

Scientific and technical documents

RECOMMENDATIONS FOR THE USE OF SELF-COMPACTING CONCRETE

AFGC / PN B@P



FOREWORD

This document is based on AFGC document "SELF-COMPACTING CONCRETE - Interim Recommendations" (July 2000) and experience acquired during the French national project B@P, under the chairmanship of Yves Malier (Ecole française du Béton, a foundation to promote and support concrete research and innovation) and the technical direction of Michel Guérinet (Eiffage). The project has enabled us to answer the remaining unsolved questions and take self-compacting concrete (SCC) out of the laboratory and onto the worksite for the successful construction of high-quality buildings and civil engineering works.

Although most of the present applications are to be found in the field of building construction (see monograph drafted by B@P and published by CIMbéton), the revised text of Fascicule 65A is based on the draft version of these recommendations and now considers SCC to be on the same level as high performance concrete (HPC). The most important development is the introduction of SCC classes (depending on the application) which should make SCC more competitive on the ready-mixed concrete market (RMC).

This French approach has also been included in the project to extend standard EN 206 (EN 206-9) and, while the European project has not yet been published, its content appears to be sufficiently stabilised for these recommendations to be published without risking any major discordance.

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1. INTRODUCTION

In the absence of any reference documents on self-compacting concrete (SCC) at the present time, the aim of these recommendations is to provide a framework for exercising sufficient control over the use of this new type of material.

They are based on bibliographic data available both in France and internationally and on work conducted by the B@P project. They take into account the European standards currently being drafted.

They concern SCC products used in both building construction and civil engineering works for compressive strengths ranging from C25/30 to C90/105.

They cover cast-in-place concrete (made in RMC plants or in-situ) and precast structural components (except for chapter 8 for which specific requirements are indicated in these recommendations when necessary).

Certain fluid concretes, although usually cast without compaction, such as pile and diaphragm wall concretes, underwater concrete and self-compacting fill, are excluded from these recommendations.

2. DEFINITIONS

SCC (Self-compacting concrete)

Very fluid, homogeneous stable concrete cast without compaction (SCC is compacted by gravity alone).

I (Flowing gap)

Dimension (in mm) of the smallest space through which the concrete must flow to correctly fill the component to be concreted. The flowing gap I takes into account the geometry of the formwork, the reinforcement layouts and the different accesses of the concrete to a given point. Appendix 1 provides the elements required to determine the flowing gap.

SFB (Slump-flow range after batching)

Admissible range of slump-flow values after batching of SCC when it leaves the production unit.

SFD (Slump-flow range at delivery)

Admissible range of slump-flow values at the time of on-site delivery of SCC.

T_m (Workability retention time)

Period between batching and the end of placement during which a given SCC retains its workability.

3. STANDARDS

On the date of publication of these recommendations, a number of standards and regulations have not been updated to take the specific characteristics of SCC into account.

EN 206-1 is applicable with the additional information in paragraph 4.3 below concerning the characterisation of fresh concrete.

In the case of factory-precast products, the prefabricated products standards apply, with the additional information in paragraph 4.3.

For civil engineering works, Fascicule 65A published by the CCTG¹ includes the necessary additional information in a specific chapter in a revised version awaiting publication.

While waiting for the fresh concrete test methods in the EN 12350 and EN 12390 series to be updated, documentation booklet FDP18-457 deals with the specific properties of SCC.

The European recommendations published in May 2005 by EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems), BIBM (Bureau International du Béton Manufacturé - European trade association of the precast concrete industry), ERMCO (European Ready Mixed Concrete Organization) and EFCA (European Federation of Concrete Admixtures Association) were taken into account when drafting this document.

4. FRESH SCC SPECIFICATIONS

4.1 Classification of SCC

The main differences between SCC and conventional concrete are its fresh concrete properties and good capacity for casting, bonding and compaction by gravity alone.

SCC is divided into three categories (number 1 to 3) according to its field of use.

The classification depends on the flowing gap, the type of application (horizontal or vertical) and the thickness (in the case of horizontal application) according to the table below:

¹ General Specifications

		Horizontal application				Vertical application	
		Thickness ≤ 300 mm		Thickness > 300 mm			
	Maximum horizontal flow distance	Less than 5 m	From 5 m to 10 m	Less than 5 m	From 5 m to 10 m	Less than 5 m	From 5 m to 10 m
Flowing gap	I ≥ 100	①		②a	②b	②a	②b
	80 ≤ I < 100	②a	②b	②a	②b	②a	②b
	I < 80	③a	③b	③a	③b	③a	③b

Class 1 corresponds to SCC used for thin horizontal concreting (less than or equal to 300 mm), with a flowing gap of more than 100 mm (formerly called self-levelling concrete).

Class 2 mainly covers SCC used for thick horizontal applications (more than 300 mm) or standard vertical concreting. The flowing gap I is greater than or equal to 80 mm.

Class 3 is reserved for SCC for which the flowing gap I is less than 80 mm (narrow parts of structures or a very high reinforcement ratio).

Classes 2 and 3 also contain two sub-classes (2a, 2b and 3a, 3b) depending on the maximum horizontal flow of the SCC in the form (5 m for 2a and 3a, 10 m for 2b and 3b).

The contractor must define and justify the SCC class corresponding to the type of structure (or part of a structure) and the placement method used.

N.B. The use of SCC increases the possibility of obtaining high quality surfaces (uniform colours, for example). In the case of architectural concrete, like conventional vibrated concrete, it must be checked at the beginning of the operation that the properties of the concrete and the placement methods used correspond to the desired results.

4.2 Workability of SCC

The workability of SCC can be expressed by three main characteristics:

- flowability (determined by the slump-flow test),
- passing ability (determined by the L-box test),
- resistance to segregation (determined by the sieve segregation test).

The operating methods for these tests are given in appendices B, C and D. They are consistent with the European draft standards on the subject (EN 12350 - Parts 8, 10 and 11)².

4.3 Fresh SCC specifications

The properties required of cast-in-place concrete, depending on the class, are given below:

	Class 1	Class 2a	Class 2b	Class 3a	Class 3b
Maximum segregated portion ¹	20 %	20 %	15 %	15 %	10 %
Minimum L-box value	No special requirement	0.80 with 2 bars	0.80 with 2 bars	0.80 with 2 bars	0.80 with 2 bars

¹ Under no circumstances must the maximum authorised segregated portion be greater than 30%; it can be greater than the value given in the table if adequate proof of non-segregation for similar applications is available (see appendix E). There must be no sign of bleeding during the test.

The figures in the table correspond to the minimum and maximum values to be respected when qualifying the mix design. They must be respected throughout the workability retention time T_m .

In the case of precast components, for which finished product conformity controls are included in the product standards and, where applicable, the certification system, two options are possible to validate the mix design:

- the SCC meets the criteria in the above table,
- the criteria in the above table do not apply to the SCC; the absence of segregation (in the field of the SFB), is then verified by carrying out specific tests on the finished product (see appendix E).

The acceptance tests are mainly based on the slump-flow test.

The slump-flow range at delivery is defined after the qualification test (see chapter 6 below).

² Other standardised tests exist - the V-funnel (EN 12350-9) and J-ring (EN 12350-12 - but they are rarely used in France.

It can be based on a target value (and admissible variations) or by designating a slump-flow class according to the following table:

Class	Slump flow (mm)
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

In no case must the SCC show any visible sign of segregation or bleeding during the slump-flow test.

In the case of high lifts, special attention must be paid to the resistance of the concrete to bleeding which can interfere with the homogeneity of the concrete and the surface quality.

5. MIX DESIGN PRINCIPLES

Rational SCC mix design methods have been proposed in the technical literature, most of which are summed up in [1] and [2]; This chapter is mainly given over to the resulting special features of SCC mix design.

5.1 Minimum fresh SCC specifications

SCC mainly differs from other concretes in its properties when fresh.

First, SCC must be able to flow under its own weight, with sufficient speed of flow. In practice, this means high slump and fast flow speed. From a more scientific point of view, and considering that concrete is a Bingham³ fluid, this implies a low shear threshold and plastic viscosity. These rheological properties can be measured using a concrete rheometer such as the BTRHEOM-LCPC [3].

SCC must also be able to pass through confined areas (in formwork with dense reinforcement, through an orifice, etc.), without requiring compaction, and high slump alone is not a sufficient criterion. When a high-slump concrete encounters an obstacle, the aggregate shears the mortar (see figure 1) and the particles tend to clump together if the mortar does not have sufficient shear strength. Dome-like structures form which stick to the fines and prevent the concrete from flowing. SCC therefore needs to have good resistance to segregation when passing through a confined area.

³ Fluid for which the shear stress τ (Pa) is a linear function of the speed gradient $\dot{\gamma}$ (1/s):
 $\tau = \tau_0 + \mu \dot{\gamma}$ where τ_0 is the shear threshold and μ is the plastic viscosity.

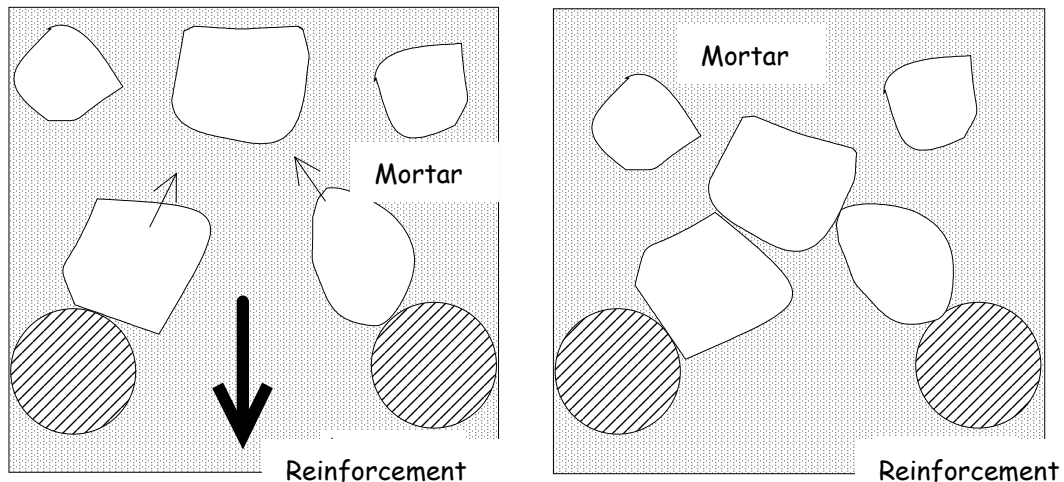


Figure 1: blocking of aggregate particles next to an obstacle

SCC must also have good resistance to static segregation (after placement) up until it sets, so that its mechanical properties will be homogeneous. Likewise, neither excessive settlement nor bleeding must occur as it can reduce the quality of bonding with reinforcements at the top of lifts compared with those at the bottom during pouring, and result in cracking.

Finally, it should be added that SCC is generally pumpable.

In conclusion, the main difficulty facing the SCC mix designer is how to reconcile seemingly contradictory properties: high slump and resistance to segregation and bleeding of the concrete.

5.2 Special features of self-compacting concrete mix design

High paste volume

Interparticulate friction limits the slump-flow and the filling ability of concrete. This is why SCC has a high volume of paste (cement + additions + admixtures + effective water + air), typically 330 to 400 l/m³, whose role is to keep the aggregate particles apart.

High fines content (<125μm)

To ensure sufficient workability while reducing the risk of segregation and bleeding, SCC has a higher fines content (in the order of 500 kg/m³) than that of conventional concrete. The fines come from the cement, additions and aggregate. However, to prevent an excessive rise in temperature during hydration, the binder often consists of two and even three parts: Portland cement mixed with flyash, blast-furnace slag, mineral filler (limestone), etc. The choice of additions and their respective proportion in SCC are designed to meet the 28-day compressive strength and durability requirements of the applicable standards (DTU 21, EN 206-1, precast product standards, etc.).

The use of superplasticizers

SCC contains superplasticizers to achieve the required fluidity. However, too much superplasticizer (close to or above the saturation dose [4]) can increase the sensitivity of the concrete to variations in water content which can cause segregation and bleeding. It is possible to combine the use of a plasticizer with a superplasticizer.

Optional viscosity-modifying admixtures

These are usually cellulose derivatives, polysaccharides and colloidal suspensions. Like fines, their role is to prevent bleeding and reduce the risk of aggregate segregation by making the paste thicker. Roughly speaking, the use of these products seems to be justified in the case of concrete with a high water/fines ratio because the fines are not always sufficient to hold the water in the concrete. They can be superfluous in the case of SCC with a low water/fines ratio (particularly when the compressive strength is greater than 50 MPa). For the intermediate concrete range, their usefulness will need to be studied on an individual basis. Viscosity-modifying admixtures are said to make SCC less sensitive to variations in water content, with consequences in terms of bleeding and segregation [5, 6]. However, in some cases, they can lead to batching problems (in the case of low dose rates), excessive air entrainment [7] and lower fluidity.

Low gravel content

It is possible to use crushed or rounded aggregate for SCC mixes.

However, since aggregate can cause blocking of concrete in confined areas, its volume should be kept to a minimum. On the other hand, the presence of aggregate increases the compaction of the granular composition of the concrete and thereby reduces the amount of binder needed to obtain the required level of workability and strength. In general, these considerations result in an aggregate/sand ratio of about 1 in SCC. Obviously, the ratio can be decreased or increased according to the confinement level (high or low reinforcement ratio).

Generally speaking, the maximum diameter of the aggregate, $D_{\max}$, in SCC is between 10 and 20 mm. The risk of blocking for a given confinement increases when $D_{\max}$ increases, which leads to a reduction in the aggregate volume. It is therefore possible to choose a higher $D_{\max}$ but only when there is little confinement.

A few important considerations

The entire range of conventional concrete strengths can be obtained with SCC by adapting the type of binder (cement, additions) and the water-binder ratio. The early strength can be affected when the concrete contains high proportions of additions, or has a high admixture content.

It is possible to produce and stabilise sufficient air in SCC using a conventional air entrainment agent to provide effective protection against freeze-thaw deterioration.

However, it seems essential to introduce the air entrainment agent before the concrete becomes completely fluid [8] (before adding all the superplasticizer, for example). Air entrainment and stabilisation seem to be more difficult, and even impossible, when the concrete inside the mixer is very fluid.

6. QUALIFICATION OF THE MIX DESIGN

When studying the mix design and conducting suitability tests, it is absolutely necessary to have a full grasp of the sensitivity of SCC to differences in composition, and particularly to variations in water content

It is only when it has been checked that the sensitivity is compatible with the manufacturing methods and equipment that the nominal mix can be validated using test specimens (compressive strength and other tests when necessary).

During the design stage, the resistance to segregation can be measured according to the water content, noting the slump flow and density (measured on concrete that has been neither vibrated nor rodded) and the results of the corresponding L-box tests. These results are then used to define an acceptable slump-flow range at delivery (SRD) and the corresponding water content range. The principle is as follows:

- the high-water-content mix design must be sufficiently stable;
- the low-water-content mix design must lead to a correct L-box result and not cause a reduction in density due to insufficient compaction by gravity.

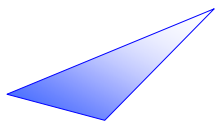
It must also be checked that the rheological properties are maintained during the required workability retention time (the slump-flow value must remain within the SFD up to T_m).

The influence of the temperature on the rheological properties of SCC can require adaptation of the admixture doses to changes in season and this could be evaluated during the design stage.

Practice shows that, like HPC, many SCC mixes do not tolerate the water variations of $\pm 10 \text{ l/m}^3$ mentioned in Fascicule 65A of the CCTG for conventional concrete. The permissible deviation is usually $\pm 5 \text{ l/m}^3$. However, the most robust mixes can be adjusted by the use of admixtures such as viscosity-modifying admixtures.

When carrying out suitability tests, which are essential for qualifying a given mix for a given mixing plant, it is recommended making at least three batches (with different water contents) in order to define the permissible slump-flow range (SFB and SFD) based on the results of the conformity checks carried out on the three concretes produced.

The instructions given in FD P18-457 for SCC are to be used to produce the test specimens, while awaiting revision of EN 12390-2.



7. PRODUCTION OF CONCRETE

7.1 General

Experience shows that SCC mixes are generally more sophisticated than those of conventional concrete and that special precautions and special inspections are required.

They include the control of ingredients, the concrete plant equipment and the manufacturing procedures, and complete the requirements of standard EN 206-1 for cast-in-place concrete and factory precast products.

7.2 Concrete plant equipment

For cast-in-place concrete, the requirements concerning concrete plant equipment and its utilisation are defined in paragraph 9.6.2 of standard EN 206-1. Additional specifications are given in chapter 2.2.3 of the certification guidelines (NF033) for the NF-BPE label for ready-mixed concrete.

In the case of factory precast products, the concrete plant equipment must enable the concrete and finished product specifications defined in the product standards to be satisfied, together with the certification guidelines where applicable (in which case the professional recommendations for concrete plants to be used for precast products designed for building contracts governed by Fascicule 65A will apply).

A concrete plant with the following minimum equipment is recommended for the manufacture of SCC:

- a mixer with a high shear rate,
- storage of aggregate out the rain and/or a reliable moisture content evaluation system for each aggregate size,
- a PLC for entirely automatic production control,
- a wattmeter or equivalent,
- moisture probes for sand.

7.3 Production procedures

In order to ensure the regular, reliable production of this type of product, monitoring and inspection procedures must be defined in the production site's quality documents, including the following:

- ingredient inspections,
- control of the water content of concrete, and particularly that of sand,
- the mixing sequence,
- inclusion of the transport time in the SFB definition,
- slump-flow inspection frequency during production.

When producing SCC, continuous inspection is necessary during the initial period (the first few days of production) by a laboratory technician trained in SCC and, if possible, throughout production (at least once a day at the beginning of production).

Since SCC is defined as being able to accept a change in water content of $\pm X$ litres per cubic meter (where X is between 5 and 10 litres/m³), it must be ensured that the procedures and equipment used enable these tolerances to be respected. This can be evaluated during the suitability test by producing three nominal batches and checking repeatability. Attention is drawn to the fact that a tolerance of ± 5 litres per cubic metre requires the use of specific procedures and equipment (a reliable indicator of consistency during mixing is essential).

The mixing sequence must be adapted so that the fresh concrete ingredients are correctly dispersed, without the presence of agglomerated fines.

It is recommended mixing the concrete using stationary equipment during the time required to obtain complete stabilisation of the wattmeter or set up a reliable procedure to measure the mixing efficiency. Whatever the case, the mixing time must not be less than 35 seconds for strengths less than or equal to 30 MPa and 55 seconds for other strengths. In the case of the on-site production of concrete that is not to be kept at least five minutes in a recipient that keeps the concrete moving (truck-mixer or receiving bin); the mixing time in a concrete plant must be at least 55 minutes [9].

During cold weather and when the effect of the temperature on the rheological properties has not been taken into account during the mix qualification stage, the rheological properties will need to be monitored for time T_m in order to ensure that the concrete remains within the slump-flow range initially specified (in order to guarantee that segregation will not take place). This operation can be carried out on the first batch of the day, for example.

7.4 Addition of admixtures on-site

The on-site addition of admixtures corresponds to the incorporation of all or some of the superplasticizer in the truck mixer on the work site. The primary concrete produced in the fixed concrete plant must obviously be especially designed to produce an SCC after the on-site addition of admixtures, and the process must be included when designing the mix. Industrial feasibility must be checked by means of a suitability test that includes the on-site admixture incorporation procedure, paying particular attention to the homogeneity of the concrete throughout the batch, and the absence of segregation.

The slump class for the primary concrete must be at least S3 (slump greater than or equal to 100 mm).

The final concrete is adapted on-site by the addition of a high-range water-reducing superplasticizer and a viscosity-modifying admixture if necessary. The other admixtures and additions are added in the concrete plant. In no case may water be

added (except for that of the admixtures). The quantities of admixtures actually incorporated (which must be determined by weighing or by volumetric measurement) must be written down in a tracking document. Concrete mixing with stationary equipment will be carried out according to paragraph 7.3. A truck mixer will be used for very high speed mixing (one minute per cubic metre) for a minimum of five minutes. The consistency will be checked for each batch before the incorporation of admixtures on-site, then after their incorporation and before placement of the concrete.

7.5 Transport

It is recommended using a truck mixer whose blades are periodically inspected.

The usual practices in terms of transport and delivery are to be respected. These include ensuring there is no water in the truck before loading, that the truck is clean, that it is kept rotating slowly to prevent segregation of the concrete, that the chute is adjusted so that the free-fall height is kept to a minimum, etc.

On arrival on the site (even in the case of on-site incorporation of admixtures), high speed mixing for at least one minute is carried out just before delivery.

Even if the properties of the concrete can change during transport, having to wait a certain time after its production in order to achieve conformity, particularly in terms of segregation resistance, is not acceptable. It is impossible to check that the concrete has been produced correctly if it segregates and, as a result, cannot be sampled correctly.

8. ON-SITE ACCEPTANCE OF CONCRETE

On-site acceptance of concrete involves checking that the concrete is suitable for placement without compaction and that it conforms to the nominal mix design.

The operation is essentially based on measuring the slump flow.

If self-compacting concrete is delivered to the site at the same time as conventional concrete, a procedure must be set up to distinguish between the two types of concrete.

The following acceptance procedure is recommended:

- sampling of a representative specimen of concrete (if the concrete is delivered by truck, it should be mixed at high speed for at least one minute),
- slump flow test using the traditional slump cone,
- checking that the results lies within the acceptance range (SFD).

It is recommended carrying out an acceptance test on at least the first batch of the day and systematically whenever there is any doubt.

9. CONCRETE PLACING

9.1 The different placement methods for SCC

During placement of the concrete in the forms, the free-fall heights and horizontal flow distance defined for the different SCC classes must be respected, unless it has been checked during previous tests that there is no segregation which could be harmful for the type of concreted component concerned.

It must also be ensured that there are no leakage points in the forms.

In the case of low viscosity SCC ($t_{500} < 2$ seconds), the maximum period of time between layers is in the order of 90 minutes [10]. For more viscous SCC and, in particular, when placing thin layers of concrete (less than 10 cm), this parameter must be backed up by a specific study (including any special concreting specifications).

Generally speaking, it is essential for the people in charge of placing the concrete to be trained in SCC concrete placement.

Accepted trade practice in the preparation of forms prior to conventional concrete placement also applies to SCC. It is essential to take particular care in preparing the substrate (watertightness), cleaning the forms (cable ties, debris), and so on.

For vertical applications, several SCC placement methods can be used, including the following:

Concrete skip with flexible pipe

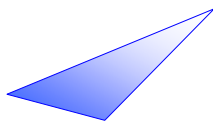
Placing self-compacting concrete by pouring it into the forms from above (even if a free-fall height of less than 5 m is respected) can give unsatisfactory results in terms of surface finish (blowholes).

SCC can be placed using a concrete skip with a flexible pipe, limiting the free-fall height of the concrete into the forms thanks to the possible reduction of the pipe diameter (80 to 100 mm maximum).

Skip with tremie pipe

A second method, similar to that used to concrete deep foundations, consists in inserting a tremie pipe into the concrete in order to avoid the fall of fresh concrete into the forms. This method has the advantage of systematically respecting all the placement precautions mentioned in the above paragraph. Keeping the pipe in the concrete during pouring prevents air entrainment during placement.

The diameter of the tremie pipe must be adjusted to suit both the geometry of the forms (height and thickness) and the density of the reinforcement (passages must be left for the pipes to go through). The diameter of the tremie pipe must obviously be



adapted to the maximum size of the aggregate used to make the SCC in order to limit the risk of plugging tube (usual pumping rules).

A funnel should be placed on top of the tremie pipe to make it easier to pour the concrete into the pipe.

Pump (with tremie pipe)

An alternative solution to the skip and tremie pipe is to use a pump which should optimise the concrete placement speed.

In principle, pumping is an appropriate placement method for SCC, since the mix design necessarily makes it pumpable. The attention of users is drawn to the possible change in fluidity of SCC when pumped.

Pump priming grout is not usually indispensable. The first 100 to 200 litres of SCC can be used to lubricate the circuit and returned to the truck mixer when possible to be blended with the rest of the concrete.

Pumping into the bottom of the form: pump with injection pipe

The last method consists in pumping the concrete in at the bottom of the forms via injection pipes located in the lower part of the formwork. This prevents the concrete from falling directly into the forms and reduces the number of site workers to the pump operator.

The concrete injection system at the bottom of the form must be designed to prevent the concrete from bouncing off the opposite side of the form (slope of injection pipe or use of a deflection plate inside the form opposite the pipe) and facilitate closing of the boxout at the end of placement (sliding hatch).

For horizontal applications, SCC can be placed by pouring it directly from the chute of the truck mixer or the concrete skip or by pumping. The surface finish is preferably achieved using a so-called "blowhole removal" bar.

9.2 Formwork

9.2.1 Preparation

Given the very fluid consistency of SCC, special attention must be paid to the watertightness of the formwork, particularly at the bottom, where spacers or special joints can be used for this purpose. However, thanks to the good cohesion of SCC, slight tightness defects (typically less than 2 mm) are tolerated and do not usually alter the surface finish.

Like vibrated concrete, when a good surface finish is required, special attention must be paid to the condition of the forms (i.e. they must be free of grease, grout and rust when metal forms are used).

It is also recommended using a high quality release oil in spray form to produce a uniform film with no drips. Any excess can be removed with a rag or scraper or any other appropriate means. Excess oil can result in blowholes and concrete build-up on the surface.

9.2.2 Resistance of the formwork to pressure from SCC

It is very important to dimension the formwork so it will resist the pressure generated by SCC during and after discharge of the concrete.

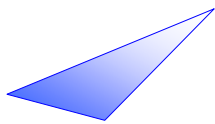
Certain SCCs have thixotropic properties when fresh which result in lower pressure than that of conventional concretes when discharged at the top of the formwork. At present, there are no recognised tests to quantify the thixotropic properties and evaluate their impact on the pressure exerted on formwork. Also, thixotropy depends on the temperature of the fresh concrete and can be altered by vibration transferred to the concrete after placement on-site (plant traffic, etc.). An indirect method to take thixotropy into account consists in measuring the tensile stress in the form rods, thus ensuring that the filling speed will leave enough time for the concrete to gelify in the lower part of the form.

It should be remembered that one of the undeniable advantages of SCC is that the discharge rate is higher, resulting in high form filling speeds that eliminate the possibility of benefiting from the thixotropic effects of SCC. A study conducted on the PN B@P experimental site in Guerville has shown that the pressure exerted by SCC on formwork is equal to the hydrostatic pressure (maximum pressure that can be exerted by concrete on a wall) when the concrete form filling speed is greater than or equal to 12 m/hr [11].

It is therefore highly recommended to dimension the forms to withstand the hydrostatic pressure unless a special study has been conducted in this respect.

It is essential to check that the forms, falsework and bracing will be able to withstand the pressure at the bottom of the formwork, that is, where it is highest. It is also important to use reinforced, watertight boxing and boxouts. Boxouts, sleeves and boxes must be suitably fixed so that they will not move when the SCC is being discharged.

In the case of concrete that is pumped or injected from the bottom, the local dynamic effects due to injection must be considered in addition to the pressure exerted by the concrete. The injection pipes must be sloped to prevent the concrete bouncing off the opposite side of the form.



9.3 Recommendations concerning the free-fall height and placement distance of SCC

When the concrete is dropped from the top, the free-fall height must be limited to **5 m** unless a special study is carried out. To optimise the surface finish, the free-fall height of SCC into the formwork must be kept to a minimum.

Generally speaking, the greater the horizontal flow distance, the more the concrete is likely to exhibit dynamic segregation. This is why, whatever the method used to place the fresh concrete, it is essential to limit the horizontal flow distance of SCC in the formwork to a maximum of 5 to 10 m on either side of the delivery point (depending on the SCC class). Since the admissible horizontal flow distance is related to the passing ability (reinforcement density, bends, boxouts, etc.), the SCC mix design chosen must take into consideration the parameters in the table in paragraph 4.3 of this document).

9.4 SCC finishing and curing

The absence of bleeding and the possible thixotropic stiffening of SCC can sometimes make the surface finish of concrete slabs problematic. SCC finishing in horizontal applications must always be carried out immediately after placement of the concrete. It is recommended using a float in order to obtain an acceptable finish on a horizontal surface.

The relatively large amount of paste (water + binder) in SCC compared to conventional concrete could make it more vulnerable to drying shrinkage, particularly as SCC is not very susceptible to bleeding. However, this tendency to lose moisture can differ considerably from one concrete mix to another, depending on the type of admixtures used as fines in the partial replacement and in addition to cement. Generally speaking, it is recommended that particular care should be taken in choosing the curing methods to be used after placement in order to prevent too much evaporation during the first hours of hardening. The rules defined for curing conventional concrete should therefore be strictly applied to SCC.

For horizontal applications, it is recommended curing immediately after concrete placement in order to prevent too much evaporation, which causes early cracking and loss of durability in concrete cover [12]. When a curing agent is used, it should be compatible with the subsequent addition of a sealing coat.

10. PROPERTIES OF HARDENED SCC

This section will mainly consider the instantaneous and delayed deformations of SCC, obtained by calculating the instantaneous modulus of elasticity, the shrinkage and creep, for which the specific features of SCC mixes seem to indicate different properties from those of conventional concretes.

The other properties (such as bond to reinforcement, tensile strength and durability) do not differ significantly from those of conventional concretes depending on their mix design.

10.1 Instantaneous and delayed deformation

The content by volume of aggregate in SCC mixes usually found in France is between 53% and 67%, while that of vibrated concrete is between 66% and 73%.

The deformation properties of concrete (modulus of elasticity, creep and shrinkage) depend on the properties of each phase and their content. Experimental and theoretical studies have shown that for the same set of ingredients and the same binder paste composition, deformation of the concrete increases when the volume of the paste increases [13]. The deformation of SCC should therefore be greater on average than that of vibrated concrete. The specialised literature shows that, although this increase in deformation exists, it is not as important as that predicted by the calculation models. First, the wide variety of mix designs and mineral admixtures used lead to a wide variety of behaviours. Second, experimental research has demonstrated the significant contribution of mineral admixtures, even when not pozzolanic, to the properties of hardened concrete [14], [15], [16]. Thus, the significantly higher mechanical properties than those of the class targeted can reduce deformability and compensate for the effect produced by the paste volume.

A detailed analysis of the instantaneous and delayed deformation properties of SCC is given in appendix F. Although it does not indicate any major change in behaviour, case-by-case tests are recommended for applications in which the corresponding properties need to be considered.

10.2 Durability

Durability is generally related to the mix design parameters in terms of compaction and the chemical nature of the binder (and the mineralogy of the aggregate for the alkali-aggregate reaction). The rules applicable to conventional concrete remain valid for self-compacting concrete (standard EN 206-1, Fascicule 65A of the CCTG, prefabricated products standards). Further details are given in appendix G.

10.3 Other properties

In principle, there is little difference between the ratio of the tensile strength to the compressive strength of SCC and that of conventional concrete [11]. However, when the tensile strength is of particular importance for a given application, it is recommended carrying out measurements during the mix design qualification tests.

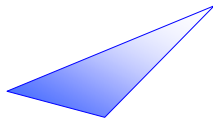
The bonding of SCC to reinforcements is similar to that of conventional concrete.

In certain configurations (upper layers of thick pieces), the better stability of SCC in terms of bleeding eliminates the defects of certain conventional concretes and can improve the quality of bonding [18].

The surfaces obtained with SCC are potentially better than those of conventional concrete, particularly with respect to defects caused by leaking forms and vibration. More uniform colours are possible. However, SCC can develop blowholes as a result of its resistance to segregation. To avoid this, placement methods should be optimised and high-slump mixes used while respecting the segregation resistance limits.

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APPENDIX A: DETERMINING THE FLOWING GAP

1. Definition

The flowing gap is the dimension (in mm) of the smallest space through which the concrete must flow to correctly fill the component to be concreted.

It is a characteristic magnitude of a part of a structure concreted in a single operation and is used to quantify the confinement that opposes the passing ability of concrete, according to the geometrical conditions, the various inserts involved (reinforcements, boxouts, prestressing, etc.) and the concrete placement methodology.

2. Determination method

The flowing gap I is determined according to the reinforcement and formwork drawings, taking any special construction requirements into account, e.g. the use of reinforcement connection systems, such as Stabox(R).

It must not be calculated on the basis of an occasional obstacle that the SCC can flow around (such as active reinforcement nodes) but by measuring the characteristic distance corresponding to a passive reinforcement grid (regularly spaced to form a screen to prevent the concrete from passing through). In particular, the concrete cover cannot be used to calculate the flowing gap since the SCC can surround the rebars without having to continuously flow between the reinforcements and the formwork.

3. Examples

- Concrete cast walls, 16 cm thick, 2 cm cover with two layers of dia 6 mm welded mesh (200 mm x 200 mm grid):

$$I = 160 - 2 \times 20 - 2 \times 6 = 108 \text{ mm (free space between two layers of welded mesh)}$$

- Bridge pier footing with HA32 steel 100 mm x 100 mm lower reinforcement mesh:

$$I = 100 - 32 = 68 \text{ mm (free space between reinforcements).}$$

- Base slab with HA20 steel 80 mm x 100 mm lower reinforcement mesh:

$$I = 80 - 20 = 60 \text{ mm (free space between reinforcements).}$$

APPENDIX B: SLUMP FLOW TEST

1. Aim

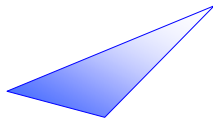
The slump-flow test is used to assess the flowability of self-compacting concrete.

2. Apparatus

- Baseplate topped with a flat metal plate (DIN type table) with an area of at least 900 mm x 900 mm (the deviation from flatness shall not exceed 3 mm), marked with two concentric circles: the first with a diameter of 210 mm $\pm$ 1 mm and the second with a diameter of 500 mm $\pm$ 1 mm (see figure 1)
- Cone (standard EN 12350-2) and weighted collar to prevent the cone lifting up during filling (the collar is used when the test is carried out by a single person). Instead of a weighted collar, the cone can have a flange at the bottom so that it can be kept against the baseplate by the operator's feet during filling.
- Rule at least 900 mm long.
- Spirit level

3. Procedure

- Check that the baseplate is on a stable, horizontal support.
- Moisten the surface of the baseplate (remove any surplus water with a rag).
- Place the cone in the centre of the 210 mm diameter circle on the baseplate.
- Place the weighted collar on the cone if necessary.
- Take a representative sample of concrete.
- Place a funnel on the top of the cone. Fill the cone, pouring continuously, until the concrete reaches the top of the cone.
- Remove the funnel, striking off with a trowel if necessary, and clean the baseplate with a wet rag if necessary.
- Raise the cone vertically using the two handles.
- Measure the time t_{500} between the moment at which the cone ceases to be in contact with the baseplate and the instant at which the concrete first reaches the 500 mm diameter circle.
- When the concrete has spread on the baseplate, measure the final diameter (d_m) and the perpendicular diameter (d_r) to within one millimetre.



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- Record the results of the two measurements. Example: "682/700 mm". If the two measurements differ by more than 50 mm, the test must be declared invalid and repeated.
- Express the final results as an average of the two values obtained, expressed to the nearest 10 mm:

$$SF = (d_m + d_r)/2$$

- The time t_{500} must be expressed to the nearest 0.5 seconds.

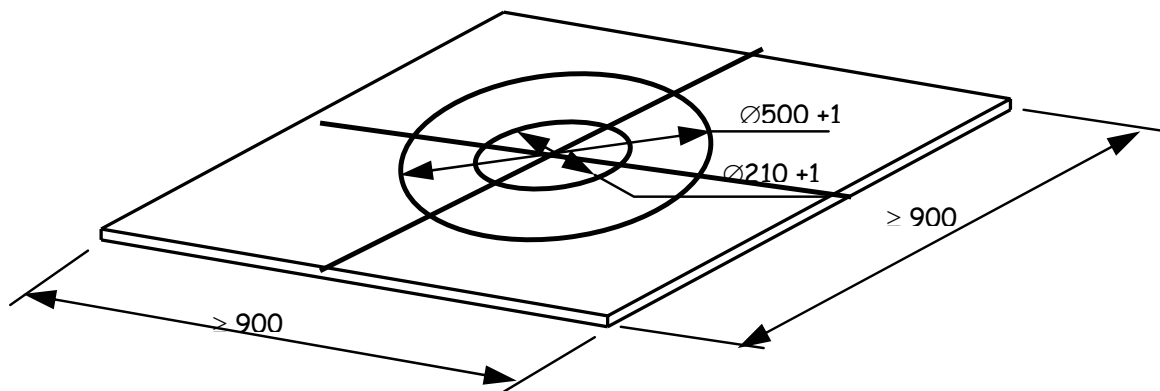
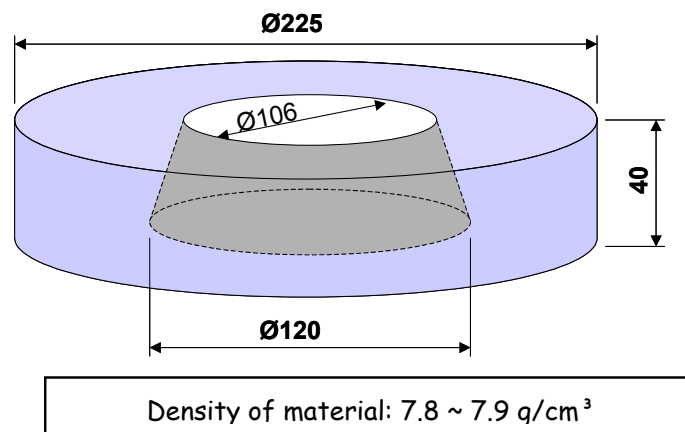
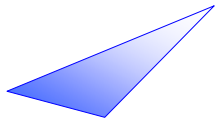


Figure 1: Slump test baseplate



N.B. all dimensions are ± 2 mm

Figure 2: Weighted collar



4. Precision

The repeatability r and reproducibility R have been determined by a programme including 8 laboratories, 16 operators and 2 repetitions and interpreted in accordance with ISO 5725: 1994.

Slump flow	< 600 mm	between 600 and 700 mm	> 700 mm
Repeatability r (mm)	/	42	22
Reproducibility R (mm)	/	43	28
Time t_{500}	< 3.5 s	between 3.5 and 6 s	> 6 s
Repeatability r (mm)	0.66	1.18	/
Reproducibility R (s)	0.68	1.18	/

APPENDIX C: L-BOX TEST

1. Aim

The L-box is used to assess the passing ability of the concrete in confined spaces and to check that placement of the concrete is not blocked by any obstructions. Two variations exist: the 2-bar test and the 3-bar test (the latter simulates more congested reinforcement).

2. Apparatus

A detailed drawing of the L-box is given in figure 1.

3. Procedure

The principle of the L-box test is described in figure 2.

The box is placed on a horizontal base and the inside surface is moistened.

The vertical part of the box is entirely filled with concrete (the volume required is approximately 13 litres). After any excess has been struck off, the concrete is left to stand for one minute.

The gate is then raised so that the concrete can flow into the horizontal part of the box through the reinforcements. The clearance between the bars is 41 mm in the 3-bar test which corresponds to civil engineering works with very congested reinforcement (typically 100 to 350 kg/m³ with clearance of at least 60 mm between bars). For less congested structures (building applications in particular), the reinforcement grid could be lightened by placing only two bars with a clearance of 59 mm between bars (see figure 3).

When the concrete stops flowing, heights H1 and H2 are measured (see figure 2) and the result is given as the passing ability $PA = \frac{H2}{H1}$, expressed to within 0.05. H1 is measured on the gate site, i.e. inside the vertical part of the box, see figure 1).

When the concrete does not flow through the reinforcement easily and the aggregate piles up behind the grid, there is usually a problem of blocking or segregation.

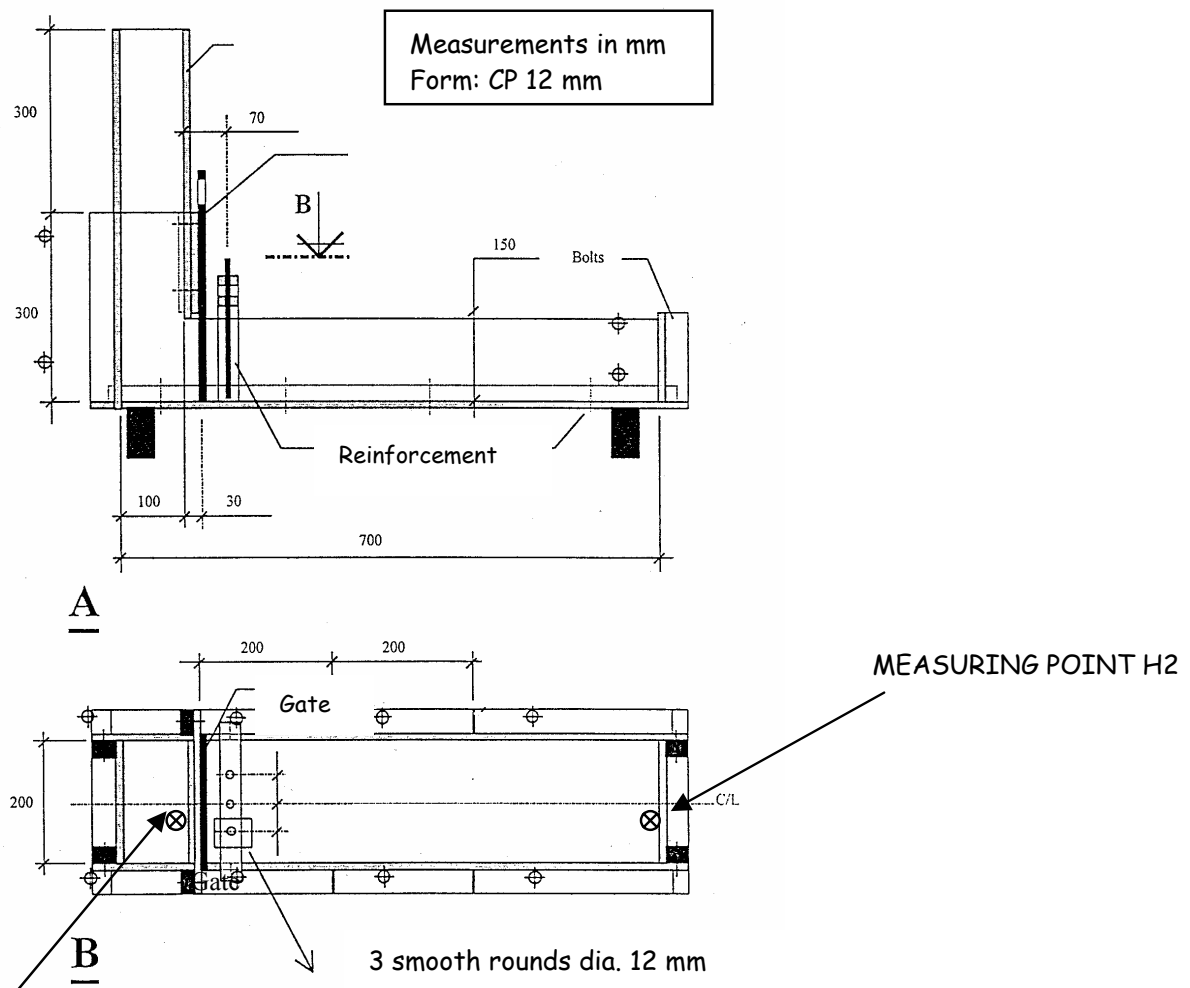


Figure 1

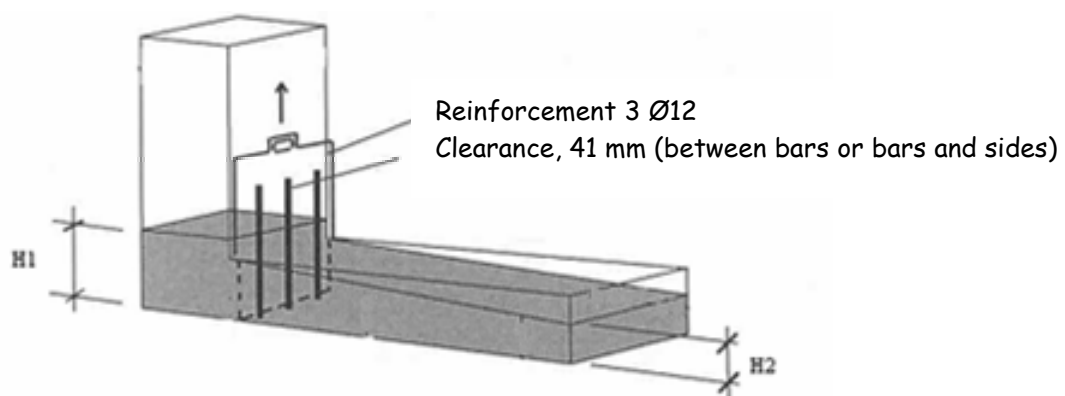


Figure 2

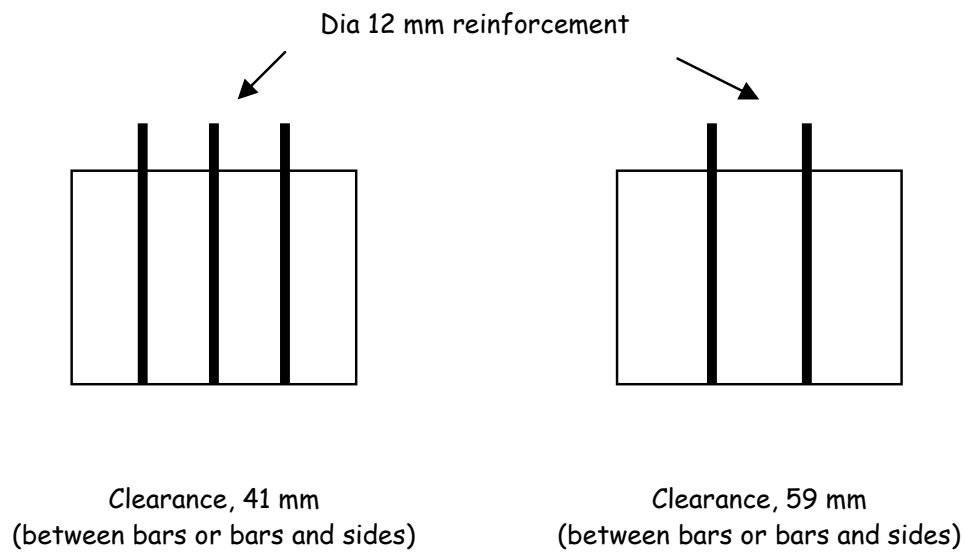


Figure 3

4. Precision

The repeatability r and reproducibility R have been determined by a programme including 11 laboratories, 22 operators and 2 repetitions and interpreted in accordance with ISO 5725: 1994.

The r and R results for the 3-bar test are given in the following table:

Passing ability - PA	≥ 0.8	< 0.8
Repeatability r	0.11	0.13
Reproducibility R	0.12	0.16

APPENDIX D: SIEVE SEGREGATION TEST

1. Aim of test

This test is used to assess the resistance of self-compacting concrete to segregation. It can be used when studying the mix design of self-compacting concrete in the laboratory, or to check resistance of the concrete to segregation on the work site.

It completes the tests used to assess the passing ability of the concrete, whether in a confined space or not, by determining the resistance to segregation.

2. Apparatus

- 10-litre bucket with an inside diameter of 240 mm (more or less 30 mm).
- Sieve with a 5 mm square aperture (perforated plate sieve as per EN 933-2) plus pan.
- Scales with a minimum capacity of 20 kg and minimum precision of 20 g.

3. Procedure

- Sampling:

in the laboratory:

mix and pour 10 litres of concrete directly into the bucket.

Time between the end of mixing and sampling < 30 s.

on-site, SCC delivered in a mixer truck:

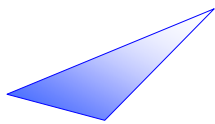
mix at high speed for 1 minute

fill the bucket with 10 litres of concrete directly from the truck chute

on-site with a concrete plant, placement by skip:

sample 10 litres of concrete from the top of the skip, using a cylindrical scoop to fill the bucket

- Cover the bucket to stop the concrete drying
- Leave for 15 minutes.
- Weigh the pan and the empty sieve
- Weigh the pan only
- Place the sieve + pan on the scales
- Tare the scales
- Observe and record the presence of any bleedwater on the surface of the bucket after 15 minutes.
- Pour $4.8 \text{ kg} \pm 0.2 \text{ kg}$ of concrete onto the sieve



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- Pour in the middle of the sieve - free-fall height of 50 cm $\pm$ 5 cm
- Note the actual mass of concrete on the sieve
- Leave for 2 minutes.
- Remove the sieve and the pan
- Reset
- Weigh the pan with the laitance. $P_{\text{laitance}} = P_{\text{pan + laitance}} - P_{\text{pan}}$
- Calculate the segregated portion with respect to the weight of the sample to within one percent:

$$SR = \frac{P_{\text{laitance}} \times 100}{P_{\text{sample}}}$$

- Note the presence of any bleeding.

4. Precision

The repeatability r and reproducibility R have been determined by a programme including 11 laboratories, 22 operators and 2 repetitions and interpreted in accordance with ISO 5725: 1994.

The r and R results are given in the following table:

Percentage of laitance SR%	≤ 20	> 20
Repeatability r	3.7	10.9
Reproducibility R	3.7	10.9

APPENDIX E: VERIFICATION OF IN-SITU HOMOGENEITY OF SCC

This method is inspired by that described in T. Sedran's doctoral thesis and is based on an assessment of how far below the surface the aggregate sinks.

Concrete test specimens are taken by core boring or sawing in order to obtain surfaces that are perpendicular to the surface of the concrete.

A line, called the counting line, is drawn on the test specimens at a distance d from the surface (see table below). The length of the counting line depends on the size of the aggregate (D_{max}).

Segregation is considered to be absent if there are at least N aggregate particles on the counting line whose dimension is greater than or equal to a critical value that is a function of (D_{max}) (see table below, 4th column).

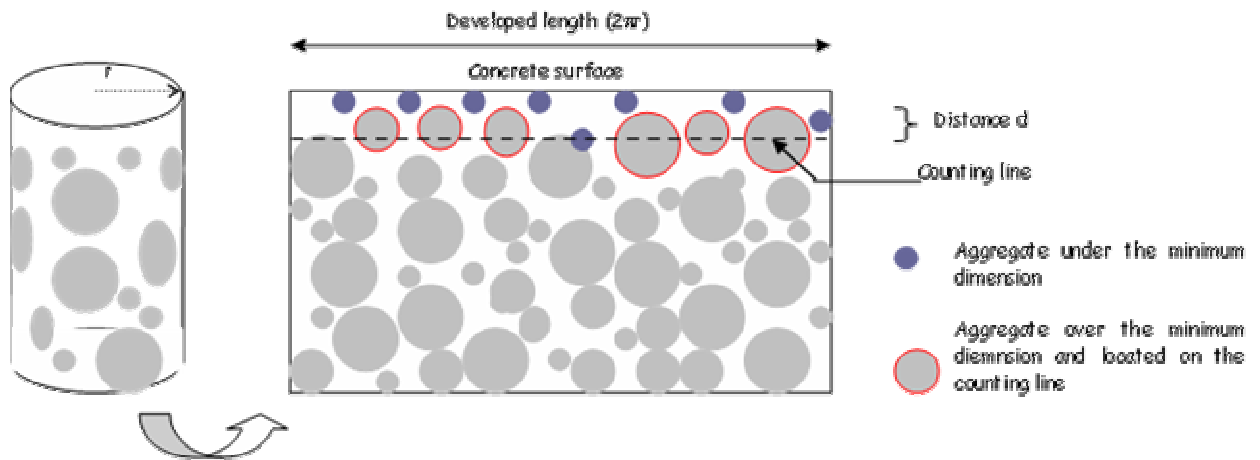
D_{max} (mm)	Length (L_c) of counting line (mm)	Distance d between the counting line and the surface (mm)	Minimum dimension of aggregate particles used for counting (mm)	Absence of segregation if the number of aggregate particles on the counting line is $\geq$
10	$600 \leq L_c^* \leq 800$	5	5	10
12	$600 \leq L_c \leq 800$	6	6	9
16	$600 \leq L_c \leq 800$	8	8	7
20	$600 \leq L_c^{**} \leq 800$	10	10	5
22	$750 \leq L_c \leq 1000$	10	11	5
31	$900 \leq L_c \leq 1200$	10	16	5

* i.e. for example, 4 core samples with a diameter of 50 mm for a D_{max} of 10 mm

** i.e. for example, 3 core samples with a diameter of 80 mm for a D_{max} of 20 mm



Recommendations for use of Self-Compacting Concrete



APPENDIX F: INSTANTANEOUS AND DELAYED DEFORMATION OF SCC

This section considers the conditions for applying European standards EN 1992-1 and EN 1992-2, known as EC2, for forecasting SCC properties, i.e. the elastic modulus, the shrinkage and creep.

1. Instantaneous modulus of elasticity

A study conducted within the scope of PN@BAP concerned the variation in concrete properties according to the paste concentration [LOU 06]. The experimental modulus results for this study (see figure 1) show an increase in the instantaneous deformation with the paste concentration, in other words, an increase in the modulus of elasticity with the aggregate concentration. When all the data are taken into consideration (see figure 2) [LOU 06, TUR 05, PON 02, STA 05, LER 96, SED 00, CUS 05, DEH 05], the variation in the modulus of elasticity as a function of the volume of the concrete matrix is partly compensated by the variations in the other parameters (particularly the type of aggregate and the compressive strength), which reduces the possibility of correcting the regulatory equation by a function of the aggregate concentration.

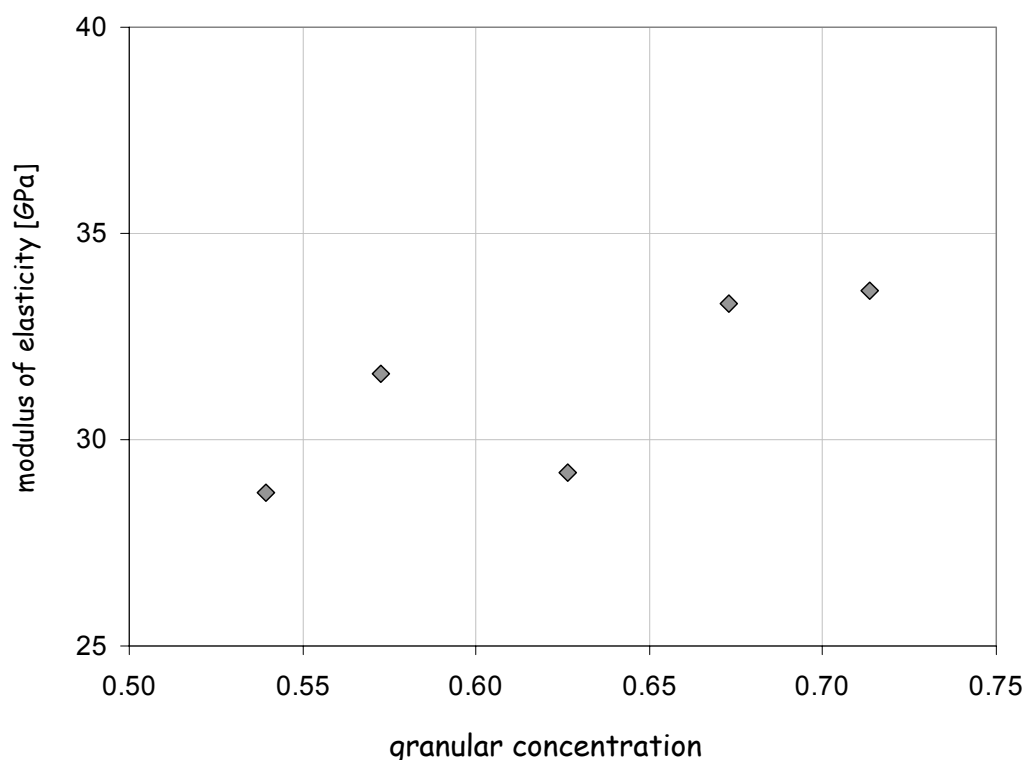


Figure 1: Experimental results for the same set of ingredients and the same cement paste mix design [LOU 06]

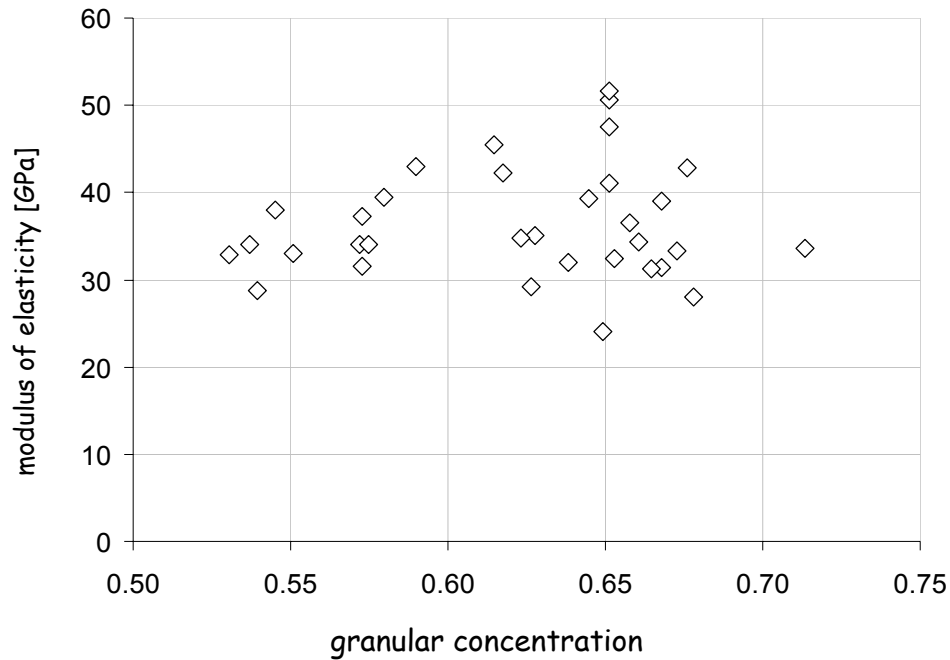


Figure 2: Experimental results obtained for all the data

EC2 proposes an approximate calculation of the average instantaneous secant modulus in [GPa] as a function of the average strength in [MPa], according to the following empirical equation:

$$E_{cm} = 22 \left(\frac{f_{cm}}{10} \right)^{0,3}$$

According to EC2, this equation applies to quartz aggregate; the modulus must be increased by 20% for basalt aggregate and decreased by 10% for limestone aggregate and 30% for clay aggregate. As a result, depending on the type of aggregate, the theoretical modulus of concrete can vary considerably (between 21 and 37 GPa for concrete with an average strength of 30 MPa, for example).

It should be noted that, for an average strength of more than 30 MPa, if the equation given by EC2 ($f_{ck} = f_{cm} - 8$ [MPa]) is applied to calculate the mean strength from the characteristic strength, the basic EC2 equation predicts a modulus which is less than that given by the BPEL law, particularly when the strength is high. If the set of data used in [LER 96c] is considered, it can be seen in figure 3 that the EC2 law considerably underestimates the modulus of vibrated concrete in widespread use in France⁴. Linear regression gives a line slope of 0.84. This, however, has no meaning, since the correlation coefficient is very low ($r = 0.3$).

⁴ This underestimation may be due to the higher average value of the modulus of elasticity of the aggregate or the use of formulation methods based on granular optimisation.

The application of EC2 to SCC is given in figure 4. The precision is better for vibrated concrete. The law overestimates the lowest moduli but its precision improves for higher moduli (but there are fewer data). The linear regression of points in figure 4 gives a line slope of 1.04 ($r = 0.55$). If only the points corresponding to moduli greater than or equal to 30 GPa are considered, the line slope goes down to 1.016, which is close to the bisector. Overestimation of the EC2 law is therefore more perceptible for concrete with a lower modulus (less than 30 GPa).

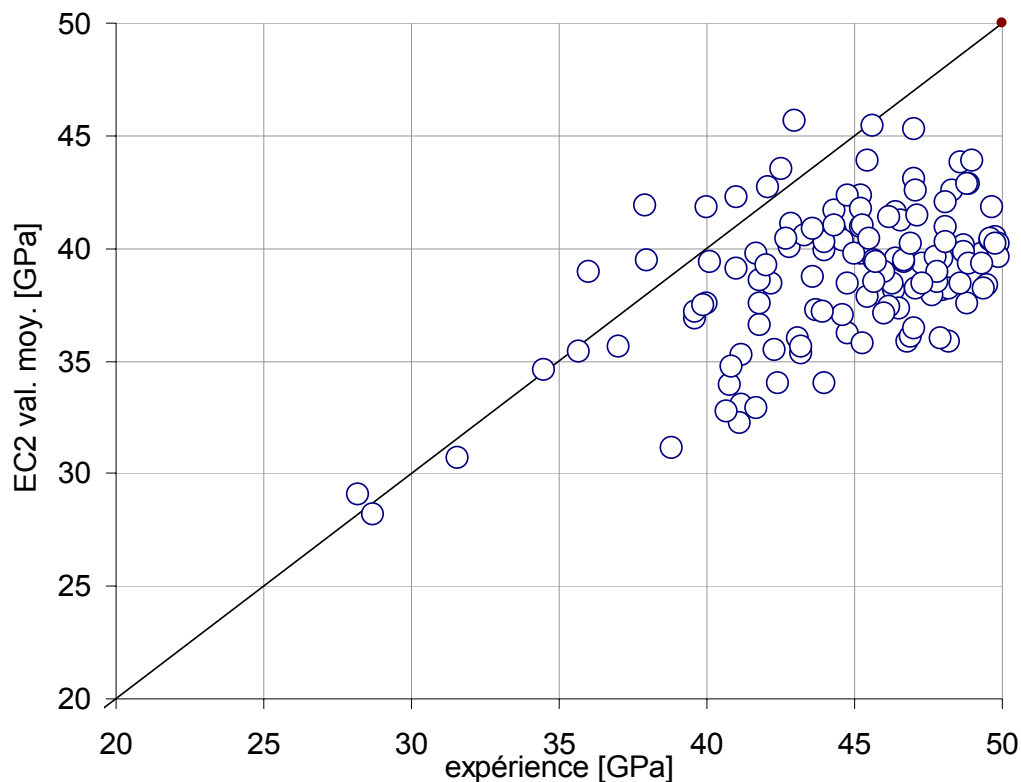


Figure 3: Comparison between the experimental results of vibrated concrete and the predictions of the modulus of elasticity given by EC2. Experimental points from [LER 96c].

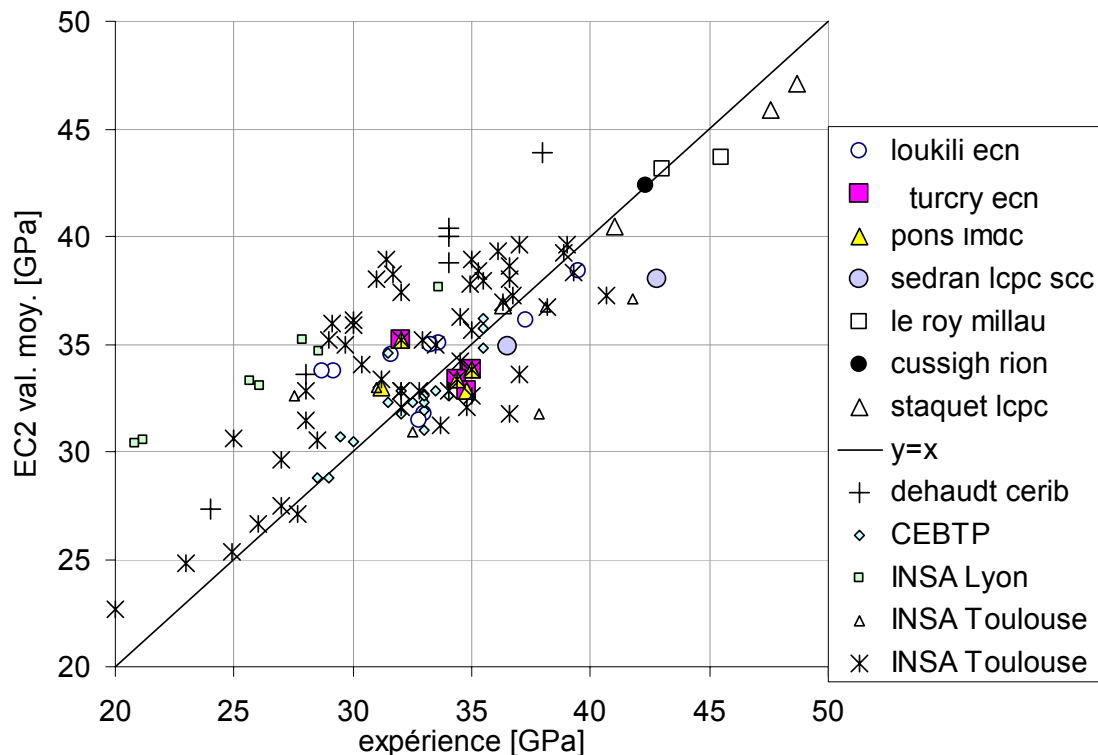


Figure 4: Comparison between the experimental results of SCC and the predictions of the modulus of elasticity given by EC2.

In conclusion, the modulus of elasticity of SCC is lower on average than that of vibrated concrete. No absolute figure can be given, but the regressions, however imprecise they may be, suggest an average difference of 24%. This difference improves the level of precision of the EN 1992-1 equation for predicting the modulus of elasticity of SCC (in comparison with that of conventional concrete). The use of the EC2 equation can therefore be accepted in standard cases. However, if a structure is sensitive to variations in the modulus of elasticity, measurements must be performed as soon as the concrete mix design has been decided upon or, failing that, simulations using physical models [DEL 00, LER 96a]. The precision will be improved by adjusting the parameters of the model according to the modulus of elasticity of concrete made with aggregate of the same origin as that of the project.

2. Shrinkage

2.1 Comparison of regulation models

To calculate shrinkage, EC2 proposes a model in EN 1992-1 (common rules applied to all buildings) and another in EN 1992-2 which specifically concerns high performance concrete (rules applied to bridges). The EN 1992-2 model is the French BPEL model applied to high performance concrete [LER 96c].

The two models make a distinction between autogeneous shrinkage and drying shrinkage with total shrinkage being the sum of these two components. Changes in the final magnitude of the total shrinkage as a function of the compressive strength are illustrated in figure 5. EN 1992-1 proposes 3 shrinkage values according to the choice of cement strength development class, i.e. classes S, N or R (S: slow, N: normal, R: rapid). The magnitude increases when the cement goes from class S to N, then from N to R. We included classes N and R in the simulations, as the shrinkage values for class S cements were considered to be too low. Upper and lower limits can thus be obtained for the total shrinkage. The EN 1992-2 predictions are higher than the upper limit of the standard model up to an average strength of 70 MPa. Above that, the predictions of the HPC model lie between the 2 limiting values of the standard model.

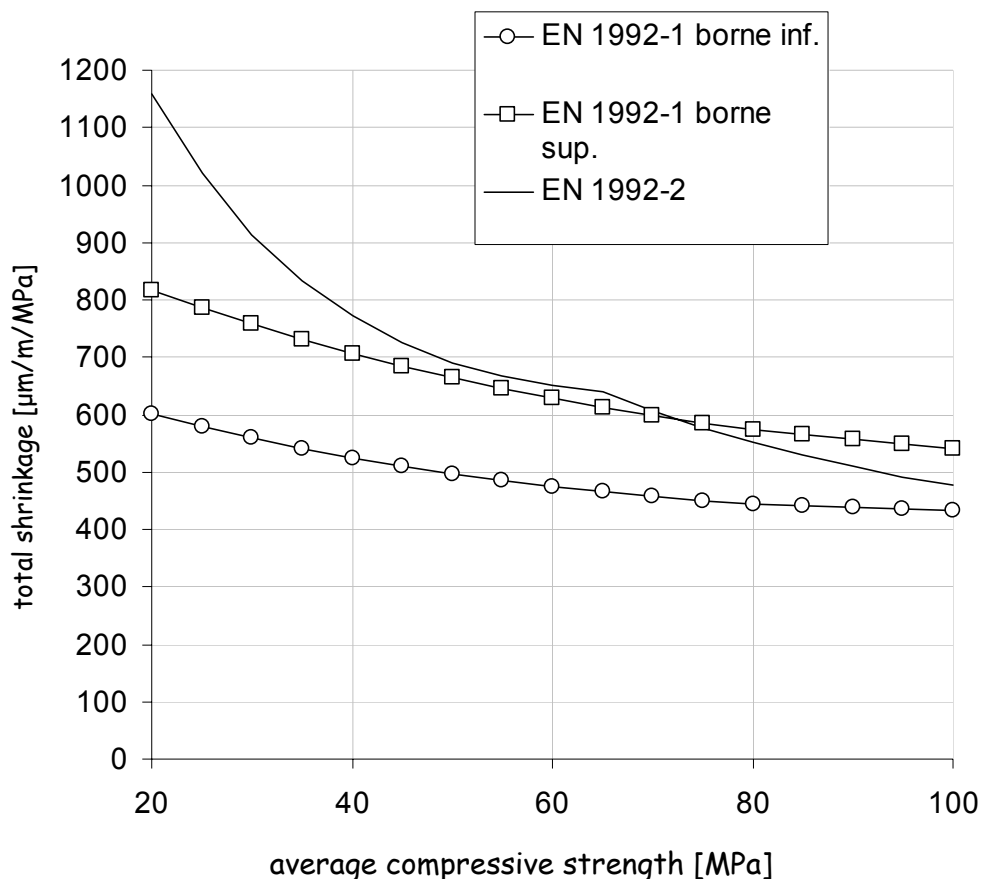


Figure 5: Theoretical evolution according to long term total shrinkage models as a function of the strength for a relative outside humidity of 50% and an average radius of 80 mm.

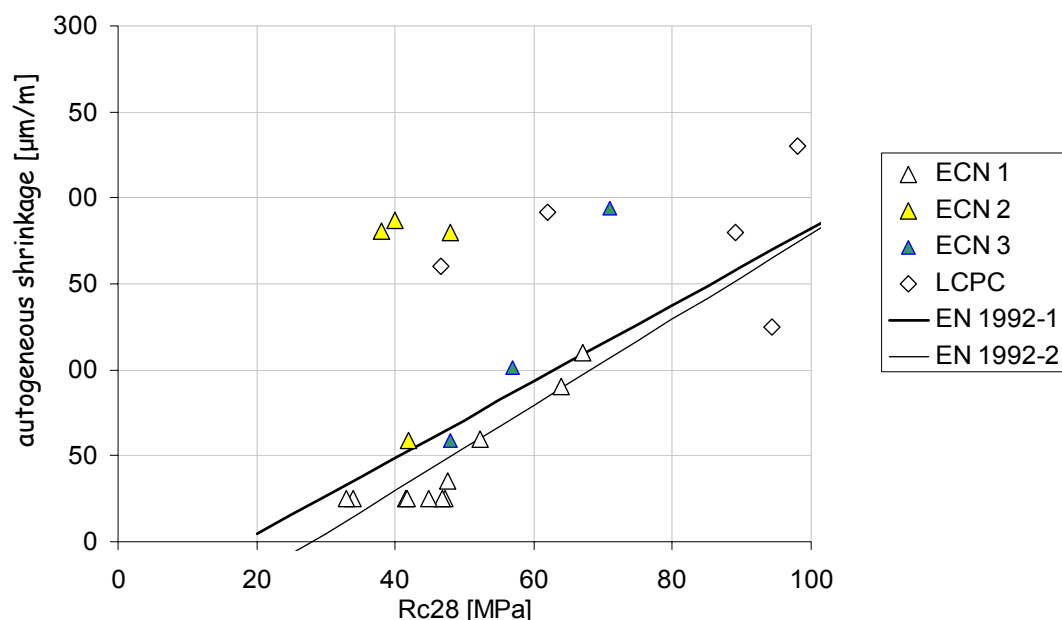
2.2 Autogeneous shrinkage

It is known that the autogeneous shrinkage increases with the strength of the concrete [BAR 00, AIT 98, LER 96a]. It is also accepted that the kinetics of autogeneous shrinkage depend on the strength development in the course of time. High

strength concretes generally develop much higher autogenous shrinkage than ordinary strength concretes both at early age and in the long term. The EN 1992 models take these differences into account (see figure 6). However, the experimental data are highly dispersed, and in particular, the measurements for certain ordinary strength concretes are very high. Two sets of points can be distinguished in figure 6.2: those correctly predicted by the two models, including high strength concretes, and those whose shrinkage is 60 to 100% higher than predicted. The second category includes all the laboratories, which means that the argument of experimental error can be reasonably eliminated, as the probability of an experimental error in three different laboratories is very low. However, this conclusion is not confirmed by the results in figure 7 showing shrinkage values for vibrated concrete that are as high as those for SCC from the same laboratory and for the same campaign.

The data corresponding to the high shrinkage values do not correspond to the low aggregate concentration values, although this would have provided a satisfactory explanation.

The EC2 models therefore considerably underestimate the autogenous shrinkage of certain SCCs. Shrinkage measurements are recommended for structures that are sensitive to autogenous shrinkage, that is, shrinkage of the concrete at an early age.



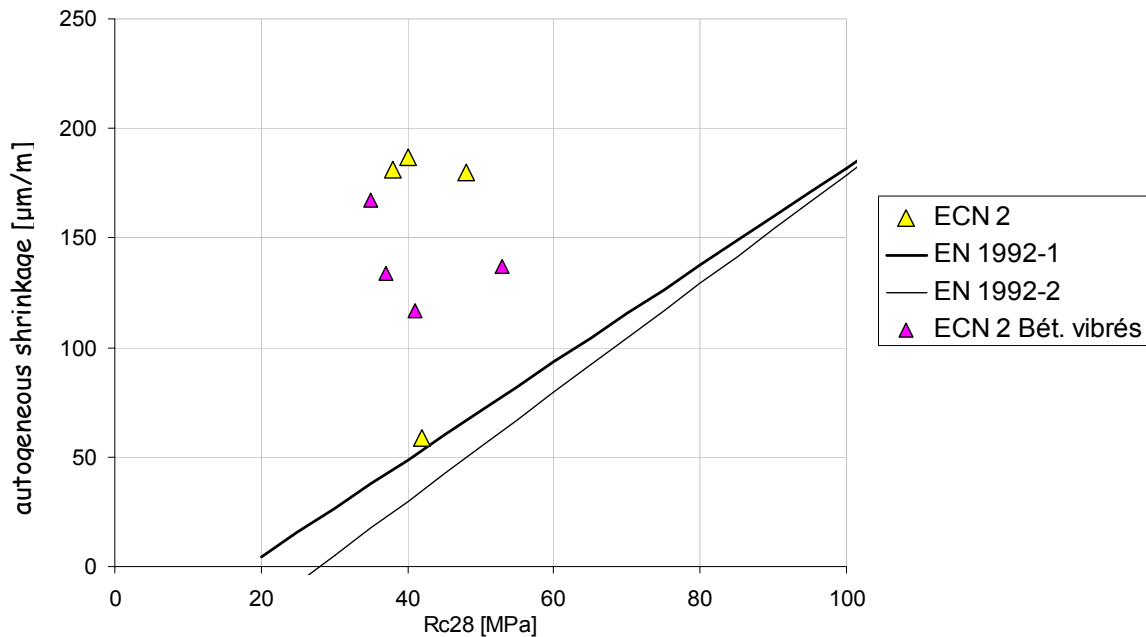


Figure 7: Comparison between SCC and vibrated concrete from the same measuring campaign

2.3 Drying shrinkage

Drying shrinkage depends on the outside relative humidity. It also depends more on the drying kinetics, which means it will be slower when the average radius of the structure is higher. We have compared the available data from the different laboratories. A comparison of the results of the EC2 models is given in figures 8, 9 and 10. The EN 1992-1 curves were calculated for N and R cements. The EN 1992-2 curve has a bump for the average strength of 63 MPa, which corresponds to the connection of two functions giving the magnitude on either side of the strength.

The precision of the models is considered to be fairly satisfactory for the LCPC and LMDC data. However, the data are closer to the upper limit value of EN 1992-1. The ECN data are more dispersed and more similar to those of the lower limit value of EN 1992-1. These data are considered low in comparison with the long-term shrinkage usually accepted for an average radius of 35 mm. However, cracking of the skin in the early stages of drying reduces shrinkage by eliminating the stress in the skin. This is particularly noticeable when the size of the specimen is small. That, in any case, is the explanation that can be given for the data in figure 9.

In conclusion, it is recommended, when predicting the drying shrinkage of SCC, to use the upper drying shrinkage limit value of EN 1992-1 or the EN 1992-2 equation.

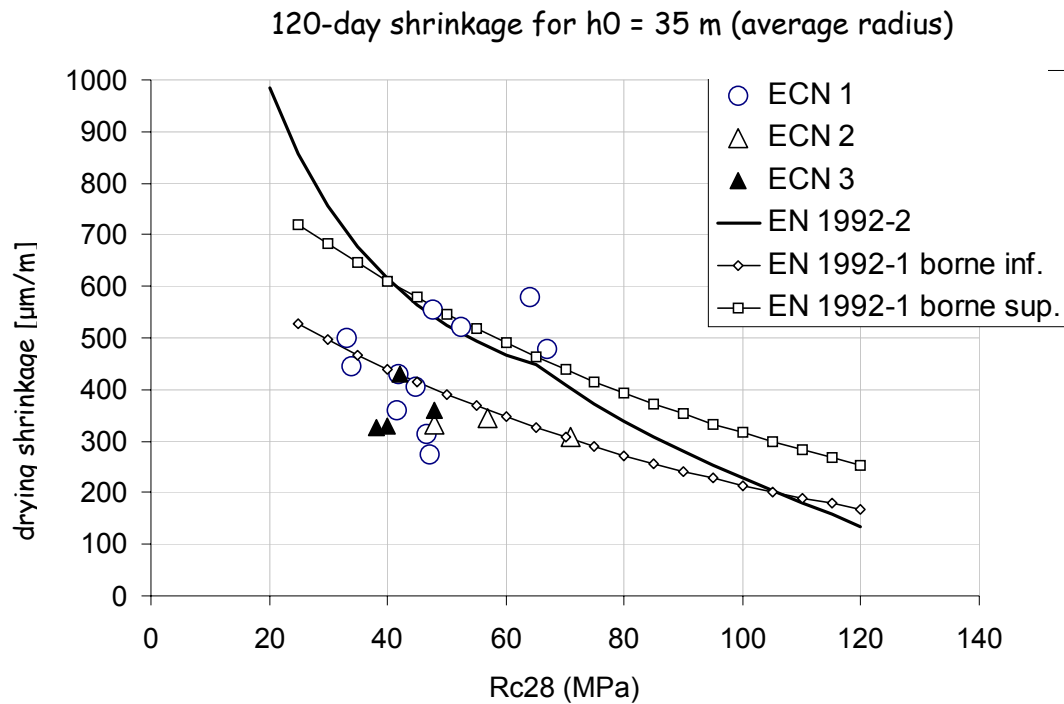


Figure 8: Development of drying shrinkage as a function of the average compressive strength ECN data (Ecole Centrale de Nantes)

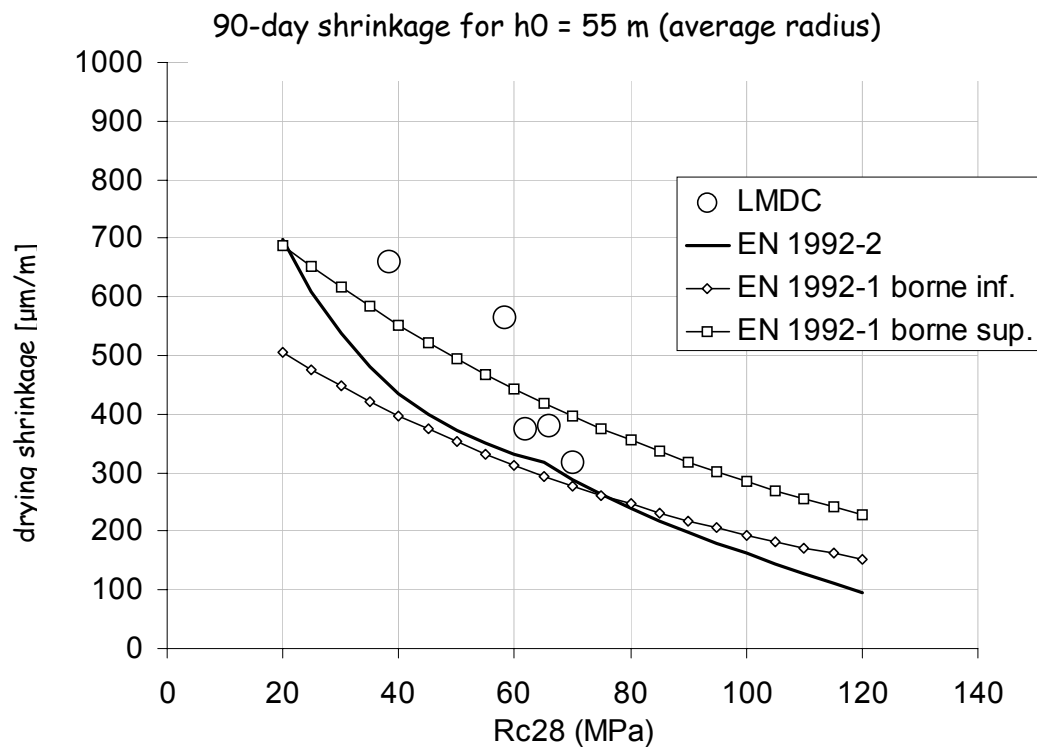


Figure 9: Development of drying shrinkage as a function of the average compressive strength LMDC data (Toulouse INSA)

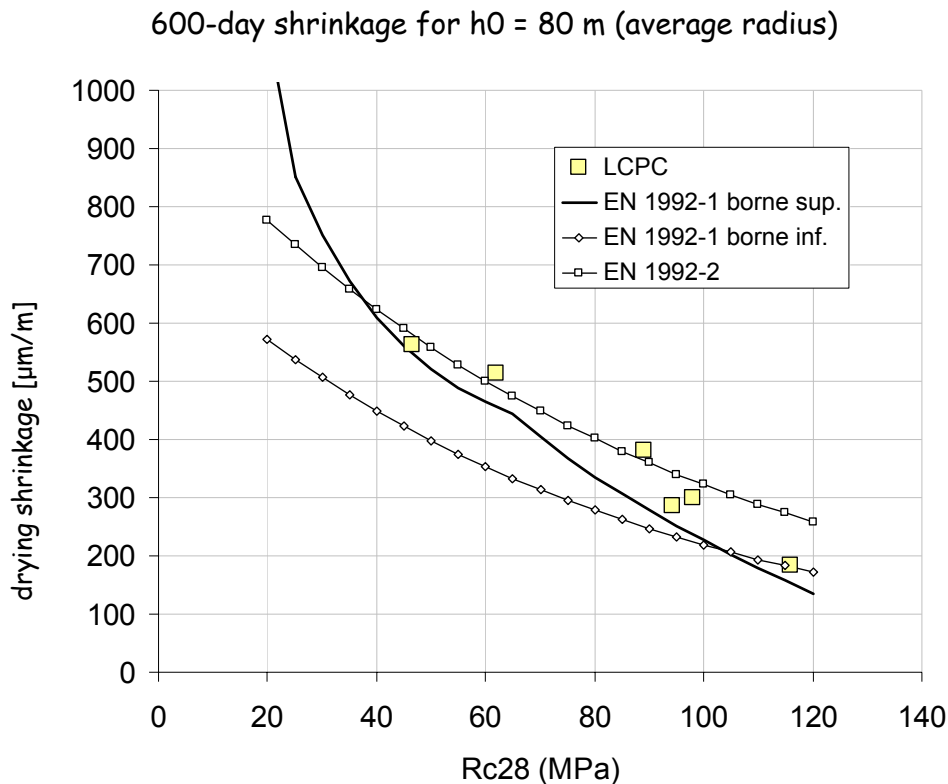


Figure 10: Development of drying shrinkage as a function of the average compressive strength LCPC data

2.4 Total shrinkage

We will now consider prediction of total SCC shrinkage (sum of endogenous and drying shrinkage), keeping the data for each laboratory separate for the reasons indicated above. The following three figures show the EN 1992-1 and 1992-2 curves. The LMDC data (see figure 11) were obtained after 3 months of drying, which is a fairly short period of time. Figure 9 shows us that the difference can be explained by the lack of precision of the autogenous shrinkage because the drying shrinkage is correctly predicted.

The ECN data (see figure 12) were obtained after 120 days for an average radius of 35 mm ($7 \times 7 \times 28$ mm specimens). The data are highly dispersed and some points are outside the shrinkage zone. An explanation was given earlier for the sensitivity of small test specimens to the effects of drying at an early age, which can lead to dispersion due to the difference in the strength development kinetics of the different concretes.

The LCPC data (see figure 13) were obtained after 600 days of measurements or, for two of the concretes, by extrapolating the shrinkage at 200 days to that at 600 days by applying the kinetics of the EN 1992-2 equation, i.e. the 200-day shrinkage was increased by 15 to 25% to determine the 600-day shrinkage. The dispersion is less marked in the present case. The values are close to the upper shrinkage limit.

In conclusion, it can be said that prediction of the total shrinkage of HPC is fairly satisfactory for both EC2 models, while that of conventional concretes is underestimated. To calculate the final magnitude, it is acceptable to use the upper limit of the EN 1992-2 model for ordinary strength SCC and that of EN 1992-2 for HPC. The development of total shrinkage deformation, however, may be poorly predicted because of possible underestimation of the autogeneous shrinkage. For structures that are sensitive to this component, measurements are recommended.

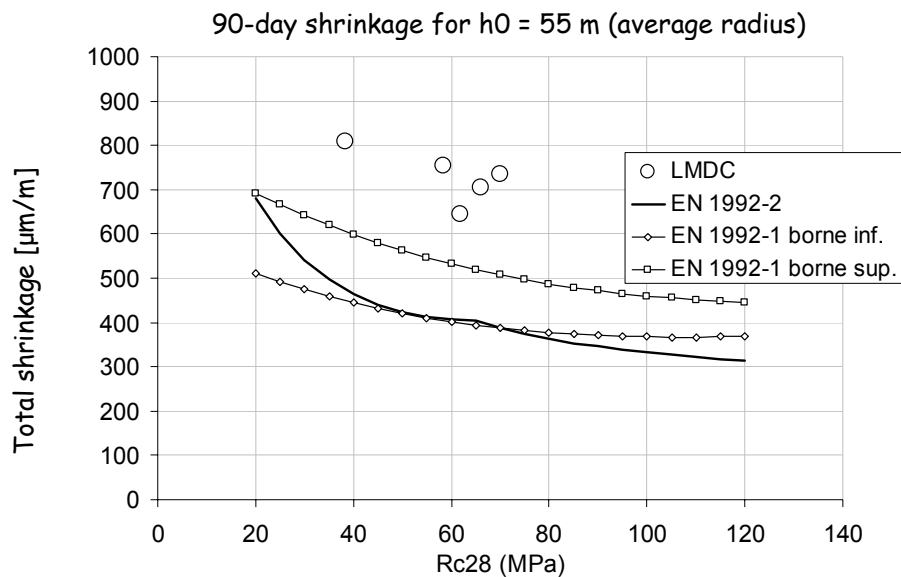


Figure 11: Development of total shrinkage as a function of the compressive strength LMDC data

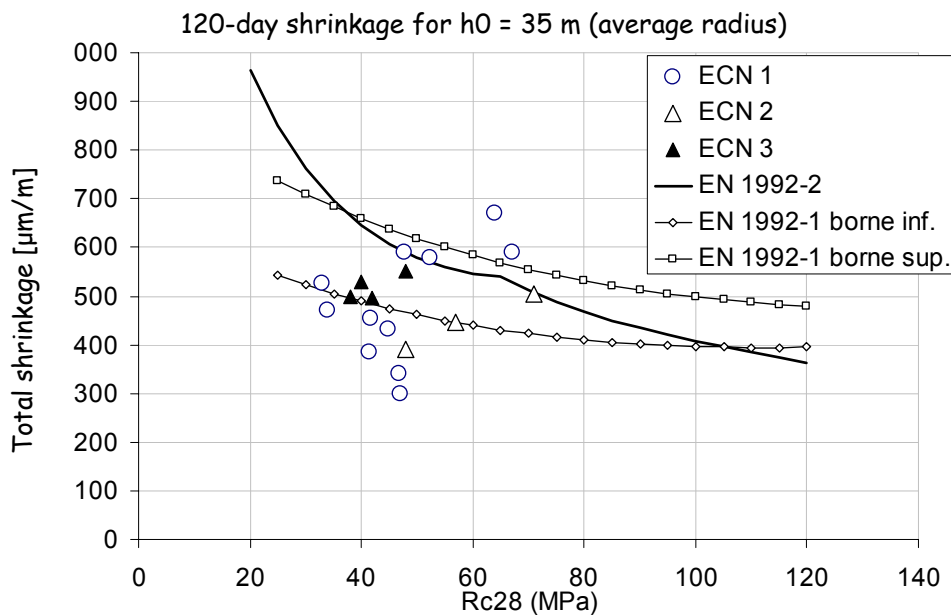


Figure 12: Development of total shrinkage as a function of the compressive strength ECN data

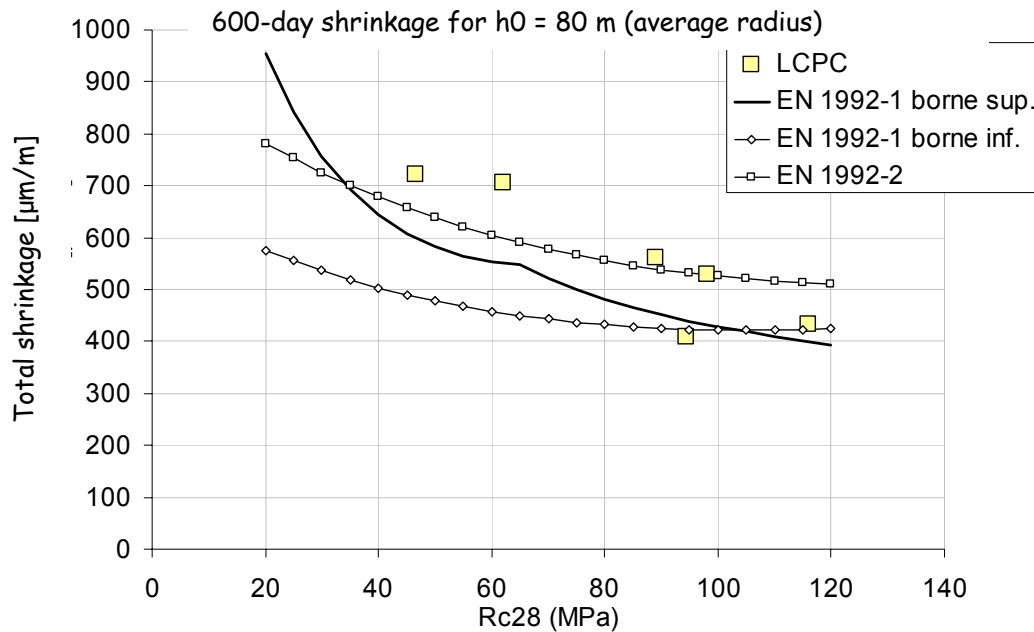


Figure 13: Development of total shrinkage as a function of the compressive strength LCPC data

3. Creep in SCC

The results of creep tests performed on SCC mixes (obtained within the framework of PN B@P and other studies) have been analysed and compared with the EC2 models. For further details, please refer to the PN B@P report "Recommendations for the calculation of shrinkage and creep in SCC" [LER 07].

The results show that the EC2 models tend to underestimate the creep deformation of SCC. When the resulting error does not compromise correct operation of the structure, it is possible to apply the EN 1992-1 model, but the secant and not the tangent modulus must be included in the creep law. In the presence of structures that are sensitive to creep, particularly those made of HPC, annex B of EN 1992-2 can be used provided it is corrected using the method developed in paragraph B104 "Experimental identification procedure" in EN 1992-2. The correction is based on creep tests.

4. Conclusion

Self-compacting concrete can develop slightly greater deformation than vibrated concrete, mainly due to a larger volume of paste.

The modulus law can be used as is for standard cases. But the modulus of elasticity must be determined explicitly if the structure is deemed to be sensitive to any deviation from the norm, just as it is for vibrated concrete.

The EN 1992-1 and EN 1992-2 autogeneous shrinkage laws underestimate the autogeneous shrinkage of SCC, sometimes to a very large extent. For structures that are sensitive to this component, measurements are recommended in order to adjust the law.

The drying shrinkage models described in EN 1991-1 (upper limit i.e. class R cement) and EN 1992-2 have a level of precision that makes them applicable to standard structures.

Calculation of the total shrinkage is affected by the lack of precision in relation to the autogeneous shrinkage but, for standard structures, it is accepted that the EN 1992-1 and EN 1992-2 laws can be used.

The EN 1992-1 creep law is more precise than that of EN 1992-2, particularly for high strength self-compacting concrete. It is accepted that this law can be used for standard structures that are not sensitive to creep variations.

In the case of structures for which it is particularly important to take delay deformation into account, it is recommended, in the case of SCC with an aggregate content of less than 66%:

- to adjust the EN 1992-2 law, based on creep tests carried out according to the method described in the standard;
- or to use the rules given in the technical assessments issued for certain prefabricated components.

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APPENDIX G: DURABILITY OF SELF-COMPACTING CONCRETE

1. Foreword

Concrete durability is the capability of a concrete to withstand the deterioration mechanisms to which it may be exposed. A concrete structure can preserve its strength and continue to fulfil its structural function throughout its specified, effective life time. Physical and chemical factors can be of both internal and external origin.

The durability of self-compacting concrete in relation to external and internal deterioration factors is governed by similar mechanisms to those observed for conventional concrete.

The following text is a reminder of the different concrete deterioration mechanisms and an analysis of the potential effect of the self-compacting character of the concrete on its durability.

2. Durability of self-compacting concrete: application of current regulations

2.1 Alkali-aggregate reaction

The choice of the aggregate to be used in view of the alkali-aggregate reaction is independent of whether or not the concrete containing the aggregate is self-compacting.

The concrete performance test is applicable to all concrete, regardless of their rheology. The only precision to be made concerns the active alkaline content of the mixes. Self-compacting concrete can contain viscosity-modifying admixtures which have not yet been standardised. The total alkalis in "traditional" admixtures for conventional concrete are considered to be active alkalis and included as such. Unless precise figures to the contrary are available, the total alkali content of viscosity-modifying admixtures will also need to be included.

2.2 Reinforcement corrosion penetration of chloride ions and carbonation

There is no reason to modify the chloride thresholds and cover thicknesses defined by the standards for a given environment. Self-compacting concrete is made from the same ingredients as conventional concrete (cement, additions, aggregate and admixtures). The presence of viscosity-modifying admixtures without chloride has no direct influence on chloride penetration processes. The same applies to carbon dioxide.

Self-compacting concrete has a higher volume of paste than conventional concrete and a specific rheology which is different from that of conventional fluid concretes. The difference can concern the interconnected porosity of self-compacting concrete due to the higher volume of paste. However, studies conducted by CEBTP and LERM on the

influence of the curing method on the durability of self-compacting concrete has shown that the diffusion coefficients of chloride ions in self-compacting concrete are of the same order of magnitude as the coefficients of conventional concretes for the same water/binder ratio ($D_{Cl^-} \approx 10^{-11} \text{ m}^2/\text{s}$ for C25/30 - SCC or not- and 10^{-12} to $5 \cdot 10^{-13} \text{ m}^2/\text{s}$ for C40/50 - SCC or not).

The carbonation kinetics under accelerated conditions are similar.

2.3 Sulphate reactions

Exogenous sulphate reactions

The durability of conventional concrete in relation to exogenous sulphate attacks is governed by the choice of binder (sulphate resisting cement or cement with blast furnace slag, flyash and silica fume additions: chemical barrier) and the porosity of concrete (physical barrier) related to the equivalent water/binder ratio. The same applies to self-compacting concrete.

Internal sulphate reaction

The concomitant factors required for delayed ettringite formation in conventional concrete are as follows:

1. Heating characterised by the temperature ($> 65^\circ\text{C}$) and the duration
2. The alkali content
3. The sulphate content
4. The tricalcium aluminate content
5. The high relative humidity and, to a lesser extent,
6. The type of aggregate.

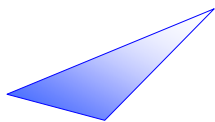
These factors are valid both for self-compacting concrete and conventional concrete. The presence of admixtures specific to self-compacting concrete does not play a direct role in the process.

2.4. Chemical attack

Like carbon dioxide transfer properties and the penetration of chloride ions, the resistance of self-compacting concrete to various chemical attacks, such as aqueous and gaseous acid environments, weak acid salts, etc., is controlled by the type of binder (blended cements) and the interconnected porosity of concrete with respect to the equivalent water/binder ratio.

3. Conclusion

Generally speaking, the strength of self-compacting concrete in relation to external and internal deterioration mechanisms can be approached by current standards, particularly documentation booklet NF P18-001, standard EN 206-1 and the precast products standards.



APPENDIX H: GUIDELINES FOR DRAFTING TECHNICAL SPECIFICATIONS FOR SELF-COMPACTING CONCRETE (SCC)

FOREWORD

These guidelines for drafting technical specifications are aimed at providing specifiers with special technical clauses concerning issues specific to self-compacting concrete that can be included in specifications.

Unless expressly otherwise indicated in this document, the special technical clauses can be included in addition to the standards and regulations in force (EN 206-1, DTU 21 and Fascicule 65 A, precast product standards including EN 13369).

The guidelines are mainly aimed at cast-in-place concrete. In the case of factory precasting, different provisions can be adopted subject to verification of conformity of the finished product. For precast concrete and, depending on both the materials and the manufacturing processes used, the test operating methods for fresh SCC and recommendations concerning the slump flow range at delivery (appendix H1) can naturally be used when necessary.

The explanatory parts of the guidelines are in ordinary characters while the clauses proposed are in *Italics*.

1. Definitions and classification

The definitions and classification of self-compacting concrete are given in the AFGC recommendations.

2. Ingredients

2.1 Aggregate

SCC is more sensitive to the fines content and the overall grading curve than conventional vibrated concrete.

The variation of fines content of the sand must meet the requirements of codes A or B of standard XP P 18-545.

It is important for SCC that the rheological properties are maintained for a sufficient period of time, particularly for cast-in-place SCC.

For SCC which is not produced on the site of concrete placement, the water absorption of the aggregate is limited to 2.5% (code A) unless it has been shown that the rheological properties of the SCC are satisfactorily maintained under real transport conditions (including pumping, where applicable) and placement.

2.2 Viscosity-modifying admixtures

Certain SCC mixes can contain viscosity-modifying admixtures.

These products, which can be either mineral or organic, are designed to reduce the sensitivity of fresh concrete to bleeding and segregation, thus increasing the strength of the concrete mix.

At present, there are no product standards for this type of admixture. The closest is the "water retention" category of EN 934-2, but it is more focussed on bleeding.

The viscosity-modifying admixtures proposed must satisfy one of the following two criteria:

Case 1:

The admixture is a water-retaining admixture according to the technical stipulations of standard EN 934-2.

Case 2:

The admixture is considered to be an addition in the meaning of paragraphs NA 3.1.47 and NA 5.1.7 of standard NF EN 206-1. In conformance to standard EN 206-1, the effect caused by the addition of a viscosity-modifying admixture therefore needs to be verified by a preliminary test. It can be carried out directly on the concrete mix design considered (conformance to specifications) or in relation to tests conducted on a reference concrete or mortar. In this case, the tests must have been carried out with the usual dose and the maximum recommended dose (for SCC applications) recommended by the manufacturer. These comparative tests concern the requirements corresponding to the "water retaining" class of standard EN 934.2, with the exception of bleeding, in which case the results must conform to the requirements of the standards.

In pursuance of article 4 of EN 934-2, the viscosity-modifying admixture must not significantly change the shrinkage of the hardened concrete. This can be measured using the method for determining dimensional stability described in ASTM C494 on a reference mortar conform to EN 480-1. A comparison is then made between a sufficiently fluid reference mortar and the same mortar (with the same water content) whose fluidity can be lessened by incorporation of the viscosity-modifying admixture. The difference in shrinkage must not exceed 35% if the shrinkage of the reference mortar is more than 0.3 mm/m and must not exceed 0.1 mm/m otherwise.

3. Mix design

3.1 General

The properties of fresh SCC are more sensitive to differences in composition than conventional concretes. Particular attention must be paid to the mix design in order to

evaluate differences in properties, particularly rheological, resulting from variations in composition and, in particular, the water content.

It is recommended that the specifier include a clause to determine the slump flow range at delivery in which the SCC retains all the required properties (see appendix H1).

The influence of the temperature on the rheological properties of SCC could lead to adaptation of the admixture doses according to the season.

In the case of cast-in-place concrete, the mix designer must determine a concrete workability retention time period, T_m , during which the concrete must respect the criteria corresponding to its class. The time can vary according to various parameters, particularly the change in temperature of fresh concrete. The mix designer must check which parameters are important and define T_m in each possible configuration.. T_m will be defined according to the maximum fresh concrete temperature during manufacture and transport.

3.2 Examples of usable technical clauses.

Unless experience proves otherwise, the specifier can use the following clauses:

The properties required for SCC, depending on the class, are given below:

	Class 1	Class 2a	Class 2b	Class 3a	Class 3b
Maximum segregated portion ⁽¹⁾	20 %	20 %	15 %	15 %	10 %
Minimum L-box value	No special requirement	0.80 with 2 bars	0.80 with 2 bars	0.80 with 3 bars	0.80 with 3 bars

(1): Under no circumstances can the maximum authorised segregated portion be greater than 30%; it can be greater than the value given in the table if proof of non-segregation for similar applications is available (see appendix E of the AFGC recommendations). There must be no sign of bleeding during the test.

The figures in the table correspond to the minimum and maximum values to be respected when qualifying the mix design. They must be respected throughout the workability retention time period T_m .

In the case of precast components, for which finished product conformity controls are included in the product standards and, where applicable, the certification system, two options are available to validate the mix design:

Option 1: the SCC meets the criteria in the above table,

Option 2: the criteria in the above table do not apply to the SCC; the absence of segregation (in the field of SFB), is then verified for the finished product using specific tests (see appendix E of the AFGC recommendations).

The inspections on acceptance or before placement of the concrete are mainly based on the slump-flow test.

The target slump flow is defined after the qualification test has been carried out (see technical documents set out below) and the admissible variations determined (see appendix H2). The target value is generally between 600 mm and 750 mm.

The slump-flow range at delivery can be defined on the basis of the target value (with a tolerance of plus or minus 50 mm) or by designating a slump-flow class according to the following table:

Class	Slump flow (mm)
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

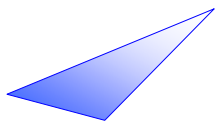
In no case must the SCC show any visible sign of segregation or bleeding during the slump-flow test.

In the case of high lifts, special attention must be paid to the stability of the concrete with regard to bleeding as it can interfere with the homogeneity of the concrete and surface quality.

The design mix is validated by technical documents consisting of a set of test results proving that the self-compacting concrete conforms to the properties required in the entire slump-flow range at delivery, SFD proposed (or at the time of placement in the case of precast structural products) and throughout the workability retention time period T_m . These results can come from laboratory tests, from test specimens produced in a concrete plant on a previous worksite or from mix development tests. The results can be recorded in an SCC data sheet (see example in appendix H2) including indications that enable conformance to the maximum values in the above table to be checked. The laboratory tests must be validated by the concrete plant tests.

If a concrete is specified according to Fascicule 65A and a study is necessary, the design mix sensitivity verification ranges will need to be adapted to the strength of the design mix and the precision of the production equipment. A detailed study programme is given in appendix H3.

In the case of suitability tests conducted as per Fascicule 65A, rheology tests will also need to be carried out (slump, sieve segregation and L-box, if applicable). In this case, the mix design can be adapted to real mixing conditions using a plasticizer or superplasticizer within a range of $\pm 20\%$.



4. Producing compressive strength test specimens

Compressive strength test specimens must be produced without contributing energy to the concrete for placement.

The provisions of FD P18-457 documentation booklet that are specific to SCC apply.

5. Ordering

5.1 Case of ready-mixed concrete

When ordering ready-mixed SCC, the specifications must conform to standard EN 206-1.

The SCC class must be indicated at the time of specification.

5.2 Case of a factory-precast product

For factory precast products that are finished products, the order must be made in reference to the national edition of the product standard and, when there is no product standard, to standard EN 13369.

For structural products, the supplier must be able to indicate the SCC class used when the SCC meets the criteria of the table in paragraph 3.2 (option 1) or the slump-flow when absence of segregation has been checked for the finished product (option 2).

Depending on the case, the product standard or standard EN 13369 systematically specifies which other standards are concerned, whether they relate to the ingredients and the concrete, or whether they concern product manufacture or the relevant Eurocode rules. The regulations concerning CE labelling are automatically covered.

6. Manufacture and transport

The manufacture and transport of SCC must conform to standard EN 206-1 in the case of cast-in-place concrete and to the product standards, including EN 13369, in the case of precast components.

The producer defines an SFB which takes into account the time between batching and placement (including any transport time between the production site and the work-site). The target SFB is usually between 600 and 750 mm and can be slightly higher than the SFD and the target value obtained during the qualification test. The SFB is indicated in the description sheet (appendix H2).

The producer pays particular attention to the production regularity, and particularly the water content. The specific procedure for this type of concrete must be written down and used by the producer. It must include the frequency with which the slump-flow must be checked during manufacture.

7. Checking conformity of the rheological properties of SCC

7.1 Frequency of inspections

The conformity of the rheological properties of SCC is checked by measuring the slump-flow.

For ready-mix concrete, the inspection frequency must be at least once per day of delivery (at the beginning of production, in particular) and no less than the frequency indicated in table 13 in standard EN 206-1.

For factory precast products, the inspection frequency is defined in the product standards, including EN 13369.

7.2 Criteria of conformity

If the SFD is defined as a slump class, the concrete is conform if the slump at the time of acceptance lies within the SFD plus the test uncertainty which is conventionally equal to 20 mm. The number of individual results located outside the SFD is limited according to table 19a in standard EN 206-1.

If the SFB is defined according to the target value, the concrete is conform if the slump at the time of acceptance lies within the SFD.

Inspections other than the slump-flow can be carried out; the maximum admissible difference between the results of individual tests and the target value limits for the class concerned is 2% for the sieve segregation test and 0.05 for the L-box test. The acceptance criterion is that given in table 19a of standard EN 206-1.

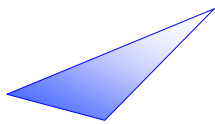
8. Acceptance

During on-site acceptance of concrete it must be checked that the concrete is suitable for placement without compaction and conforms to the nominal mix design. The above acceptance consists in visual inspections and slump-flow measurements. The acceptance criterion is that given in § 7.2.

During delivery, it is recommended mixing the concrete at high speed for one minute at least before placement begins.

A visual inspection must be carried out on each batch delivered and the slump-flow measured at least for the first batch of the day and systematically whenever there is any doubt.

If self-compacting concrete is delivered to the site at the same time as conventional concrete, a procedure must be set up to distinguish between the two types of concrete.



If the concrete is made in a concrete plant on-site, the rules in chapter 7 will apply, in which case, the SFB is generally the same as the SFD.

9. Placement

Before carrying out the first placement operations, and particularly when the flowing gap I is less than 60 mm, the specifier can ask for a mock-up to be produced (when specified in the contract) under the same conditions as the structure being produced (pumping, reinforcement, formwork, etc.) to check that the requirements have been respected.

Whatever the method used to place the fresh concrete and in the absence of sound references to the contrary, it is essential to limit the horizontal flow of SCC in the formwork to maximum of 10 m.

Likewise, the free-fall height is limited to 5 m.

The curing requirements of draft standard EN 13670-1 and EN 13369 in the case of structural precast products must be respected. For horizontal applications, curing with an appropriate product is strongly recommended. In the case of subsequent adhesive-bonding of a covering and if a film-producing curing product is used, the latter must be removed according to accepted trade practice, unless a special study is carried out.

10. Appendices

H1 Definition of the slump-flow range on acceptance for SCC

H2 Fresh SCC properties: technical data sheet

H3 Laboratory study report (adaptation of Fascicule 65A)

APPENDIX H1: DEFINITION OF THE SLUMP-FLOW RANGE AT DELIVERY FOR SCC

An SCC mix can only be used in a defined slump-flow range at delivery (SFD). SF_{min} and SF_{max} are the outside limits defining the slump-flow range.

They are such that:

- when the slump-flow is equal to SF_{min} , the L-box slump-flow specifications are still respected.
- when the slump-flow is equal to SF_{max} , the specifications relating to segregation (sieve test) are still respected.

To check this point, tests are conducted on the nominal mix design during the site preparation phase by varying the water content in order to vary the slump-flow within the range to be verified.

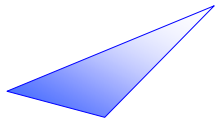
In general, the conventional difference between SF_{min} and SF_{max} is 100 mm, but it can be adapted according to the strength of the mix.

APPENDIX H2: FRESH SCC PROPERTIES:

TECHNICAL DATA SHEET

STANDARDISED NAME OF CONCRETE					
USE REFERENCES	Name of work-site				
	Concrete supplier				
	Volume of concrete (m ³)				
	Period				
	Application	Vertical		☐	
		Horizontal		☐	
	Class	1	☐	3a	☐
2a		☐	3b	☐	
2b		☐			
Properties of nominal mix **		T ₀	T ₃₀	T ₆₀	T _m [*]
	Slump flow (mm)				
	Segregated portion (%) (sieve test)				
	L-box ratio (L-box test)				
Properties of high- water-content mix design **	Slump flow (mm) (SF _{max})				
	Segregated portion (%) (sieve test)				
Properties of low- water-content mix design **	Slump flow (mm) (SF _{min})				
	L-box ratio (L-box test)				

	SF _{min}	SF _{max}
FEF***		
FER****		



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* *Specify the workability retention time T_m =*

** *Specify the temperature of the concrete during manufacture =*

*** *SFB: slump-flow range after batching*

**** *SFD: slump-flow range at delivery*

APPENDIX H3: LABORATORY DESIGN STUDY

The design study, conducted in the laboratory, consists in making a nominal batch and a set of batches corresponding to the high and low water content mixes, in order to evaluate the sensitivity of the mix to variations in composition.

A sample is taken from each batch and the following tests are carried out:

- a slump-flow monitoring test (up to T_m),
- a sieve segregation monitoring test (at t_0 and t_{30}),
- an L-box slump-flow monitoring test (at t_0 and T_m),
- a test to determine the 28-day compressive strength, the result of which is the arithmetical mean of the measurements taken on 3 samples.

The high and low water content batches are as follows:

- 2 batches with different water contents [usually $\pm X$ l/m³ with respect to the nominal mix, but this value can be increased if the mix permits (X is defined by the batch producer according to their production equipment, while remaining between 5 and 10)],
- in the case of sand with more than 6% of fines (less than 0.063 mm diameter) and when the fines content variation of the sand is greater than 3, two batches corresponding to variations of ± 25 kg/m³ in the binder fraction (cement + additions), in proportion to the respective quantities of cement and additions, in order to simulate variations in the fines content.

The design test is deemed to be conclusive if:

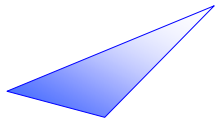
- for the nominal mix and each of the high and low water content mixes, the results of the fresh concrete tests (slump, segregation and L-box tests) are satisfactory throughout the workability retention time T_m .
- for the nominal mix, the results of the compression test, f_{CE} , satisfy the following two conditions:

$$\text{Condition 1: } f_{CE} \geq f_{C28} + \lambda (C_E - C_{\min})$$

$$\text{Condition 2: } f_{CE} \geq f_{C28} + 2S$$

f_{C28} is the characteristic specified compressive strength

$C_{\min}$ is the minimum 28-day compressive strength that can be respected for the cement chosen, observed over a significant period of time during the supplier's self-inspection



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C_E is the 28-day compressive strength of the cement used to carry out the test

λ is a coefficient of 1, unless proof is given to the contrary

S is the expected standard deviation of the strength distribution (at least equal to 3 MPa)

$$f_{cE} \geq f_{c28} + \lambda (C_E - C_{\min})$$

$$f_{cE} \geq f_{c28} + 2S$$

f_{c28} is the characteristic specified compressive strength

- for high and low-water content batches, the results of the 28-day compressive strength tests are included in the range of $f_{cE} \pm 15 \% f_{cE}$



