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10.1 Significance of self-compacting concrete

In many aspects self-compacting concrete (SCC) (“self-consolidating concrete” in North America) can be considered the concrete of the future. SCC is a family of tailored concretes with special engineered properties in the fresh state. SCC flows into the formwork and around even complicated reinforcement arrangements under its own weight while remaining homogeneous. Thus SCC is not vibrated like conventional concrete. This drastically improves the working environment during construction and the productivity and potentially improves the homogeneity and quality of the concrete. In addition, SCC provides larger architectural freedom in structural design.

Highly flowable concretes have been used for many years for underwater concreting of unreinforced or lightly reinforced low-grade structural elements. The availability of new types of admixtures started the development of SCC in Japan in the 1980s. SCC is especially popular in Denmark; in 2015, 30% of the ready-mixed concrete produced in Denmark was SCC, followed by 5% in France, 4% in Japan and Norway, and 3% or less in the remaining countries participating in the survey [European Ready Mixed Concrete Association (ERMCO), 2016]. If including the consistency classes S-4 and S-5, Israel, Norway, and Spain are leading with above 90%, followed by Italy and Russia above 80%, Japan above 60%, and Denmark and Finland at 50% of the ready-mixed concrete production having consistency class S-4 or above [European Ready Mixed Concrete Association (ERMCO), 2016]. Reasons for the still limited use of SCC in many countries include lack of knowledge transfer and training, slightly higher material cost, and unclear distribution of responsibility for end quality between the concrete producer and contractor.

10.1.1 Productivity

The use of SCC reduced the construction time for the anchorages of the Akashi-Kaikyo Suspension Bridge, Japan, from 2.5 to 2 years. It is estimated that productivity in the building industry will be improved by 5%–10% by the successful use of SCC. For horizontal castings the estimated reduction in man hours is as large as 50% (Nielsen, 2007a).

10.1.2 Working environment

The working environment is improved through the reduction by more than half of the noise, from about 95 to 85 dB(A) at building sites and even more at precast plants. The most significant improvement of the working environment is achieved for vertical castings, where the ergonomics during casting and compaction of conventional concrete are extremely stressful (Nielsen, 2007c).

The present chapter describes the selected properties of SCC. The properties and use of SCC are illustrated through a few case histories, and future trends are briefly described. The chapter concludes with a list of sources of further information.

10.1.3 Definitions

For the purpose of this chapter, the definitions given by Day, Holton, Domone, and Bartos (2005) are applied, see Table 10.1.

10.2 Selected properties of self-compacting concrete

SCC is characterized by its ability to flow into the formwork and even around complicated reinforcement arrangements under its own weight and without segregating. Therefore the key engineering properties of fresh SCC are filling ability, passing ability, and segregation resistance, see Table 10.1. These key engineering properties are mainly controlled by the rheological properties of the concrete and geometrical constraints. Until the fluidity of the cast SCC is reduced, either due to thixotropic (Table 10.1) stiffening or hydration, the SCC will affect the formwork pressure and the air-void stability; thus, these issues are also discussed.

The composition of SCC varies much between countries, as illustrated by the variations in powder and water contents (Wallevik, 2003b), see Table 10.2. This is due to a combination of tradition and availability of resources. The differences in composition of SCC affect many of the engineering properties, such as strength, shrinkage, creep, and durability. The influence of the constituent materials on these engineering properties may be found in standard textbooks on concrete technology and concrete design.

10.2.1 Fresh SCC—a suspension and a composite material

In the fresh state, that is, before hydration takes place and reaction products are formed, concrete consists of a granular material (particles) embedded in a liquid (matrix), forming a wet granular material (suspension) with particle sizes ranging from the submicron scale to the centimeter scale.

The properties of the fresh SCC can, to a large extent, be explained by the volume fraction and properties of the granular material and the matrix, that is, by composite models. Depending on the scale at which the phenomena are explained and to what extent the interactions between the granular phase and possible

Table 10.1 List of definitions according to Day et al. (2005)

Term	Definition
Addition	Finely divided inorganic material used in concrete in order to improve certain properties or to achieve special properties
Admixture	Material added during the mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete
Binder	The combined cement and hydraulic addition
Consistence	A measure of the ease by which fresh concrete can be placed
Filling ability	The ability of concrete to flow into and fill completely all spaces within the formwork, under its own weight
Flowability	The flow of fresh concrete when not restricted by formwork and/or reinforcement
Mortar	The fraction of concrete paste plus those aggregates less than 4 mm
Paste	The fraction of concrete comprising powder, water, air, and admixtures where applicable
Passing ability	The ability of concrete to flow through tight openings such as spaces between steel reinforcing bars without segregating or blocking
Powder (fines)	Material of particle size smaller than 0.125 mm, it includes this size fraction in cement, additions, and aggregates
Robustness	The capacity of concrete to retain its fresh properties when small variations in the properties or quantities of the constituent materials occur
Segregation resistance (stability)	The ability of a concrete to remain homogeneous while in its fresh state; during transport and placing, that is, in dynamic conditions, and after placing, that is, in static conditions
Self-compacting concrete (Self-consolidating concrete) (SCC)	Concrete that is able to flow under its own weight and completely fill the formwork, while maintaining homogeneity even in the presence of congested reinforcement, and then consolidate without the need for vibrating compaction
Thixotropy	The property of a material (e.g., fresh concrete) to rapidly lose fluidity when allowed to rest undisturbed but to regain its fluidity when energy is applied
(Traditional) vibrated concrete	Concrete characterized by the need to be vibrated to achieve full compaction
Viscosity	The resistance to flow of a material once flow has started (an abbreviation of the term plastic viscosity)
VMA	Admixture added to fresh concrete to achieve cohesion and segregation resistance
Yield stress	The stress or force needed to initiate flow

VMA, Viscosity modifying admixture.

Source: Reproduced from Technical Report 62: Self-compacting Concrete: a Review. Published by The Concrete Society & available to purchase from The Concrete Bookshop (www.concretebookshop.com).

Table 10.2 Very rough estimation of compositions and rheological properties of self-compacting concrete in selected countries.

Country	Powder (kg/m ³)	Water (kg/m ³)	Paste volume ^a (L/m ³)	Yield value (Pa)	Plastic viscosity (Pa s)
Sweden	>550	180	363	0–30	50–100
The Netherlands	>550	190	373	0–10	60–120
Japan	>550	170	353	0–30	50–120
France	?	?	?	0–10	>60
Switzerland	<450	200	350	0–50	110–20
Norway	<450	170	320	10–50	30–45
Iceland	<450	180	330	10–50	20–40
Denmark	<450	160	310	30–60	<40
United Kingdom	>500	210	377	10–50	50–80
Germany	>500	180	347	0–10	60–90
United States	>500	190	357	0–20	40–120

^aCalculated by the book chapter authors assuming powder density 3000 kg/m³.
Source: After Wallevik, O. H. (2003). Rheology – A scientific approach to develop self-compacting concrete. In: 3rd int RILEM symp self-compacting Concrete. Reykjavik: RILEM (Wallevik 2003b).

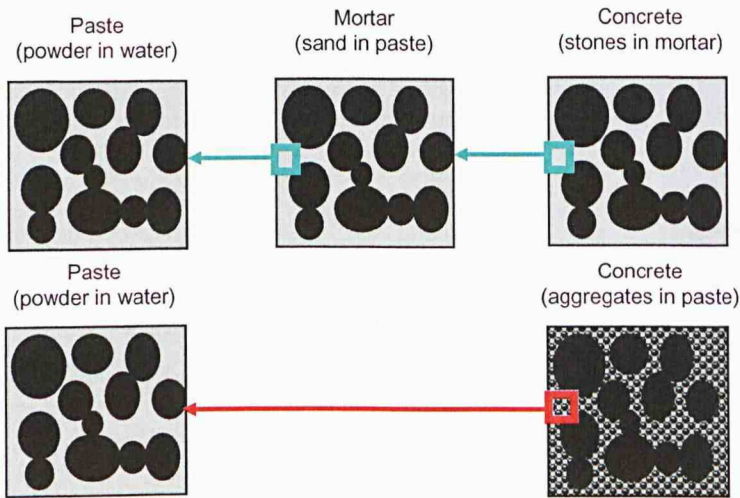


Figure 10.1 Sketch of fresh paste, mortar, and concrete as granular material (particles) in a liquid (matrix) forming a suspension. See Table 10.3 for all combinations.

particles in the matrix phase can be neglected, the matrix phase may be considered to be either the water, the paste or the mortar (Fig. 10.1 and Table 10.3). To simplify the models and the computations, the homogeneous phase (the matrix) should be considered to contain as large a portion of the suspension as possible.

Table 10.3 Granular material (particles) in a liquid (matrix) forming the suspensions: paste, mortar, and concrete.

Matrix	Paste	Mortar	Concrete
Water	Powder	Powder and sand	Powder, sand, and stones
Paste	—	Sand	Sand and stones
Mortar	—	—	Stones

10.2.2 Composite model—based proportioning methods

Composite model—based proportioning methods have been introduced, for example, the Particle Matrix Model (PMM) (Mørtzell, Smeplass, Hammer, & Maage, 1996) and the Solid Suspension Model (SSM) (de Larrard, 1999; Sedran & de Larrard, 1994; Sedran, De Larrard, & Angot, 1994).

The SSM relates rheology directly to the maximum packing fraction of all solids in full agreement with solid suspension theory, see for example, Eqs. (10.2)–(10.4). The compressible packing model (de Larrard, 1999; Sedran & de Larrard, 1994; Sedran et al., 1994) is used to determine the maximum aggregate packing and subsequently the aggregate fraction to obtain the required rheological properties. The paste is either considered having a constant solid fraction (de Larrard, 1999) or the solid fraction is determined by a simple fresh paste test (Sedran, 1999).

In PMM the volume fraction of filler modified paste including air voids is considered the suspending phase (matrix), and an empirical model relates the concrete rheology to the rheology of paste, the particle volume, and the void space (Eigen packing) of particles. The coarse aggregate fraction is composed using empirical Eigen packing data to minimize the void space. A matrix surplus (excess paste) of 30–60 L/m³ is required to facilitate flow. Lately, a microproportioning approach is being developed, where new ways of modeling the matrix rheology based on powder surface area are introduced to reduce the need for empiricism in proportioning with multiple powders (Cepuritis et al., 2017).

10.2.3 Filling ability and rheological properties

The flow characteristics of SCC—and other materials—can be described by rheology. Several rheological models have been proposed. Vibrated concretes and many SCCs flow according to the Bingham model, which contains two rheological parameters: yield stress and plastic viscosity:

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (10.1)$$

where τ and τ_0 are the stress and yield stress of the suspension, μ is the plastic viscosity, and $\dot{\gamma}$ is the shear rate. SCC may also exhibit shear thickening behavior according to the Herschel–Buckley model (de Larrard, Ferraris, & Sedran, 1998).

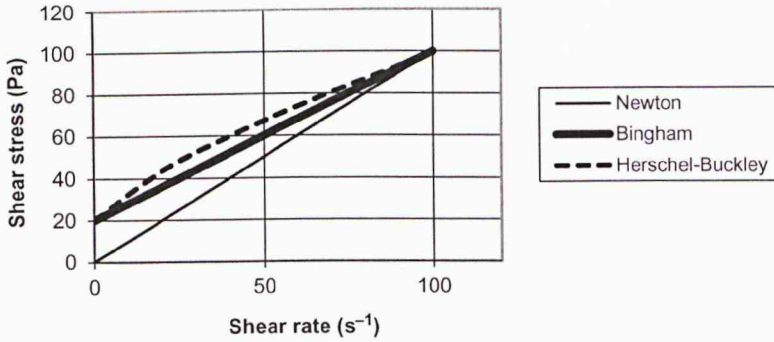


Figure 10.2 The Newton ($\tau = \eta \dot{\gamma}$), Bingham ($\tau = \tau_0 + \mu \dot{\gamma}$), and the Herschel–Buckley ($\tau = \tau_0 + A \dot{\gamma}^B$) models; parameters selected: $\eta = 1$; $\tau_0 = 20$, $\mu = 0.8$; $A = 2.5$; $B = 0.75$. Source: After Banfill, P. F. G. (2006). Rheology of fresh cement and concrete. *Rheology Reviews* 2006 (pp. 61–130). The British Society of Rheology (Banfill, 2006).

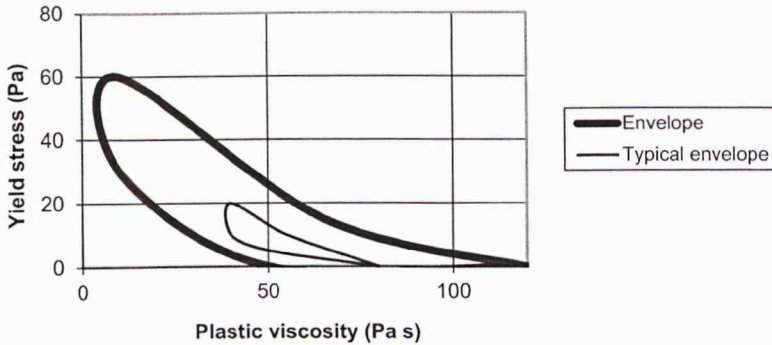


Figure 10.3 suggested approximate envelope of yield stress and plastic viscosity for SCC. Restricted flow is observed for concretes with high rheological properties, whereas segregation is observed for concretes with low rheological properties. SCC, Self-compacting concrete. Source: After Wallevik, O. H. (2002). Practical description of rheology of SCC. In: *SF day of the our world of concrete*. Singapore (Wallevik, 2002).

Sometimes an apparent Herschel–Buckley behavior may be explained by a lack of equilibrium during testing (Geiker, Brandl, Thrane, Bager, & Wallevik, 2002). The Bingham and the Herschel–Buckley models are together with the simplest rheological model—the Newtonian model—illustrated in Fig. 10.2.

For SCC to flow by its own weight, both the yield stress and the viscosity must be low; however, too low a viscosity causes instability. Typical rheological properties of SCC are yield stress: 0–60 Pa (~ 30 Pa) and viscosity: 20–120 Pa s (Table 10.2 and Fig. 10.3). It should be noted that the absolute values of the rheological parameters are sensitive to the measurement equipment (see for example, Ferraris et al., 2004).

The more solids a suspension contains, the less fluent but also the more stable it will be. A minimum amount of water is needed to obtain the flow of cement paste, approximately 50% by volume. Examples of volume fraction of solids, $\varphi_{w/c}$, varying w/c are $\varphi_{0.25} = 0.56$, $\varphi_{0.30} = 0.51$, $\varphi_{0.40} = 0.44$, $\varphi_{0.50} = 0.39$, $\varphi_{0.60} = 0.35$ (assumed density of cement 3150 kg/m^3). The effect of volume fraction and maximum volume fraction on viscosity is often described using the Krieger–Dougherty equation (Krieger & Dougherty, 1959):

$$\frac{\eta}{\eta_{\text{matrix}}} = \left(1 - \frac{\phi}{\phi_{\text{max}}}\right)^{-[\eta]\phi_{\text{max}}} \quad (10.2)$$

where η is the viscosity of the suspension, η_{matrix} is the viscosity of the suspending fluid, ϕ is the volume fraction of particles in the suspension, ϕ_{max} is the maximum volume fraction of particles in the suspension, and $[\eta]$ is the intrinsic viscosity of the matrix, which is 2.5 for spheres. The Krieger–Dougherty equation is based on the assumption of a Newtonian (i.e., without a yield stress) and homogeneous matrix. The more angular and elongated the particles are, the higher the viscosity (and yield stress) and less fluid the suspension will be (Geiker, Brandl, Thrane, & Nielsen, 2002).

A similar equation was proposed by Coussot et al. (Ildefonse, Allain, & Coussot, 1997) for the yield stress of a suspension, where noncolloidal forces act between the particles, and there is a gap between the suspended particles and possible particles in the matrix, that is, the matrix is considered homogeneous as in effective medium theory (Farris, 1968):

$$\frac{\tau_0}{\tau_{0,\text{matrix}}} = \left(1 - \frac{\phi}{\phi_{\text{max}}}\right)^{-m} \quad (10.3)$$

where τ_0 is the yield stress of the suspension, $\tau_{0,\text{matrix}}$ is the yield stress of the suspending fluid, ϕ is the volume fraction of particles in the suspension, ϕ_{max} is the maximum volume fraction of particles in the suspension, and m is a constant; $m = 1$ for $\phi < 0.6$ and a broad particle size distribution.

Tomosawa et al. proposed models for viscosity and yield stress of cement-based materials taking into account the grading of the aggregates (Oh, Noguchi, & Tomosawa, 1999). Other composite models for the effect of aggregates on the flow of concrete have been proposed (de Larrard, 1999). Taking into account interparticle forces that occur in superplasticized cement paste, Flatt (2004) found that the yield stress be calculated from

$$\tau_0 = m_1 \frac{(\phi - \phi_0)^2}{\phi_{\text{max}}(\phi_{\text{max}} - \phi)} \quad (10.4)$$

where m_1 is a function of the particle size distribution, and ϕ_0 is the percolation solid fraction.

The flow of paste containing colloidal (c. $<1\ \mu\text{m}$) particles is improved by breaking down agglomerates of the fine particles and stabilizing the deflocculated particles; this is done by mixing and addition of plasticizers. The effect of plasticizers and mixing intensity on the flow properties of colloidal suspensions was dealt with by Wallevik (2003a). Other models for the thixotropic behavior of concrete are also available (Roussel, 2006b).

The flowability—and the resistance to segregation—depends on hydrodynamics, interparticle forces, and the difference in gravity of the particles. The controlling effects vary, depending on particle size, particle concentration, and flow rate (Cousot & Ancey, 1999). Differences between flow of SCC with low content of coarse aggregate and conventional concretes may be explained by the viscous flow of SCC versus the possible presence of frictional forces in conventional concrete (Roussel, 2006a). The PMM (see Section 10.4.3) uses the terms matrix dominance and particle dominance for these two cases (Mørtzell et al., 1996).

Requirements for workability depend on form geometry, reinforcement density, and casting technique. Besides rheological measurements, several empirical methods are applied to characterize the filling ability of SCC; see Section 10.5 for further information.

10.2.4 Passing ability

An insufficient passing ability can be caused by poor filling ability or poor segregation resistance. However, even if requirements to filling and segregation are fulfilled, insufficient passing ability can be due to blocking of aggregates in narrow paths. Blocking develops easily when the size of aggregate is large relative to the size of the opening, if the aggregate content is high, and if the shape of the particles deviates from spherical, as is the case for crushed aggregate. Several empirical methods are applied to characterize the passing ability of SCC; see Section 10.5 for further sources of information.

10.2.5 Resistance to segregation

Segregation introduces heterogeneities and can significantly reduce the performance and service life of the concrete element. Segregation is caused by differences in gravity of the constituent materials and appears in fresh concrete as coarse aggregate settlement, paste separation, and bleeding. Coarse aggregate settlement may take place either during flow (dynamic segregation) or when stagnant (static segregation) and can be a main problem of SCC.

Comparing the physical phenomena that potentially lead to flow-induced particle migration in concrete, Spangenberg, Roussel, Hattel, Stang, et al. (2012) showed that gravity-induced particle migration dominates industrial casting of concrete, while in the case of pumping, shear-induced particle migration together with the wall effect dominates.

The gravity-induced sedimentation rate of a single particle, that is, the worst case, can be calculated from Stoke's law assuming unhindered settling in a Newtonian liquid. The larger the density differences between particle and matrix, the larger the particle and the lower the viscosity, the higher the sedimentation rate.

In line with this, Spangenberg, Roussel, Hattel, Vidal Sarmiento, et al. (2012) showed that gravity-induced migration during casting is mostly affecting the coarsest particles. Investigating beams cast with SCC, they observed two types of heterogeneities in the final concrete element: a decrease in the coarse aggregate with the horizontal distance from the casting point and a vertical multilayer structure. Based on both experimental and numerical results, they concluded that high casting rates reduce the magnitude of gravity-induced particle migration.

Studies of stability of paste and matrix of SCC have shown sedimentation behavior with the gradients of solid fraction and the absence of "classical" bleeding with a sharp front (Peng & Jacobsen, 2013; Peng, Jacobsen, De Weerd, & Pedersen, 2014; Pierre, Perrot, Picandet, & Guevel, 2015). Low permeability due to large amounts of well-dispersed particles and/or increased viscosity of the fluid due to the use of viscosity modifying admixture (VMA) could explain this.

The yield stress has been found to be a criterion for the coarse aggregate static stability of SCC (Roussel, 2006b; Ramge, Proske, & Kühne, 2010). For typical values of density and paste yield stress, a critical particle size for stability of approximately 16 mm can be calculated.

Focusing on the matrix properties, there are principally two different ways to increase the segregation resistance of SCC: either by introducing VMAs (see Table 10.1) (Khayat, 2012) or by adding fine particles.

Several empirical methods are applied to characterize the stability (segregation resistance) of SCC; see Section 10.5.

As part of the research and development work in the Concrete Innovation Centre, COIN, a study was conducted to compare laboratory methods for the characterization of segregation resistance to performance in a full-scale wall casting (10 m long, 0.2 m wide, and 0.6 m high) (Martius-Hammer, Kjellmark, Smeplass, & De Weerd, 2015). The segregation resistance of a stable and an unstable SCC was characterized with four methods (visual segregation index, rheological segregation, settlement column, and T-box, see Table 10.9). The main conclusions of this study were that the stability of the stable concrete was predicted with four of four laboratory methods, while the lack of segregation resistance of an unstable concrete was detected by three of four methods; the T-box test appeared less reliable. The results are encouraging in terms of valid methods for the performance testing of stability of SCC in full-scale applications (Martius-Hammer et al., 2015).

Although knowledge has been gained on the stability of SCC (see for example, Bethmont, Schwarzenruber, Stefani, & Leroy, 2003; Roussel, 2006b; Wallevik, 2003a) and the abovementioned references, the stability of SCC needs further attention in terms of recommendations for material composition and rheological parameters as well as test methods and acceptance criteria.

10.2.6 Formwork pressure

The high workability of SCC invites to high casting rates. However, casting walls at high rate may result in large formwork pressures. The formwork pressure is affected by the concrete properties, casting technique, and formwork characteristics. The most important factors are the concrete yield strength, casting rate, and height (Billberg, 2012; Khayat, Assaad, Mesbah, & Lessard, 2005). If concrete is pumped from the bottom of the formwork, the full height of the concrete will be in motion, and the pressure will be as high as the full hydrostatic pressure plus the pump pressure (Billberg, 2012). On the other hand, if not in motion, possible thixotropic properties of SCC can reduce the formwork pressure (Ovarlez & Roussel, 2006). A number of models for prediction of lateral formwork pressure when casting with SCC were summarized by Billberg (2012), who pointed out the need for verification by field data.

10.2.7 Air-void stability

Obtaining a stable air-void system in highly flowable concrete, such as SCC, is difficult. Possible incompatibilities between plasticizer and air entrainer and incompatibilities between admixtures and binders are known to cause air-void instability (e.g., Jacobsen, Ollendorff, Geiker, Tunstall, & Scherer, 2012). Recent experience with highly flowable fly ash concrete (Shpak, Turowski, Vimo, & Jacobsen, 2017) showed that combinations of copolymer-based superplasticizers and tenside-based air entraining admixtures seem to provide robustness against variations in powder and SP dosage.

Hydrostatic head in fresh concrete when casting walls at high rates may result in large pressures at the bottom of the form and subsequent compression of the air voids. Laboratory investigations suggest that the pressure-related changes of the air-void structure may be estimated directly in the air-void spacing calculation by reducing void volume by using Boyle–Mariotte’s law:

$$pV = \text{constant} \quad (10.5)$$

where p is the pressure and V is the volume. Full-scale wall castings revealed that factors other than the form pressure also influence the air-void structure, for example, the method of placement, where form filling from the bottom was found to reduce the content of larger pores, as shown in Fig. 10.4 (Jensen, Hasholt, & Geiker, 2005).

10.2.8 Pumpability

The pressure required to pump SCC is dominated by its viscosity (Feys, 2012). Most ready-mixed concrete is placed on site using pumping with high-capacity piston pumps. The probability of the blockage of pipes and hoses is increased if the tendency to segregation is high. This is explained by the “forward coarse aggregate

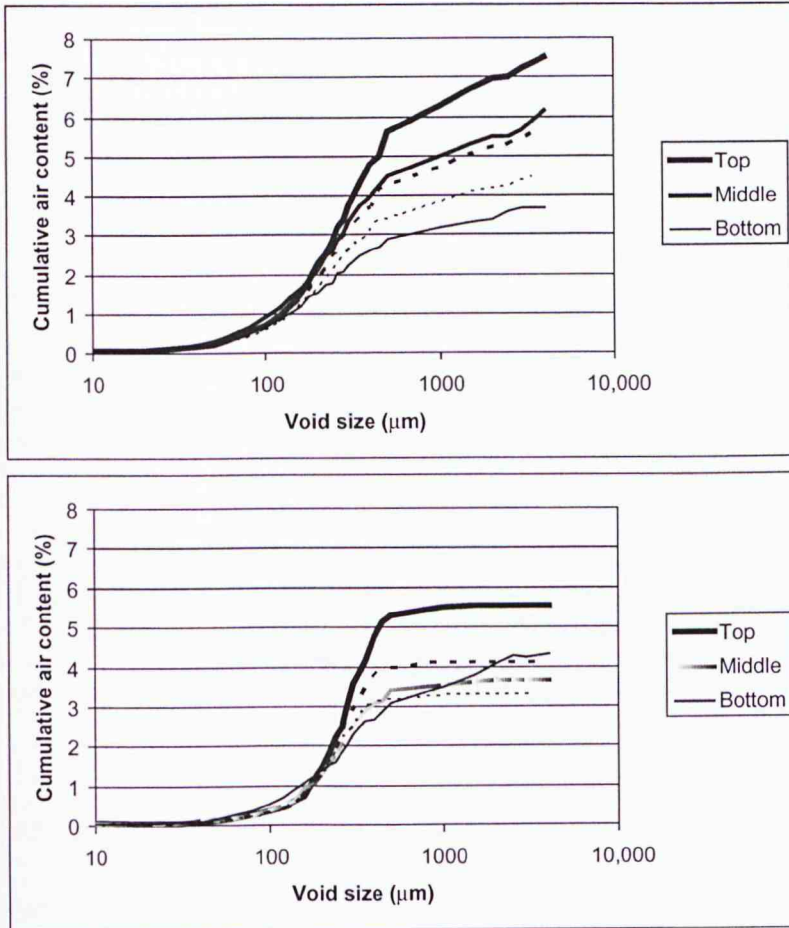


Figure 10.4 estimated (*dotted lines*) and measured air-void distribution according to EN 480-11 in full-scale wall casting (3.9 m high), cast with air-entrained SCC from a ready-mixed plant. Top: Concrete poured 0.5 m above surface. Bottom: Form filled from bottom. SCC, Self-compacting concrete.

Source: After Jensen, M. V., Hasholt, M. T., & Geiker, M. R. (2005). The effect of form pressure on the air void structure of SCC. In: 4th int RILEM symp self-compacting concrete. Chicago: Hanley Wood.

particle segregation” mechanism described in Kaplan, De Larrard, and Sedran (2005). Stability is therefore central to avoid problems in pumping. In addition, safe procedures for lubricating hoses and pipes before start of pumping are important. The lubrication of the hoses and pipes can be done with circulating water and then careful circulation of SCC back to the concrete drum before pumping at full capacity starts.

SCC flow through pipes and hoses can be predicted assuming plug flow lubricated by a thin layer of filler modified paste (Jacobsen, Vikan, & Haugan, 2010). The thickness of the layer that forms, presumably due to a combined wall- and shear-induced particle migration effect, was found to be 0.5–1 mm in several studies (Choi, 2012; Choi, Roussel, Kim, & Kim, 2013; Jacobsen et al., 2010; Kaplan, 2001).

10.3 Applications/case studies

A few case histories are presented here. The first case is the most recent and illustrates the successful use of self-compacting concrete to comply with requirements to aesthetics. The next two cases are demonstration projects and illustrate some of the challenges experienced in connection with both horizontal and vertical castings; the third case describes the use of SCC in concrete filled steel tubes (CFT). The use of SCC in vertical castings is still much less common than the use of SCC in horizontal castings, such as floors, and these cases were (among others) selected to support the use of SCC in vertical castings.

Information on economy and productivity is not dealt with here, and some information on this were given in the introduction. Other case histories can be found in (e.g., American Concrete Institute, 2007; Day et al., 2005) proceedings of the various international conferences on SCC.

10.3.1 *Case 1: Multipurpose sports facility at Uranienborg, Oslo, Norway, 2017–19*

Design and supervision of the construction were undertaken FUTHARK ARKITEKTER AS on behalf of the Undervisningsbygg Oslo KF, Oslo Kommune. The multipurpose sports facility provides $20 \times 32 \text{ m}^2$ for playing. The facility is placed underground between the local school and church on Nordahl Rolfsens Plass, Oslo.

Requirements to the aesthetical appearance of the concrete surfaces led to the use of self-compacting concrete with a high slump flow (700 mm) and low tolerances ($\pm 20 \text{ mm}$). Special attention by the concrete producer, NorBetong, to the development of a robust concrete composition and tight quality control and supervision by the contractor, Veidekke Entreprenør AS, led to a successful result.

The mix design for the concrete used for all exposed surface is given in Table 10.4. Among others, walls 9 m in height were cast in one go with a rate of 1.2 m/h. The inlet was gradually lifted during the casting to maintain a position below the upper surface of maximum 0.5 m. The surfaces achieved are illustrated in Fig. 10.5.

Table 10.4 Composition of the self-compacting concrete for casting of all visual concrete at the multipurpose sports facility at Uranienborg, Oslo. For comparison a traditional Norwegian concrete mix B45 according NS EN 206 is listed also (kg/m^3).

	Traditional B45	Mix design for Uranienborg
Low-alkali Portland cement CEM II/A-V 42.5N	382	359
Fly ash	0	105
Silica fume	12	14
Water	154	176
Air (BASF)	1.2	1.2
Superplasticizer (BASF)	3.1	4.1
Sand 0-8 mm (Svelvik)	923	965
Stones 8–16 mm (Gunnar Holt, Vormsund)	890	672

Source: Courtesy of Skjeggerud, M. 29 May 2018 (2018) (Skjeggerud, 2018).



Figure 10.5 Construction of multipurpose sports facility at Uranienborg, Oslo, Norway. Left: Newly cast walls. Mid: Columns and beams. Right: Achieved surface quality.

Source: Photographs courtesy of Frode Skåttun, Veidekke Entreprenør AS, Norway. Skåttun, F. 30 May 2018. RE: Personal communication.

10.3.2 Case 2: small bridge over new motorway at Give, Denmark, 2006–07

Design and supervision of the construction were undertaken by Gimsing & Madsen A/S on behalf of the Danish Road Directorate. The bridge is a two-span 63 m long post-tensioned concrete bridge. The bridge served as a demonstration project in connection with a 3.5 million USD R&D project exploiting the possibilities of SCC in Denmark.

The concrete specifications of Danish Road Directorate were adjusted with regard to control of fresh concrete properties and trial testing. The concrete

Table 10.5 Composition of the first trail mix and mixes for abutments and deck of small SCC bridge over new motorway at Give, Denmark, cast 2006–07. For comparison a traditional Danish concrete mix for extra aggressive environment is listed also (kg/m^3).

	Traditional E40	First trail mix	Abutment/ Columns	Bridge deck
Low-alkali sulfate resistant Portland cement CEM I 42.5N	406	360	—	—
Rapid hardening Portland cement CEM 52.5R	—	—	381	380
Fly ash	81	82	86	87
Silica fume	18	12	12	12
Water	169	152	176	166
Air CP 326 1:1	0.71	0.09	0.06	0.34
Conplast 212	3.5	—	2.88	3.4
Structuro A1510	—	—	4.56	5.7
Glenium sky 525	—	0.95	—	—
Sand 04 mm E	603	718	626	618
Stones 4–8 mm, E	302	290	277	274
Stones 8–16 mm E	668	691	697	700

Source: After Nielsen, C. V., Thrane, L. N., & Pade, C. (2007). *SCC demobro* [Online]. Taastrup, Denmark: Danish Technological Institute. Available from: <http://www.scc-konsortiet.dk/18794> [Accessed] (Nielsen, Thrane, & Pade, 2007).

contained three binders: rapid hardening Portland cement, fly ash, and silica fume (Table 10.5). Pretesting included full-scale trials of casting techniques and performance testing with regard to durability.

Challenges and outcomes are summarized in Table 10.6 and Fig. 10.6. According to Nielsen, Glavind, Gredsted, and Hansen (2007), SCC has great potential for use in foundations as well as vertical and highly reinforced structural elements, such as columns and abutments, but may not be optimal for structural elements, such as bridge decks, which have strict requirements for the finish of the slightly sloped upper surface.

10.3.3 Case 3: walls in basement, Danish Broadcasting Corporation, 2005–06

Design and supervision were undertaken by MT Højgaard A/S for the Danish Broadcasting Corporation. The case comprises five lightly (88 kg/m^3) reinforced concrete wall elements each 4 m high, 5 m long, and 0.5 m wide. Besides acting as walls in a basement, the wall elements served as a demonstration project in connection with a 3.5 million USD R&D project and experimental verification of numerical simulation of form filling in connection with Thrane's PhD project (Thrane, 2007a). The aim of the full-scale wall castings was to obtain experience on (1) the relationships between the fresh concrete workability, casting technique, and the form filling behavior; (2) form pressure; (3) surface finish; and (4) air-void

Table 10.6 Challenges and outcomes experienced in connection with the casting of a highway bridge in self-compacting concrete (SCC).

Challenge	Outcome
Robust composition of SCC	Sensitive to variations of constituent materials and external conditions as weather and casting stops (1 h transport time OK)
Long distance between concrete plant and construction site	The concrete was sensitive to rain during casting
Contradictive requirements to workability	One hour transport acceptable (max 30°C experienced)
A. Low flowability to allow for the establishment of slope	A. OK if slump flow 500–550 mm. Slope of 3% was established
B. High flowability to allow proper form filling	B. Partly OK (see finish of form surfaces)
C. High segregation resistance	C. OK, even with 10 m flow distance
D. Pumpability	D. Partly OK, change of cement type and admixtures during pretesting, see Table 12.5
Finish of upper surface of deck	Manual floating needed after leveling
Finish of form surfaces	Risk of visible spacers and imprints of formwork, see Fig. 12.5

Source: After Nielsen, C. V. (2007b). Danmarks første vejbro i selvkompakterende beton. In: *Spektakulære projekter (meeting)*. Copenhagen, Denmark: Danish Concrete Society (Nielsen, 2007b).



Figure 10.6 Small SCC bridge over motorway at Give, Denmark. Left: Casting and finishing of bridge deck. Mid and right: Examples of casting and improper compaction around spacers. SCC, Self-compacting concrete.

Source: Photographs courtesy of Left: SCC-Konsortiet, Denmark, Mid and right: Aalborg Portland Group.

structure and frost resistance (Section 10.2.6). Numerical modeling was used to study the flow patterns in order to provide a qualitative means of understanding flow-induced segregation and the development of surface air voids.

The testing was carried out using three different inlet positions and two different SCCs. The walls are referred to as V1–V5. During filling the inlet was either movable relative to the free surface, 0.50 m below or 0.50 m above, or fixed relative to the form, 0.20 m above the bottom (Fig. 10.7). Some information on the concretes are given in Table 10.7. The rheological properties of the concretes were

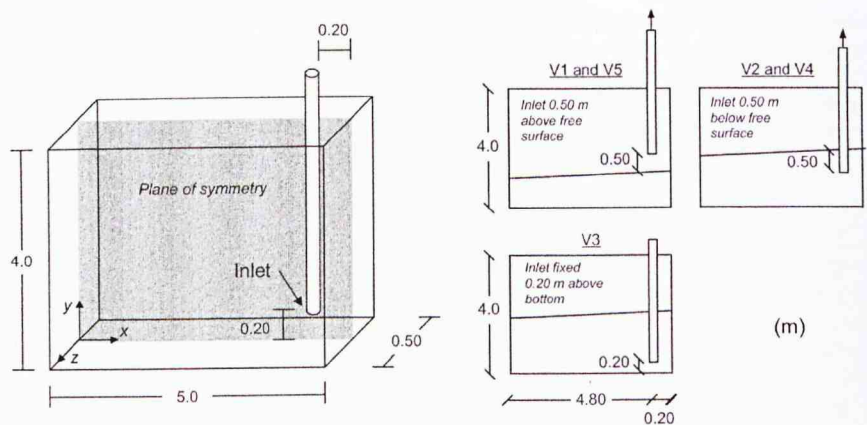


Figure 10.7 The formwork geometry of five full-scale walls (V1–V5) applying different filling methods. During casting of walls V2, V4 and V1, V5 the initial position of the inlet was 0.20 m and 0.50 m above the bottom, respectively, and the inlet was gradually lifted during the casting to maintain the shown position relative to the surface. Wall V3 was cast with an inlet fixed relative to the form, 0.20 m above the bottom (Thrane et al., 2007).

Table 10.7 Environmental class, target binder content and w/b, and measured rheological properties of the concretes used for the wall castings.

	Unit	Walls V1–V3	Walls V4 and V5
Environmental class		Extra aggressive	Moderate
Binder content	kg/m ³	439	327
w/b		0.33	0.49
Plastic viscosity	Pa s	60	35
Yield stress	Pa	20	60 and 45

Source: After Thrane, L. N. (2007b). *Formfyldning med SCC*, DR Byen, SCC-Konsortiet, delprojekt P33 [Online]. Taastrup, Denmark: Danish Technological Institute. Available: <http://www.scc-konsortiet.dk/18794> [Accessed] (Thrane, 2007b).

determined using a prototype of a measuring device (4C rheometer) (Thrane & Pade, 2005). Blocking was not observed during form filling and a complete form filling was obtained.

Form geometry and reinforcement configuration did not prevent high casting rates of up to 25 m/h. However, casting rates may have to be lowered due to finish and form pressure. Segregation was initiated when the concrete was forced sharply upward (against gravity). It was speculated that flow-induced segregation may be traced back to the combined effect of shear-induced particle migration and gravity-induced segregation due to differences in density. The concrete mix with higher yield stress was less prone to exhibit flow-induced segregation. Although not observed for the investigated concretes, increased plastic viscosity is also expected to improve the resistance to segregation. With respect to surface quality, high shear

Table 10.8 Requirements to the concrete to successfully implement the concrete filled steel tubes (CFT) technology.

Property	Requirement
Variability	Every batch must fulfill the requirements 100%
Flowability	Slump flow 650 ± 50 mm and t_{500} less than 8 s for 120 min (excluding pumping)
Stability	Not the smallest sign of separation
Pumpability	Pumpable up to 400 m in one go

Source: Courtesy of Danzinger, M. (2007).

rates at the form surface contributed positively in terms of reducing the number of air voids (Thrane, Stang, & Geiker, 2007).

As discussed in Section 10.2.6, a reduction in air content is to be expected in fresh concrete exposed to high form pressure. According to DS 2426, concrete exposed to a combination of salt and frost should have air-void content in hardened concrete larger than 3.5% and spacing factor smaller than 0.20. All tested samples fulfilled these requirements except three cores from the bottom of V1, where the total air-void content was 3.4%. All concretes showed satisfactory frost resistance according to SS 13 72 44 (Thrane, 2006).

10.3.4 Case 4: Mori Tower Roppongi Hills, completed in 2003

The introduction of self-compacting concrete initiated the development of construction methodologies, such as CFT, which stands for “concrete filled steel tubes.” SCC is poured into steel tubes, which form the frame of the building. The most important achievement of CFT is the saving of construction time due to the significantly improved speed of casting. According to Danzinger (2007), the concrete must fulfill the requirements summarized in Table 10.8 to successfully implement the CFT technology. For the actual job a 60 MPa concrete was cast into steel tubes of 2 m diameter and 120 m height. The concrete was made from a low-heat cement, 165 kg/m³ water and 1.55% (by weight of cement) polycarboxylate-based superplasticizer, and had a w/c at 0.32. This concrete had a slump flow of 68 cm, decreasing to 64 cm after 120 min; a T50 (time to 50 cm spread) at 5–7 seconds and 28-day compressive strength of 92 MPa (Danzinger, 2007).

10.4 Future trends

This section addresses the major challenges and opportunities of SCC: sustainability, robustness and compatibility of constituent materials, modeling of flow and virtual mix design.

10.4.1 Sustainability

A challenge for the entire concrete industry is to improve the sustainability of concrete structures. Sustainable development is defined by the World Business Council for Sustainable Development as “forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs” (www.wbcsd.ch). Considering concrete structures, their entire service life needs to be considered, and they should be made from renewable resources and cause low emissions of pollutants (e.g., CO₂) as well as low energy use during construction, operation and maintenance, and demolition. Some SCCs contain large amounts of powder (see Table 10.2, and Table 10.1 for definition of powder), and in some countries, the powder is mainly cement. As for other types of concrete, an expected future trend is to decrease the cement content in particular and powder content in general. Increasingly, packing programs for optimization of the aggregate grading and minimization of the paste content are becoming a tool supporting proportioning (see Section 10.2.2).

As mentioned in the introduction, SCC potentially improves the productivity, work environment, and the quality of the hardened concrete; all contributing to a sustainable development. SCC is therefore expected to be the concrete of the future.

10.4.2 Robustness and compatibility of constituent materials

Robustness, that is, the capacity of concrete to retain its fresh properties when small variations in the properties or quantities of the constituent materials occur, is central for the success of SCC. SCC is generally more sensitive to variations in content and properties of the constituent materials than conventional concretes. For instance, some concrete producers have experienced difficulties in controlling the moisture content of the aggregates sufficiently. It is anticipated that robustness of mixes will be facilitated both via improved procedures and mix design. Establishment of a so-called workability window during pretesting may assist in the selection of mixes that are less sensitive to variations in the content and properties of the constituent materials (Kordts & Breit, 2003). Concrete is primarily made from local materials, and there are limitations to possible mix compositions. Addition of filler such as limestone powder, clay and fines from aggregate crushing or addition of limited amounts of VMA improves the resistance to segregation (Section 10.2.4).

Only about half of the water needed to obtain sufficient workability is needed for the hydration of the cement. Unreacted water appears as pores that decrease both strength and durability. To limit the water content in SCC, superplasticizers are used. The performance of superplasticizers depends, among other things, on the cement chemistry and the mixing schedule. Superplasticizers may be intercalated (adsorbed) in the calcium aluminate phases and thus lost for dispersion purposes; also sulfate ions have been found to decrease the efficiency of some

polycarboxylates due to competitive adsorption (Flatt, 2012; Flatt, Martys, & Bergström, 2004). It is anticipated that improved knowledge on the compatibility of constituent materials will be developed and brought into practice.

10.4.3 Modeling of flow and virtual mix design

An overview of computational methods for modeling the flow of concrete can be found in Roussel, Geiker, Dufour, Thrane, and Szabo (2007) and Thrane (2012).

Numerical simulation of the flow of concrete has been a fast-growing research field, which has provided fundamental understanding of the flow behavior of fresh concrete during mixing, casting, and testing. For example, modeling single fluid flow, Thrane (2007a) explained insufficient surface finish by limited flow in the selected areas of a wall element, while Roussel, Staquet, Schwarzenruber, Le Roy, and Toutlemonde (2007) explained defective casting of a prechambered composite beam. Spangenberg, Roussel, Hattel, Stang, et al. (2012) combined computation of the global flow of composite and evolution of the local volume fraction of particles to explain the mechanism of coarse aggregate segregation during form filling. Finally, based on work by Skocek et al. (2011) and Svec, Skocek, Stang, Geiker, and Roussel (2012) the lattice Boltzmann method was used to predict flow-induced fiber orientation in concrete elements (e.g., Zirgulis, Svec, Geiker, Cwirzen, & Kanstad, 2016b). Examples of simulations can be found at <http://osv.dti.dk/webgl/>. The simulations illustrate, among others, the impact of reinforcement (none, one-way, or two-way) on the fresh concrete flow and fiber distribution during casting of a small slab. Simulations of the influence of reinforcement layout on fresh concrete flow and fiber distribution in steel fiber-reinforced self-compacting concrete were in (Zirgulis, Svec, Geiker, Cwirzen, & Kanstad, 2016a) compared to experimental observations; selected figures are reprinted as Figs. 10.8 and 10.9.

An objective of future research and development will be to further improve the basic understanding of the flow behavior of SCC and to enable large-scale prediction of form filling and possible particle orientation and segregation.

Another objective will be to improve the engineering tools used in concrete mix design, both to ensure filling ability and to prevent segregation in a given flow regime. The proportioning of SCC should ideally be based on target or recommended rheological properties. Moving from experience-based to mechanism-based proportioning facilitates mix design using a variety of binders and aggregates of robust SCC with tailored properties.

10.5 Sources of further information and advice

10.5.1 Guidelines

Several methods have been proposed to characterize filling ability, viscosity, passing ability, and segregation resistance of SCC (Table 10.9).

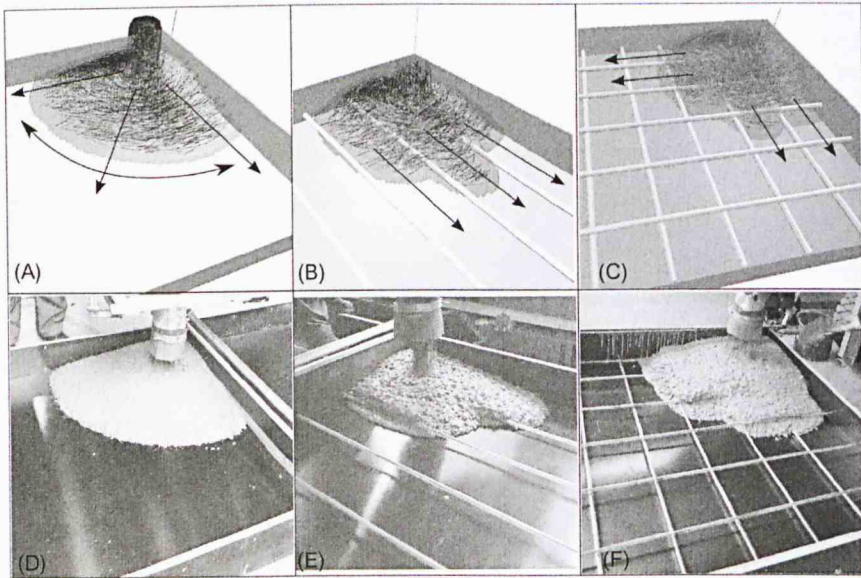


Figure 10.8 Influence of reinforcement bar layout on flow of steel fiber-reinforced self-compacting concrete during casting of slabs from left: without reinforcement, with unidirectional reinforcement, and with grid reinforcement. Snapshots from the simulated casting videos (A, B, C) and the actual casting videos (D, E, F). The *arrows* indicate the principal flow directions (Zirgulis, Svec, et al., 2016a).

European guidelines for self-compacting concrete were prepared in 2005 based on a review of best practice by five European organizations: BIBM, Cembureau, ERMCO, EFCA, and EFNARC (The European Precast Concrete Organisation BIBM, The European Cement Association (Cembureau), The European Ready-Mix Concrete Organisation (ERMCO), The European Federation Of Concrete Admixture Associations (EFCA) & The European Federation Of Specialist Construction Chemicals And Concrete Systems (EFNARC), 2005). The guidelines represented at the time of publication a state-of-the-art document addressed to specifiers, designers, purchasers, producers, and users who wish to enhance their expertise and use of SCC. American guidelines were prepared by the American Concrete Institute (2007). The guidelines are currently (2018) considered an “active standard” ASTM.

Early guidelines were, among others, prepared by the Japan Society of Civil Engineers (Omoto & Ozawa, 1999), the Norwegian Concrete Association (Norwegian Concrete Association, 2002), the Swedish Concrete Association (Swedish Concrete Association, 2002), and the Concrete Society United Kingdom (Day et al., 2005).

Also, international organizations such as RILEM (Bartos et al., 2002; Skarendahl & Billberg, 2006; Skarendahl & Petersson, 2000) have prepared state-of-the-art reports and recommendations. Special attention should be paid to the report of RILEM TC 188-CSC (Skarendahl & Billberg, 2006) and the parts of the report of ACI TC 237 and the European Guidelines that address the processes of construction (execution).

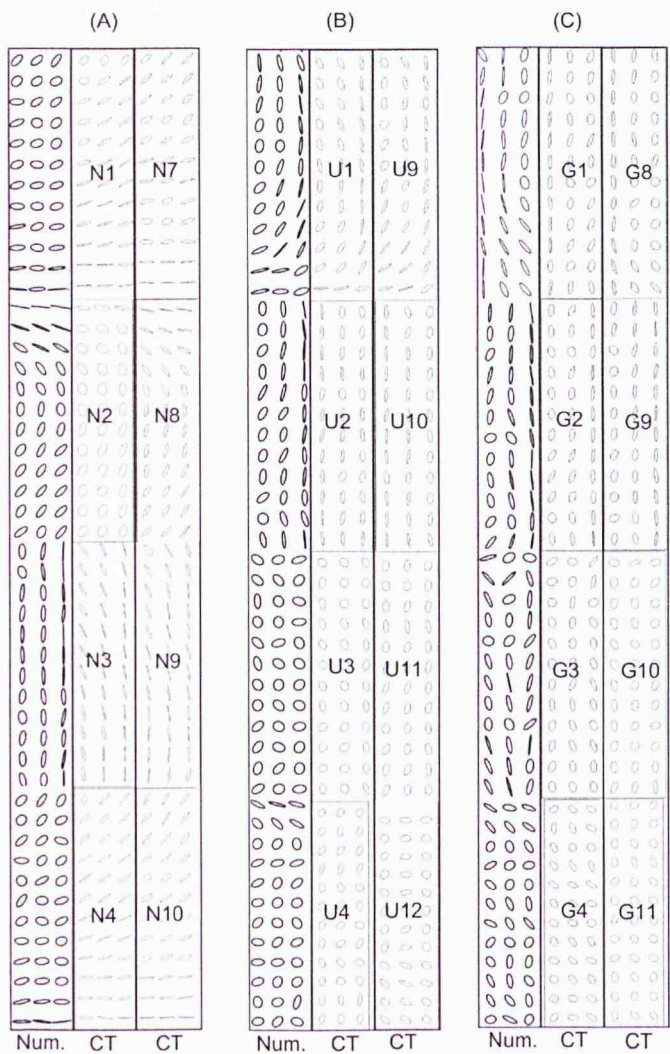


Figure 10.9 Simulated and experimental observations of steel fiber orientation in beams cut from slab cast from fiber-reinforced self-compacting concrete. Typical fiber orientation in bottom half of slab from numerical simulation (Num.) and CT scan for each pair of slabs: fiber orientation in (A) non-reinforced beams, (B) unidirectionally reinforced beams, and (C) beams with grid reinforcement (Zirgulis, Svec, et al., 2016a).

10.5.2 Standardization

SCC is covered by the European materials standard for concrete, EN 206:2013 including standards for testing, and the American Concrete Institute report ACI 237R-07 Self-consolidating concrete (considered “active standard” by ASTM) and ASTM standard test methods. Table 10.10 summarizes the present (2018) state of

Table 10.9 Selected methods for tests for self-compacting concrete.

Test	Property			
	Filling ability	Viscosity	Passing ability	Segregation resistance
Slump flow	Total spread	t_{500} time	—	(Paste rim)
J-ring	Total spread ^a	t_{500} time ^a	Stop height, total flow ^c	—
Kajima box	Flow time	—	Visual	—
V-funnel	—	Flow time ^b	(Blocking at orifice)	—
Orimet	—	Flow time ^b	(Blocking at orifice)	—
O-funnel	—	Flow time ^b	(Blocking at orifice)	—
L-box	—	—	Blocking ratio ^c	—
T-box ^d	—	—	passing ability ratio	Penetration depth after motion
Penetration	—	—	—	Depth
Sieve segregation	—	—	—	Percent passing 5 mm
Settlement column	—	—	—	Segregation ratio
Rheological segregation ^e	—	—	—	Segregation after impeller rotation in rheometer
Visual segregation index ^f	—	—	—	Visual assessment after slump flow test

^aIf OK passing ability.

^bIf no blocking at orifice.

^cIf OK filling ability.

^dEsmailkhanian et al. (2014).

^eCussigh and Bonard (2004).

^fLervik and De Weerd (2011).

Source: After Day, R., Holton, I., Domone, P., & Bartos, P. (2005). Self-compacting concrete – A review. In: *Technical report no. 62*, Surrey, UK, Concrete Society; and where mentioned Cussigh, P., & Bonnard, V. (2004). Testing-SCC. Summary report of WP 3.3 tests for resistance to segregation. In: Report DITC/VBo/Pha/2888/04/ G6RD-CT-2001-00580, E. U. G. C. N. (ed.). Nanterre, France CMT Construction; Esmailkhanian, B., Feys, D., Khayat, K. H., & Yahia, A. (2014). New test method to evaluate dynamic stability of self-consolidating concrete. *Materials Journal*, 111; Lervik, K., & De Weerd, K. (2011). Visual segregation index, memo. In: *COIN report*, SINTEF, Norway.

Table 10.10 American and European standards for self-compacting concrete (2018).

	Standardization body	
Test	ASTM	CEN
Sampling	C172	EN 12350-1
Slump flow	C1611/C1611M-14	EN 12350-8:2010
J-ring	C1621/C1621M-17	EN 12350-12:2010
V-funnel		EN 12350-9:2010
L-box		EN 12350-10:2010
Penetration	C1612/C1612M-17	
Sieve segregation		EN 12350-11:2010
Settlement column	C1610/C1610M-17	
Others than tests		
Definitions		EN 206:2013, 3.1.1.14
Others	ACI 237R-07	EN 206:2013 Informative annex F to EN 13670:2009

Table 10.11 Guidelines for consistence, viscosity, passing ability, segregation classes, and tolerances on target values when testing according to EN.

Consistence class	SF1	SF2	SF3	Tolerances on target values
Slump flow (mm) EN 12350-8:2010	550–650	660–750	760–850	± 40
Viscosity class	VS1/VF1	VS2/VF2		Tolerances on target values
t_{500} (s) EN 12350-9:2010	< 2.0	≥ 2.0		± 1
V-funnel (s) EN 12350-9:2010	< 9.0	9.0–25.0		± 3 if target < 9 ± 5 if target ≥ 9
Passing ability class	PL1/PJ1	PL2/PJ2		Tolerances on target values
L-box ratio EN 12350-10:2010	≥ 0.80 with 2 rebars	≥ 0.80 with 3 rebars		– 0.05 (Day et al., 2005)
J-ring blocking step (mm) EN 12350-12:2010	≤ 10 with 12 rebars	≤ 10 with 16 rebars		
Segregation class	SR1	SR2		Tolerances on target values
Segregation resistance (%) EN 12350-11:2010	≤ 20	≤ 15	–	

Source: After EN 206:2013 and where mentioned Day, R., Holton, I., Domone, P., & Bartos, P. (2005). Self-compacting concrete – A review. In: *Technical report no. 62*. Surrey, UK: Concrete Society.

standardization within the American and European standardization bodies, ASTM/ACI and CEN. EN 206:2013 states the European requirements for consistence (workability) in the form of consistence classes (Table 10.11). Proposed tolerances when using target values are also given in Table 10.11.

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