. Compared to vibrated concrete it is at this stage of development less robust and requires more knowledge, competence and skill of personnel, more closely controlled properties of the constituent materials and greater care in production and delivery. The technology also requires greater skill and care in the casting operation. These conditions call for an increased focus on training of personnel and on quality assurance issues.

12.10 Testing

The specific behaviour of SCC requires new test methods, in particular for evaluating workability. Such methods exist but further work is needed on standardisation. As SCC is acting as a liquid, no need for special treatment like tampering and vibrating is needed during the test procedure. This implies that the testing should be done on the bulk material, i.e. in the mixer, in the pump

etc. Such a development would eliminate sampling and allow a quality assurance that is not disturbing the process, allowing corrections before it is too late, and drastically saving time and need of personnel for testing. Ideally such a development should target measurement of rheological data.

12.11 Hardened concrete properties

The main focus for the work on SCC is naturally given by the fresh concrete properties but the material technology of course also warrants further studies and development on the properties in the hardened state. This requires studies of the microstructure, in particular on the structure of hydration product, interfacial transition zones and pore structure. The microstructural feature of SCC is showing more isotropy and denseness which leads to potential improvements in durability as well as strength. The deformation properties have to be better understood in order to limit the tendencies of increase of especially shrinkage. Studies of deformation properties are vital in the mapping of the property profile of any SCC material. Bond to reinforcement is, in most studies done so far, indicating better values for SCC and less distribution of the bond over the sections. The potential of SCC to give better surfaces has been shown in many applications but there is still not enough understanding of the involved parameters to consider this potential in design. The decisive parameters in materials design, formwork materials as well as processing technique will hopefully be clarified with accuracy in practice.

References

1. Self-Compacting Concrete (1999) Proceedings of the first international RILEM symposium, Stockholm 1999. Skarendahl Å, Petersson Ö (eds) RILEM proceedings 7, 1999, pp 790
2. Self-Compacting Concrete (2000) State-of-the-art report. Skarendahl Å, Petersson Ö (eds) RILEM report 23, 2000, pp 150
3. Self-Compacting Concrete (2001) Ozawa K, Ouchi M (eds) Proceedings of the second international symposium, Tokyo 2003, p 742

4. Self-Compacting Concrete (2003) Proceedings of the third international RILEM symposium, Reykjavik 2003. Wallevik O, Nielsson I (eds) RILEM proceedings PRO 33, 2003, pp 1030
5. SCC'2005-China (2005) 1st International symposium on design, performance and use of self-consolidating concrete, Changsa 2005. Yu Z, Shi C, Khayat KH, Xie Y (eds) RILEM proceedings PRO 42, 2005, pp 730
6. SCC 2005 (2005) Shah S (ed) The proceedings of the second North American conference on the design and use of SCC and the fourth international RILEM symposium on SCC, Chicago, 2005, pp 1270
7. EFNARC (2002) Specification and guidelines for self-compacting concrete. Feb. 2002, p 29. Free pdf copy downloadable from <http://www.efnarc.org>
8. BIBM, CEMBUREAU, EFCA, EFNARC, ERMCO (2005) The European guidelines for self-compacting concrete: specification-production and use. May 2005, p 62. Free pdf copy downloadable from each of the organisations homepages, e.g. <http://www.efnarc.org>
9. Casting of Self-Compacting Concrete (2006) State-of-the-art report. Skarendahl Å, Billberg P (eds) RILEM report 35, 2006, pp 41