



Guidelines for Mix Design of SCC

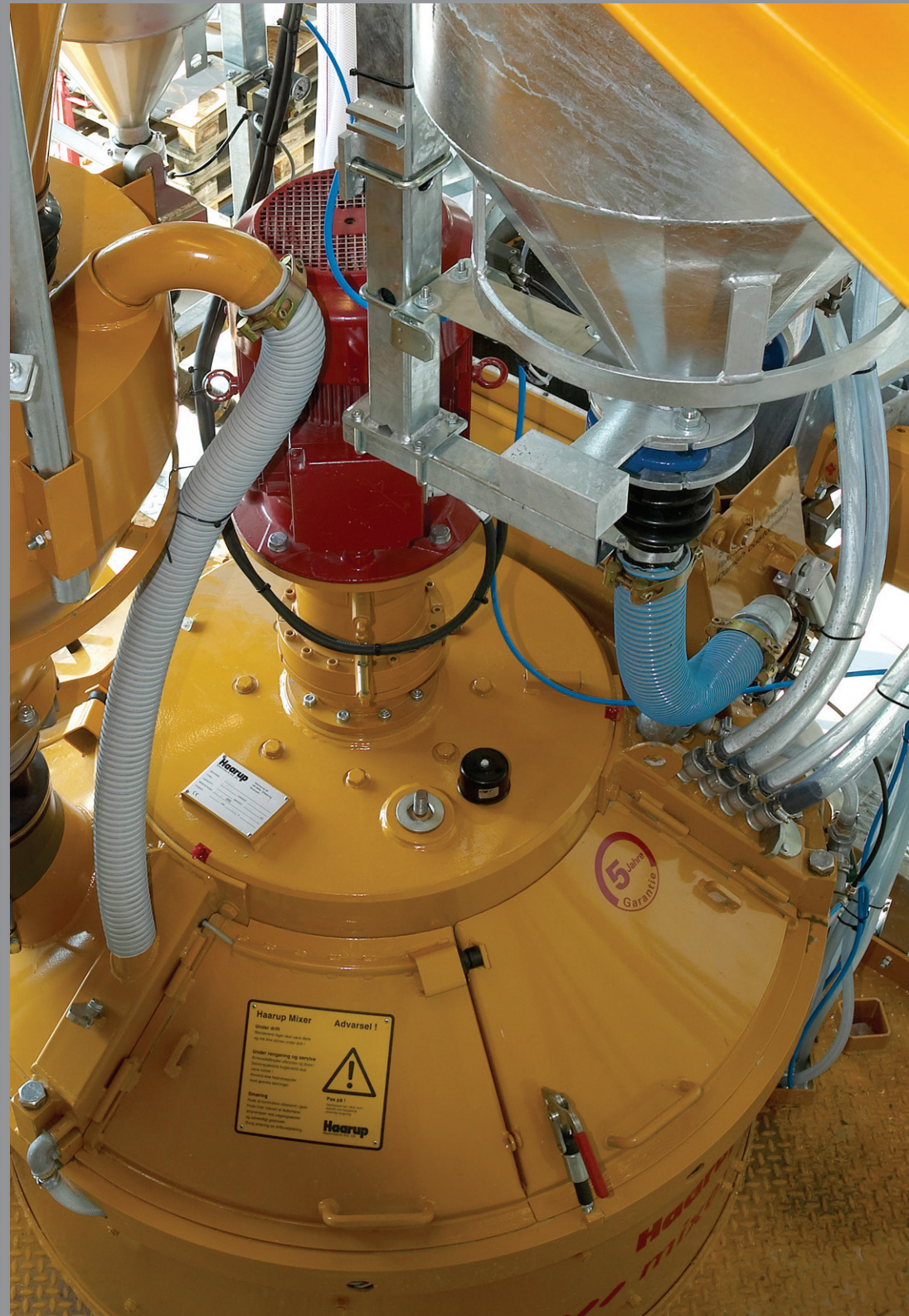
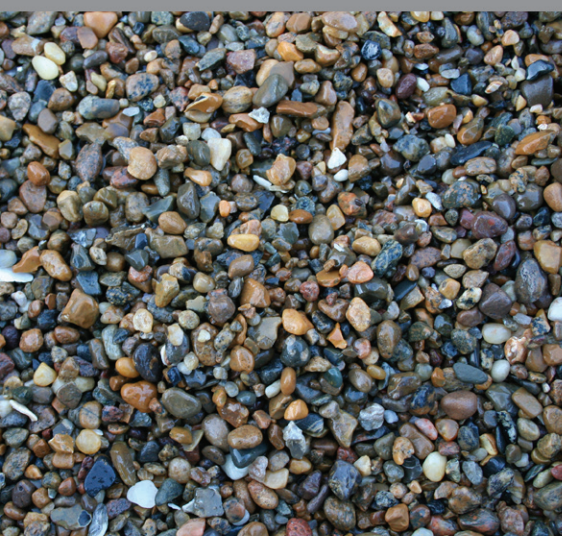


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Cover page photo shows the Danish Technological Institute concrete mixing facility and aggregate materials for concrete

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Preface

The SCC Consortium was an innovation consortium supported by the Danish Ministry of Science, Technology and Innovation during the period 2003-2007.

One of the most important results of the SCC Consortium's work is the drafting of two guidelines providing advice and instructions on the mix design of SCC and the jobsite execution with SCC.

The Guideline for mix design of SCC is in part intended to promote the use of SCC in Denmark and in part contribute to a better understanding of the correlation between concrete composition and the flow properties (rheology) of SCC.

The concrete producer can use the Guideline to hopefully obtain greater knowledge about how concrete composition influence flow properties which in turn control the casting and finishing properties of the SCC, i.e. the concrete producer achieves a greater understanding of the contractors's wishes, needs and requirements.

Other interested parties can benefit from reading the Guideline to gain a better general understanding of the challenges related to SCC mix design.

SCC Consortium, August 2007

SCC Consortium's core partners were:

- *Danish Technological Institute, Concrete Centre (Consortium coordinator)*
- *Aalborg Portland A/S (Cement manufacturer)*
- *Unicon A/S (Ready-mixed concrete manufacturer)*
- *MT Højgaard a/s (Contractor)*
- *Betonelement a/s (Precast concrete manufacturer)*
- *DTU-IMM (Technical University, R&D)*
- *Videometer A/S (Supplier of high-tech equipment)*

*www.SCC-Konsortiet.dk/english
www.VoSCC.dk*

1. Introduction

SCC is the abbreviated term for Self-Compacting Concrete. The term pertains to the most promising new invention in the concrete industry in the past 20 years. Compared to traditional concrete, SCC does not require vibration during casting. Thus a number of work operations can be omitted resulting in increased productivity and markedly improved working environment.

The biggest difference between traditional concrete and SCC is in the consistency in the concrete's fresh state. Figure 1.1 shows traditional slump concrete and SCC. It is clear that the slump measurement does not have any significance for SCC, and the slump flow measurement is the most used measurement to indicate the SCC consistency. However, the so-called plastic viscosity is also needed to fully describe the flow properties of SCC. The other important concrete properties, such as strength, stiffness, durability, etc., are by and large identical for SCC and traditional concrete.

Taking advantage of SCC's flow properties makes it possible to cast around closely spaced and complex reinforcement without the use of vibration. SCC is capable of complete form filling even in complex formwork geometries that are difficult to access with a poker vibrator.

SCC is expected to help reduce casting errors such as honeycombs and provide concrete with higher surface quality. SCC is also well suited for pumping into inaccessible formwork with top side shuttering, etc.

The Guideline is primarily intended for people who have the responsibility for the concrete mix designs in a concrete producing enterprise. However, the content can potentially also be used as background material for teaching aspects of SCC technology at the technical educational institutions.

The Guideline describes the influence which the specific mix design parameter (such as the specific material) has on SCC flow properties. It provides guidance on how to adjust a concrete recipe to achieve the desired flow properties so they are adapted to the method of execution and the type of structure being cast, as well as providing a stepwise conceptual approach on how to design a new SCC mixture from a given set of raw materials.

The execution aspects of SCC are described in detail in "Guideline for Execution of SCC", SCC Consortium, August 2007. The Guideline is based on experience obtained with Danish raw materials and for slump flows in the range of 450 mm to 700 mm.

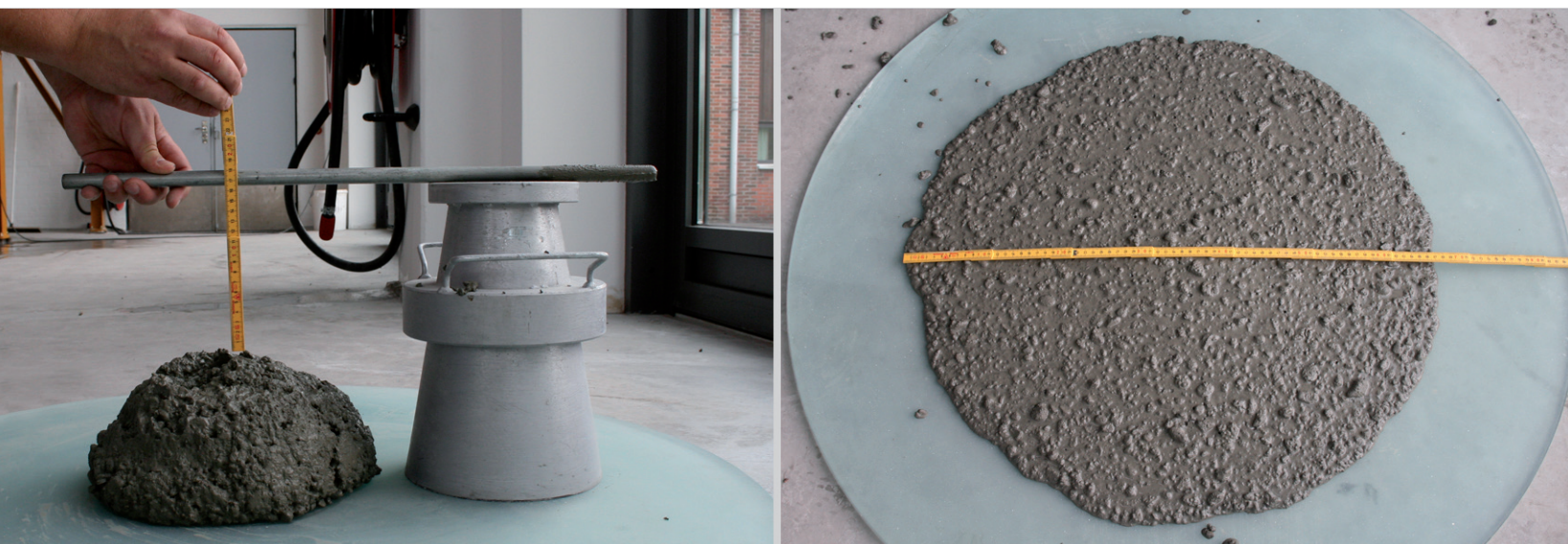


Figure 1.1. Left: The slump of traditional concrete is measured as the settling of a 300 mm high concrete cone. Right: For SCC the slump flow is measured as the diameter of the collapsing concrete cone. The slump of traditional concrete is typically in the range of 100-200 mm, while the slump flow of SCC is typically 500-700 mm.

2. Flow properties of SCC

Traditionally the slump flow is used to describe the SCC flow properties, but it has been demonstrated that at least two parameters are required to describe the flow properties adequately. The flow properties of SCC are thus characterized by the following parameters:

- The yield stress τ_0 describes the concrete's flowability, i.e. how far the concrete can flow. The yield stress is closely related to the slump flow. A high yield stress corresponds to a low slump flow and vice versa.
- The plastic viscosity η_{pl} describes how viscous the concrete is. A high viscosity means a sticky SCC that is hard to move around (thick and flows slowly). Conversely, a low viscosity means a SCC that flows quickly and is easy to work with.

Materials with flow properties that can be characterised by a yield stress and a plastic viscosity are Bingham materials. The significance of the two parameters is illustrated in Figure 2.1.

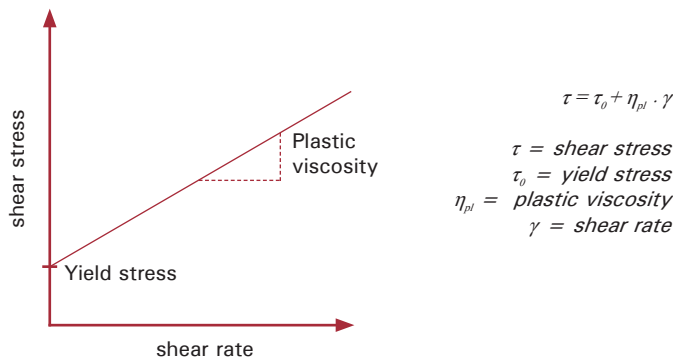


Figure 2.1. Flow curve for a Bingham material such as SCC.

The concrete workers regard the two concretes with the same slump flow but with low and high viscosity respectively, as easy flowing and sticky/slow flowing respectively. The two concretes will flow the same distance, but the flow rate will be different. The observed effects of changing the rheological parameters in relation to how the concrete is viewed by the user are shown in Figure 2.2. The Danish experiences with the significance of the rheological parameters in relation to execution with SCC are shown in Figure 2.3.

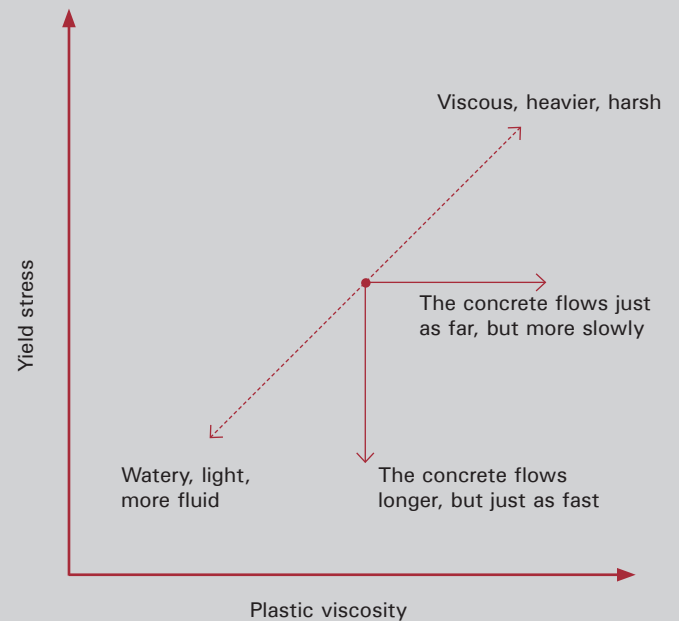


Figure 2.2. The influence of the rheological parameters on how SCC flows and are viewed by the user (the concrete worker).

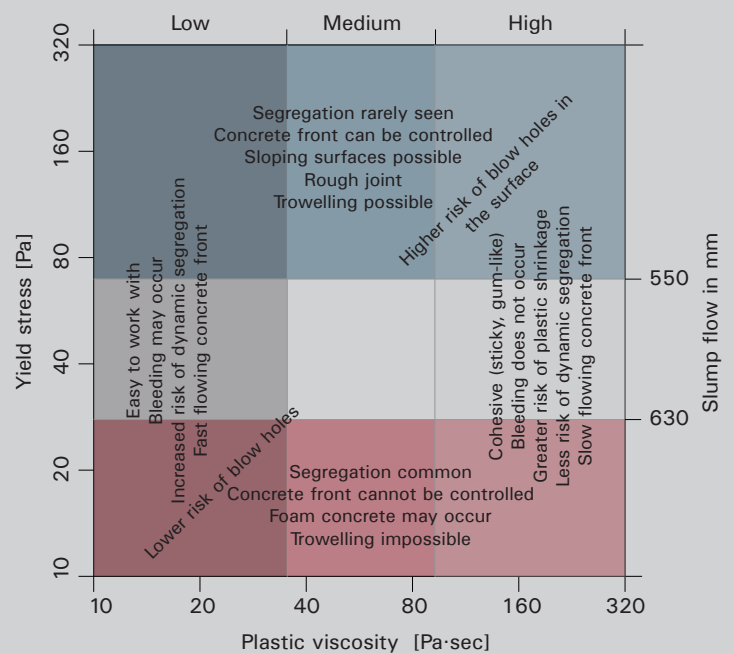


Figure 2.3. The correlation between the rheology of Danish SCC concrete and the execution experiences. Slump flow measurement provided in mm on the right, vertical axis.

2.1 MEASURING FLOW PROPERTIES

Rheological parameters can be determined using a rheometer such as the Icelandic BML viscometer or using the 4C-Rheometer system developed at the Danish Technological Institute (Figure 2.4). The 4C-Rheometer is based on implementation of an automated slump flow test where the rheological parameters are determined by analysis of the spread versus time curve. Numerical simulation of slump flow is the basis of the analysis. The BML viscometer is a “classic” rotation viscometer where the rheological parameters are determined based on knowledge of the flow field between the two coaxial cylinders.

It is possible to correlate the determination of the slump flow to a time measurement of the number of seconds the concrete takes to flow out to a slump flow diameter of 500 mm (t_{500}). A fast flow is equal to low viscosity and vice versa. In situations where it is not practicable to determine the rheological parameters using a 4C-Rheometer or BML viscometer, for example, one can alternatively estimate the rheological parameters based on the slump flow and the t_{500} parameters using Figure 2.5.

Note that the measurement of t_{500} is typically not very accurate.



Figure 2.4. 4C-Rheometer (top) and BML viscometer (bottom).

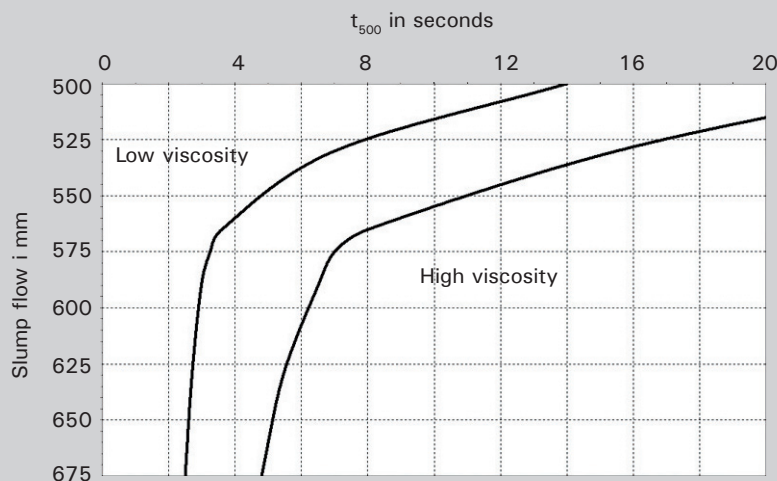


Figure 2.5. The dependency of t_{500} on slump flow and viscosity class.

3. Material model - SCC composition

To predict how changes to the composition of the concrete affect the workability of the concrete, it is advantageous to have a material model that is based on physical/chemical principles rather than pure empiricism. Naturally, it is a prerequisite that there are methods to measure workability parameters that accurately and definitely characterize the flow properties of self-compacting concrete – this issue was discussed in the previous section.

Such a material model is presented below. The model was developed in Japan by S. G. Oh, T. Noguchi and F. Tomosawa (“Toward Mix Design for Rheology of Self-Compacting Concrete”, Proceedings of the First RILEM International Symposium on Self-Compacting Concrete, pp. 361-372, 1999), and can in the majority of cases explain the changes observed in SCC rheological properties resulting from changes to the material composition.

The model expresses the two rheological parameters, plastic viscosity and yield stress, in the following form:

$$\eta_{pl} = \eta_{paste} \cdot (a_{\eta} \cdot \Gamma^{-b_{\eta}} + 1) \quad (3.1)$$

$$\tau_0 = \tau_{0,paste} \cdot (a_{\tau} \cdot \Gamma^{-b_{\tau}} + 1) \quad (3.2)$$

- η_{pl} is the plastic viscosity of concrete
- η_{paste} is the plastic viscosity of concrete’s paste phase
- τ_0 is the yield stress of concrete
- $\tau_{0,paste}$ is the yield stress of the concrete paste phase
- Γ is the relative paste layer thickness around aggregate particles
- a_{τ} , a_{η} , b_{τ} , and b_{η} are constants (defined by the specific production facility)

The flow properties of the concrete are regarded as being direct proportionally dependent upon the paste’s yield stress and plastic viscosity. When Γ is increased (thicker paste layer around aggregate), the parentheses in (3.1) and (3.2) will slowly approach a value of 1, and the flow properties for the concrete will be equal to that of the paste. Conversely, when Γ is reduced and the paste layer thickness approaches zero, both yield stress and plastic viscosity of the concrete will increase without an upper limit. The material model is based on the principle that concrete can be regarded as a two phase system consisting of aggregate and paste, where the paste is divided into:

- paste necessary to fill the cavities between aggregate
- excess paste (the remainder)

The amount of excess paste is crucial to the concrete flow properties. The material model assumes that the excess paste is divided over the surface of all aggregate particles into a thin layer that is proportional to the size of the individual aggregate particle. The larger the particle, the thicker the layer, but viewed relatively to the diameter of the particle, the layer thickness is the same for all particles. Thus the relative paste layer thickness Γ is identical around all particles:

$$\Gamma = \frac{t_{paste,1}}{d_{aggregate,1}} = \frac{t_{paste,2}}{d_{aggregate,2}} \quad (3.3)$$

Figure 3.1 shows two aggregate particles with paste layers identical relative thickness Γ , i.e. equation (3.3) applies.

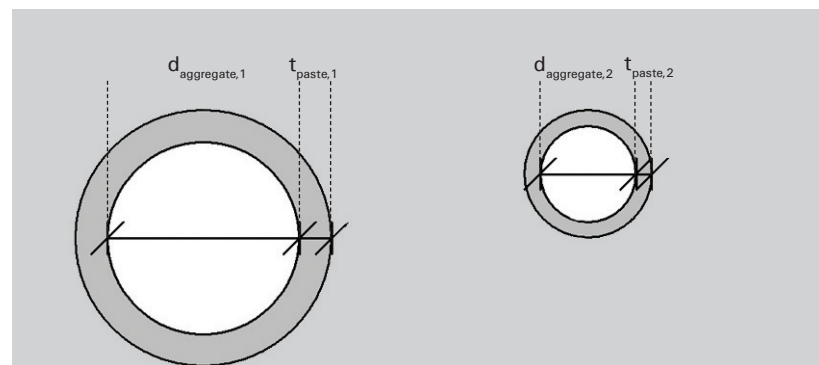


Figure 3.1. Shows two aggregate particles with paste layers identical relative thickness Γ , i.e. equation (3.3) applies.

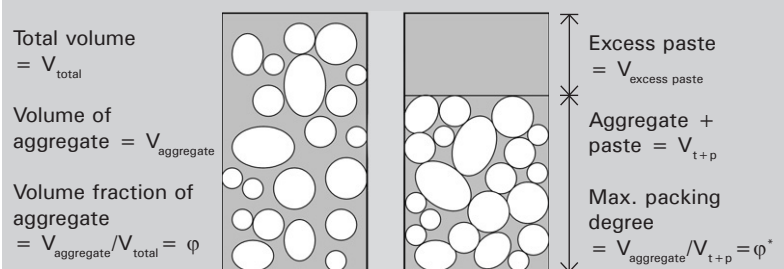


Figure 3.2. Illustration of the two phases of concrete, i.e. aggregate and paste. On the right the aggregate in the concrete has been compressed to its maximum packing defined as the packing degree ϕ^* . The volume fraction of the aggregate is termed ϕ and is illustrated on the left.

Based on Figure 3.2 the excess paste can be expressed as follows using the packing degree φ :

$$V_{\text{total}} = V_{\text{excess paste}} + V_{t+p}$$

$$\Downarrow$$

$$V_{\text{excess paste}} = V_{\text{total}} - \frac{V_{\text{aggregate}}}{\varphi^*} \quad (3.4)$$

Now divide by V_{total} that can be regarded as a unit volume and the excess paste is expressed as:

$$V_{\text{excess paste}} = 1 - \frac{\varphi}{\varphi^*} \quad (3.5)$$

In the model it is now assumed that, for a spherical shaped aggregate particle with diameter d , the excess paste is evenly distributed at a constant thickness t .

$$\text{Excess paste} = O_{\text{sphere}} \cdot t = \pi \cdot d_{\text{sphere}}^2 \cdot \Gamma \cdot d_{\text{sphere}}$$

$$\Downarrow$$

$$\Gamma = \frac{\text{Excess paste}}{6 \cdot V_{\text{sphere}}}, \quad \begin{cases} O_{\text{sphere}} = \pi d_{\text{sphere}}^2 \\ V_{\text{sphere}} = \frac{\pi d_{\text{sphere}}^3}{6} \end{cases} \quad (3.6)$$

where O_{sphere} = the surface area of the sphere and V_{sphere} = the volume of the sphere is inserted. If (3.5) is inserted into (3.6), after dividing by the reference volume V_{total} , we have:

$$\Gamma = \frac{V_{\text{excess paste}}}{6 \cdot \varphi} = \frac{1 - \frac{\varphi}{\varphi^*}}{6 \cdot \varphi} \quad (3.7)$$

The relative paste thickness can thus be expressed using the general expression:

$$\Gamma = \frac{1 - \frac{\varphi}{\varphi^*}}{f/k \cdot \varphi} \quad (3.8)$$

where

- φ is the aggregate packing degree
- φ^* is the aggregate maximum packing degree
- f/k is a factor that describes the aggregate particle shape – is equal to six for the perfect sphere and higher for all other geometries. The more the particle shape deviates from the sphere, the higher its value.

For Danish SCC concrete Γ will typically be at values between 0.02 and 0.05.

The material model (3.1) and (3.2), together with (3.8), predict that the rheology of a concrete is a function of the paste composition through its rheology expressed by $(\eta_{\text{paste}}, \tau_{0,\text{paste}})$, of the aggregate composition (φ^*), of the aggregate particle shape (f/k), and of the volumetric ratio between paste and aggregate expressed by φ .

Thus, basically, the workability of a concrete can be adjusted either by adjusting the paste workability (η_{paste} or $\tau_{0,\text{paste}}$) and/or by adjusting the relative paste thickness (Γ). If the plastic viscosity or the yield stress of the paste phase is increased, the plastic viscosity or yield stress of the concrete increases as well. If the relative paste thickness of a concrete is increased, then the plastic viscosity and the yield stress of the concrete decrease – see Figure 3.3 as well.

In Chapter 4 the influence of specific changes to the concrete composition is discussed and supported by experimental measurements, and the material model is used to explain the observations made.

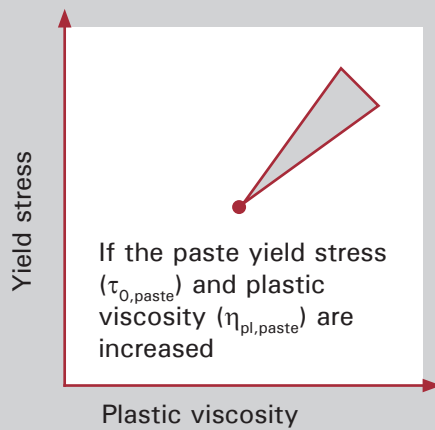
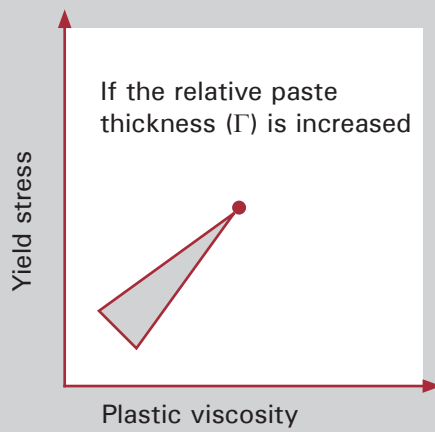


Figure 3.3. Fundamental changes to the rheology of a concrete as predicted by the material model.

4. Composition and flow properties

4.1 AMOUNT OF AGGREGATE (ϕ)

The volume share of aggregate in SCC is significant for its workability just as it is for conventional slump concrete. Experiences with slump concrete have been that when the aggregate content is decreased, the slump increases, e.g. Popovics, "Betonbogen" ["The Concrete Book"], 2nd Edition, page 681 and CtO Beton-Teknik, November 2, 1999, Aalborg Portland. "Pakningsberegninger anvendt til betonproportionering" ["Packing calculations used in concrete proportioning"]. The latter shows, among other things, that an increase in the volume fraction of the aggregate equal to 10 litres per m^3 reduces the slump by 50 mm. Unfortunately, no comparable data are available for SCC, but it is clear that an increase in the volume fraction of the aggregate will mean a higher yield stress (lower slump flow) and a higher plastic viscosity. This is also consistent with the material model that predicts that an increase in the volume fraction of the aggregate (ϕ), which is equal to the relative paste thickness (Γ) being reduced, leads to an increase in both the yield stress and the plastic viscosity.

Table 4.1 shows an example of the effect of increasing the paste content (decreasing the volume fraction of the aggregate). Both yield stress and plastic viscosity decrease when the amount of paste (l/m^3) is increased. This is consistent with the material model, see Figure 3.3, as an increase in the paste content means an increase in the relative paste thickness (Γ).

4.2 AGGREGATE SHAPE (f/k)

It is very significant whether rounded or angular aggregate is used in SCC. Angular grain requires more paste per m^3 than round grain, which is also known from conventional slump concrete. As shown in Figure 4.3, the same yield stress can be achieved with a composition that calls for approximately 50 litres/ m^3 less paste if round sea dredged materials are used rather than crushed granites. If it was possible to use glass beads (both as coarse and fine aggregate), it would be possible to save an additional 50 litres/ m^3 paste compared to the natural rounded aggregate.

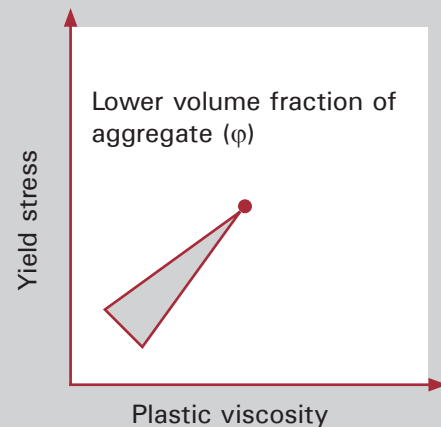


Figure 4.1. If the aggregate amount (ϕ) is reduced, both the plastic viscosity and yield stress are reduced.

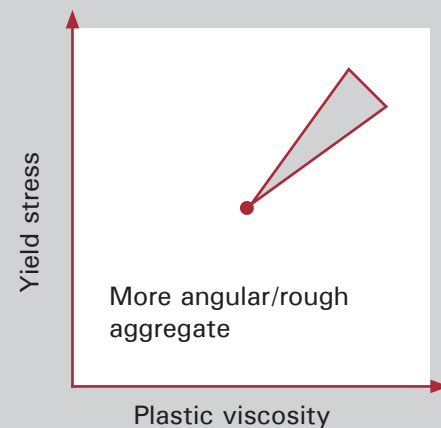


Figure 4.2. If the angularity or roughness (f/k) of the aggregate is increased, then both the plastic viscosity and yield stress increase as well.

Concrete	Aggregate (l/m ³)	Excess paste (l/m ³)	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·s)
A	712.1	140	495	94	44
B	699.7	155	580	44	39
C	691.4	165	620	32	29

Table 4.1. Changes to the rheological parameters as a result of increasing paste content in SCC.

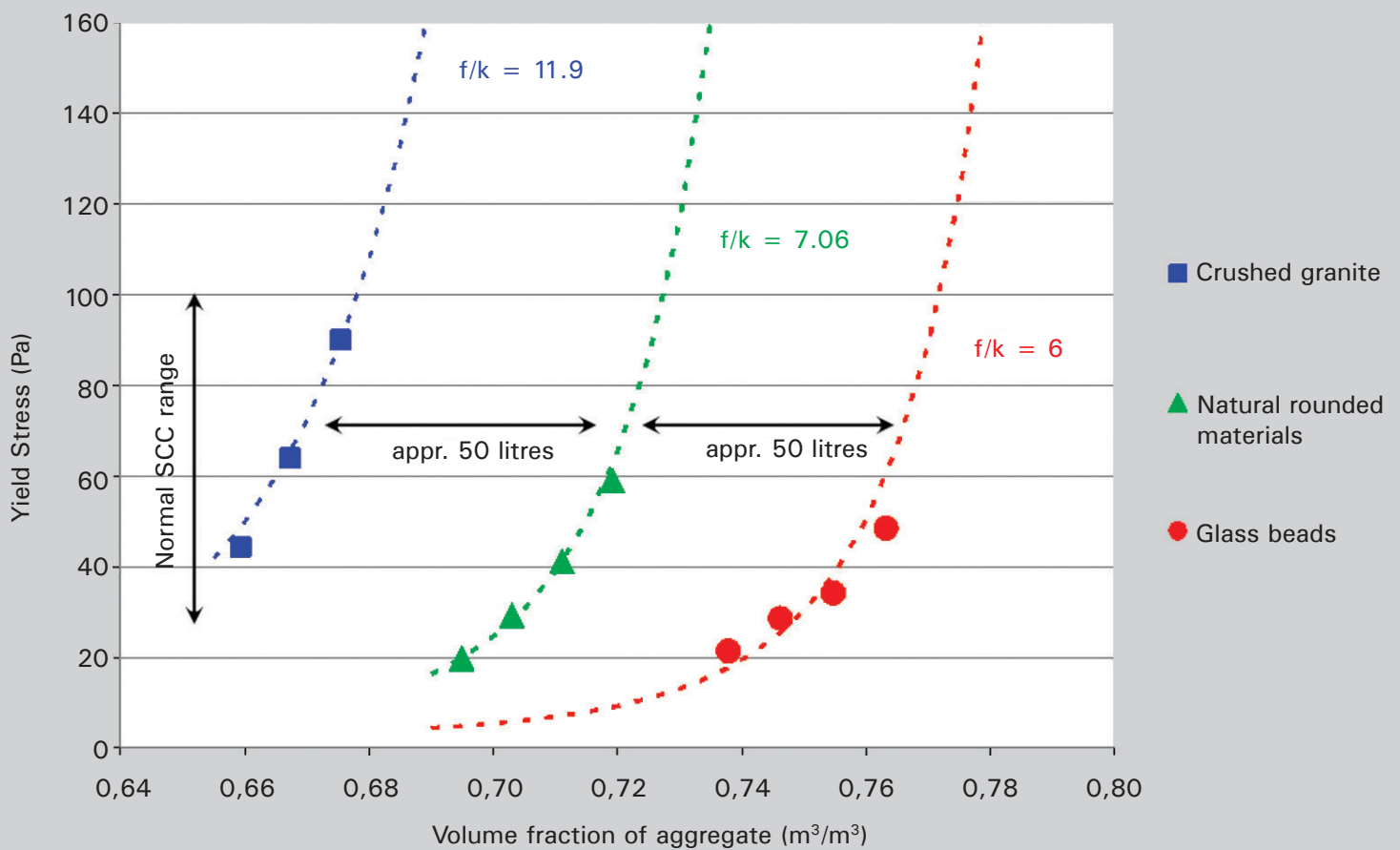


Figure 4.3. The influence of the aggregate shape and roughness (f/k) on yield stress of SCC illustrated from plotting yield stress as a function of the volume fraction of aggregate in the concrete. Dashed lines and f/k values estimated based on the material model (Equation 3.2).

4.3 FINE AGGREGATE GRAIN CURVE

For fine aggregate combined as a mixture of different fractions of dried quartz sand, an increase in the fineness of the aggregate will cause both the plastic viscosity and the yield stress to increase when the rest of the concrete composition remains constant (Table 4.2). However it is important to note that it is relatively complex to evaluate the effect of the fine aggregate grain curve on the flow properties of SCC. In order to conclusively evaluate the influence of the fine aggregate grain curve on flow properties it is necessary to work with a type of fine aggregate where density, particle shape, etc., are identical for all of the fine aggregate particles, regardless of size. For natural materials it will rarely be possible to comply with these requirements, and it is not possible to draw direct comparisons between two different sources of aggregate. It should also be noted that the packing degree of the fine aggregate, and consequently of the composite aggregate, is likely to change when the fine aggregate grain curve is altered. It is also not known what influence the fine aggregate grain curve has on SCC's sensitivity towards the natural variations of the properties of the raw materials, e.g. perhaps a finer grain curve makes for more robust SCC mix designs.

4.4 WATER TO CEMENT RATIO

The realistic scenario to consider in connection with the w/c-ratio is the influence on the plastic viscosity under the prerequisite that the yield stress (slump flow) remains constant. If the w/c-ratio is reduced, it will require the amount of superplasticizing additive to be increased to maintain the slump flow. An increase in the plastic viscosity is also observed, which is likely due to the fact that the paste solid matter content is higher the lower the water/cement ratio is. Table 4.3 shows an example of the influence of the w/c-ratio on rheological parameters. Concretes A and B were mixed at a ready mixed concrete production facility and were identical in composition, apart from the w/c-ratio which was 0.59 and 0.40 respectively. As the table shows, the plastic viscosity of the low w/c-ratio concrete was significantly higher than that of the high w/c-ratio concrete.

4.5 FLY ASH

Fly ash is commonly used in Danish SCC. Fly ash consists of spherical particles that are approximately the same size as cement grain, but with a significantly lower density averaging approximately 2300 kg/m³. In Denmark fly ash has a k-factor of 0.5. Consequently, 2 kg of fly ash replaces 1 kg of cement when calculating the water/cement ratio. Therefore, when proportioning concrete and the paste content is kept constant, the fly ash will replace both cement and water. Higher fly ash content in concrete will result in increasing the solid matter volume in the paste due to the k-factor and the lower density of the fly ash. This results in the plastic viscosity increasing as well as the need for superplasticizing admixture, i.e. is analogous to a reduction of the water/cement ratio.

Table 4.4 shows the results of some measurements on SCC concrete with varying fly ash content but at constant paste content and water/cement ratio.

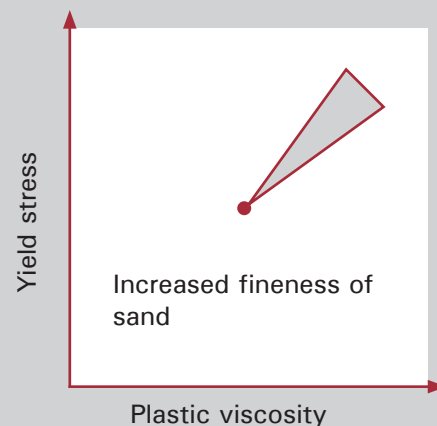


Figure 4.4. If the fineness of the sand is increased while maintaining the same fine to coarse aggregate ratio the yield stress and the plastic viscosity increase.

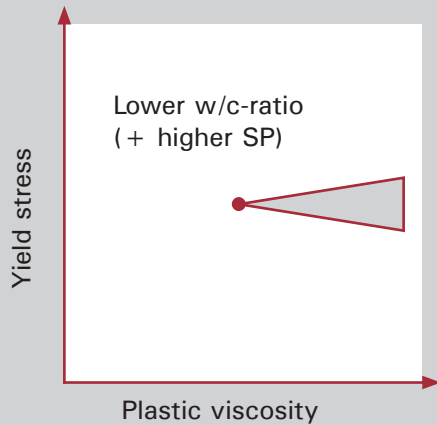


Figure 4.5. Lower w/c-ratio increases the plastic viscosity when the yield stress is kept constant (constant paste volume).

A lower w/c-ratio requires more superplasticizing additive (SP) if the volume of paste remains constant.

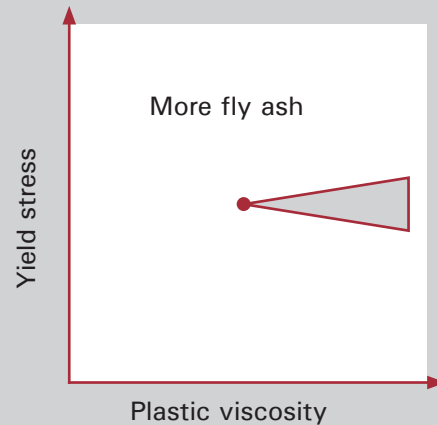


Figure 4.6. Higher fly ash content increases the plastic viscosity at constant yield stress (constant w/c-ratio and paste content). Higher fly ash content increases the need for SP (constant w/c-ratio).

Concrete	Fine aggregate	Passing 0.250 mm (%)	SP dosage (% af powder)	Water/cement	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	Fine	30	0.79	0.38	400	265	191
B	Medium	20	0.79	0.38	430	191	86
C	Coarse	10	0.79	0.38	540	64	68

Table 4.2. Effect of the fine aggregate grain curve on the rheological parameters of SCC.

Concrete	Aggregate (l/m ³)	Water/cement	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	341	0.59	630	30	47
B	341	0.40	675	21	223

Table 4.3. Lower w/c-ratio increases the plastic viscosity at constant yield stress and paste content. Superplasticizing additive dosage was 0.9% for Concrete A and 1.6% for Concrete B.

Concrete	Cement:Fly ash (vol:vol)	Paste (l/m ³)	Water/cement	SP kg/m ³	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	60:40	300	0.59	1.17	570	44	11
B	50:50	300	0.59	1.51	565	46	22
C	40:60	300	0.59	1.60	580	41	28

Table 4.4. Higher fly ash content increases the plastic viscosity when the yield stress, water/cement ratio and paste content is kept constant.

4.6 SILICA FUME

Silica fume consists of spherical particles that on average are approximately 100 times smaller than cement grain, and has a significantly lower density averaging approximately 2200 kg/m³. Silica fume has a k-factor of 2. Consequently, 1 kg of silica fume replaces 2 kg of cement when calculating the water/cement ratio. If the cement paste content otherwise remains constant, replacement of cement with silica fume leads to an increase in the water content of the concrete. Higher silica fume content in concrete will thus result in a reduction of the solid matter volume in the paste due to the k-factor as this effect is not fully counteracted by the lower density of silica fume compared to cement.

Table 4.5 shows an example of how higher silica fume content affects the rheological properties of SCC concrete as the w/c-ratio, the paste content and the slump flow remain constant. It shows that the plastic viscosity decreases when the silica fume content is increased. For example, the plastic viscosity drops down to approximately half if 14 volume percent cement is replaced with silica fume.

4.7 SUPERPLASTICIZING ADDITIVE (SP)

SP is necessary to produce SCC. When the dosage of SP is increased, the concrete's yield stress decreases while the plastic viscosity remains largely unaffected.

Table 4.6 shows an example of the influence of the dosage of SP on the rheological parameters.

There are many types of superplasticizing additives on the market, and they are not all equally suited to every type of concrete. Thus there are examples of incompatibility between cement type and superplasticizer, where it has simply been impossible to achieve satisfactory flow properties such as e.g. sufficiently low yield stress of SCC.

4.8 VISCOSITY MODIFYING AGENTS (VMA)

VMA are commonly used for SCC in some countries, but in Denmark this type of additive is only used moderately. Based on results for two types of VMA, it seems that this type of additive exclusively affects the rheological properties through an increase in the yield stress. The term VMA covers a wide range of chemically very different compounds, and it cannot be ruled out that there are products that have a different effect on the rheological parameters than the one described here.

VMA can be used to "save" a concrete that would otherwise segregate due to an excessively low yield stress. There has also been hypothesised that VMA may have a positive effect on the pumpability of SCC, which could certainly be the case, but has yet to be convincingly documented.

Table 4.7 shows examples of the influence of VMA on the rheological properties of SCC.

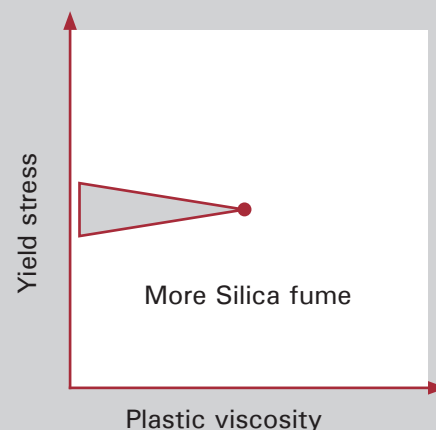


Figure 4.7. Miosilica reduces the plastic viscosity for maintained yield stress, paste content and w/c-ratio. Silica fume contents greater than approximately 8% by volume of the power increase the need for SP (constant w/c-ratio).

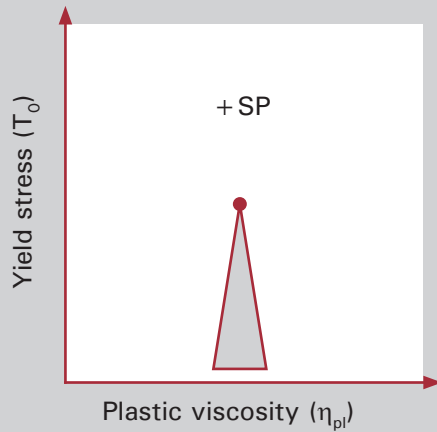


Figure 4.8. A higher dosage of superplasticizing additive reduces the yield stress. A higher dosage of superplasticizing additive does not affect the plastic viscosity significantly.

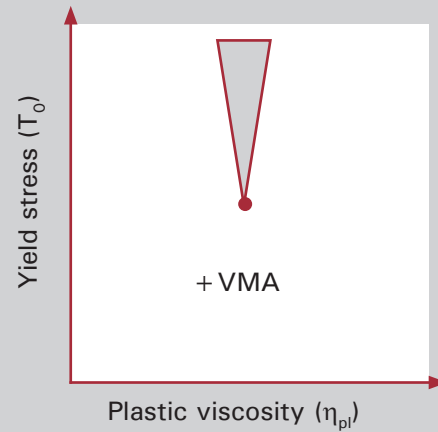


Figure 4.9. Addition of VMA increases the yield stress. Addition of VMA does not affect the plastic viscosity significantly.

Concrete	Cement:Silica fume(vol:vol)	SP (kg/m ³)	Paste (l/m ³)	Water/cement	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	100:0	3.85	300	0.38	545	59	85
B	96:4	3.77	300	0.38	520	74	64
C	92:8	4.03	300	0.38	540	62	59
D	86:14	4.18	300	0.38	480	110	39
E	75:25	4.95	300	0.38	500	90	37

Table 4.5. Influence on the rheological parameters as a result of a higher silica fume content at "constant" yield stress, w/c-ratio and paste content.

Concrete	SP dosage (% of powder)	Water/cement	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	0.79	0.38	191	86
B	0.89	0.38	37	79
C	0.97	0.38	27	65

Table 4.6. Influence on the rheological parameters as a result of a higher dosage of superplasticizing additive at constant w/c-ratio and paste content.

Concrete	VMA (% af powder)	Water/cement	Slump flow (mm)	Yield stress (Pa)	Plastic viscosity (Pa·sec)
A	-	0.59	615	33	24
A	0.20 %	0.59	570	48	30
B	-	0.42	575	46	62
B	0.30 %	0.42	480	110	65

Table 4.7. Rheological parameters of two concretes prior to and after addition of VMA.

4.9 AIR ENTRAINMENT

Air entraining admixture is frequently used in Denmark, even in concrete that does not have requirements for frost resistance. Air entraining admixture should probably be regarded as part of the paste phase, even though air does not have the same effect on improving workability as paste. This is illustrated in Figure 4.11, which shows that when maintaining the same volume of paste + air, the slump flow decreases at increasing air content in the concrete. Figure 4.12 shows the effect of increasing the amount of entrained air at the expense of aggregate. The result is that the slump flow increases with increasing air entrainment up to an air content of approximately 6%, after which the slump flow is not affected by further air entrainment. Replacement of air with aggregate is analogous to reducing the volume fraction of aggregate which, according to the material model, should also lead to a higher slump flow (yield stress) and to a lower plastic viscosity. However, the latter could not be confirmed in the tests as plastic viscosity was not measured.

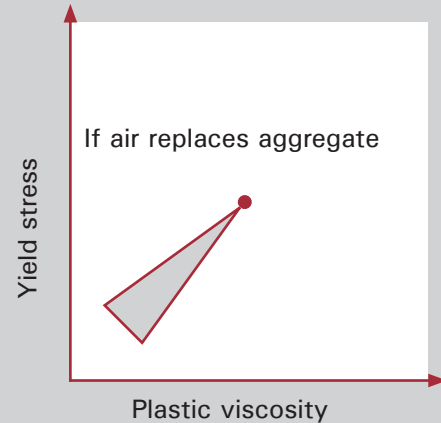


Figure 4.10. If air replaces aggregate, the workability is increased up to approximately 6% entrained air. Increasing the air admixture content to above 6% by volume does not contribute to increased workability. A volume paste provides greater workability than the same volume of entrained air.

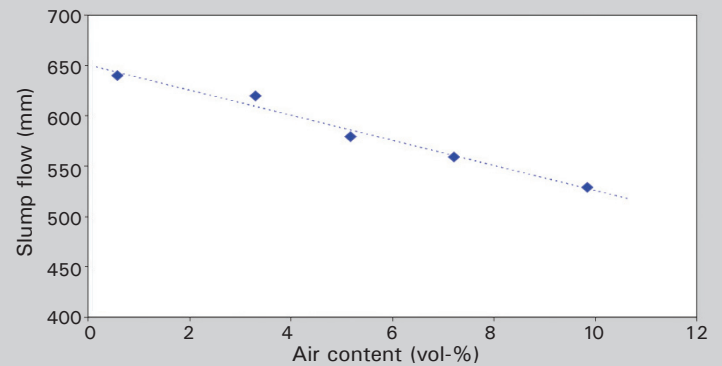


Figure 4.11. Slump flow as a function of air content for concrete with constant paste + air content. A volume of paste provides greater workability than the same volume of entrained air.

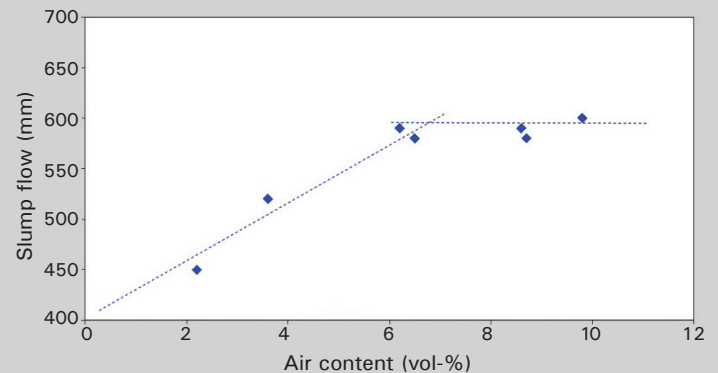


Figure 4.12. Slump flow as a function of air content for concrete with constant paste content and increasing air content. Replacing aggregate with air improves workability (higher slump flow) up to approximately 6% entrained air.

4.10 ADJUSTING THE RHEOLOGY OF A CONCRETE MIX DESIGN

To adjust the rheology of an existing mix design, Table 4.8 can provide inspiration for how to do so through changes to the concrete composition.

MIX DESIGN CHANGE	YIELD STRESS	PLASTIC VISCOSITY
More paste (less aggregate)	↓	↓
More SP	↓	↓
More fly ash	remains constant	↑
More silica fume	remains constant	↓
More VMA	↑	remains constant
Higher water/cement ratio	remains constant	↓
More rounded grain shape	↓	↓
Increased fineness of fine aggregate	↑	↑

Table 4.8. Effect of mix design adjustments on the rheological parameters of SCC. The green field means that the value of the parameter is reduced by the stated change, red means that the value increases, yellow means that the parameter is not affected.

5. Concept for developing a new SCC

Composition of Danish SCC is not very different from that of traditional slump concrete. The most important difference is that SCC has higher paste content. The following gives a step-by-step description of a concept for designing of an SCC mix from the bottom. Subsequently, an example of implementation of the described concept is provided.

1. The packing degree of the individual aggregate materials is determined, see CtO Beton-Teknik [*Concrete Technology*]. "Pakningsberegninger anvendt til betonproportionering" [*Packing calculations used for concrete proportioning*].
2. A packing simulation calculation is performed for the combination of aggregates, for example, using a utility program such as 4C-Packing (from the Danish Technological Institute). 4C-Packing combines three aggregate fractions and provides a triangular diagram of the packing degree as a function of the volume percentage of each aggregate. A combination of aggregate that is slightly on the mortar rich side of the packing optimum is selected, i.e. in the area where iso-curves are far from each other so that variations in the aggregates will have limited influence on the packing degree. Figure 5.1 shows an example. If economically justifiable, a higher fine aggregate content may be used from a rheological standpoint.
3. The exposure and strength class are given based on the specifications for concrete, which sets requirements for the type of cement, mineral additives and minimum water/cement ratio. The powder composition is thus established the traditional way. Knowing the desired powder combination (it is assumed here that a combination of cement and fly ash are used, however, other combinations of powder, silica fume, lime filler, etc., may be used, the formulas just need to be corrected to count for this) and the water/cement ratio, the water requirements can be calculated using the following expression:

$$\left(\frac{v}{c}\right)_{\text{eqv}} = \frac{m_v}{m_c + K_{fa} m_{fa}} \quad \text{and} \quad x_{fa} = \frac{m_{fa}}{m_c} \quad (5.1)$$

which includes a cement + fly ash powder combination, as is often the case with Danish SCC. The index equiv means that water/cement ratio is calculated taking the k-factor, K_{fa} , into consideration. The weight of fly ash divided by the weight of cement is termed x_{fa} . The two expressions combine into a new expression for the water content as a function of the powder combination:

$$m_v = m_c \left(\frac{v}{c}\right)_{\text{eqv}} (1 + K_{fa} x_{fa}) \quad (5.2)$$

and the fly ash content is determined by

$$m_{fa} = x_{fa} m_c \quad (5.3)$$

4. SCC is typically defined by a specified slump flow, which corresponds to amount of excess paste in the concrete. A good starting point for a target slump flow of 550 mm will be 140 l/m³ excess paste for rounded aggregate and 180 l/m³ excess paste for crushed aggregate, if the concrete does not contain air entraining admixture. If the concrete does contain air entraining admixture (target 5-6% air), the starting point should be approximately 20 l/m³ less of excess paste. The amount of aggregate and excess paste are related in the following expression:

$$V_{\text{aggregate}} = (1 - V_{\text{excess paste}}) \varphi^* \quad (5.4)$$

where, φ^* is the selected packing degree obtained from the packing analysis. When the aggregate volume and aggregate density are known, the weight of the specific aggregate fractions can be easily calculated.

5. Using the total volume balance the content of the remaining constituent can now be calculated from the following expression:

$$V_v + V_c + V_{fa} = 1 - V_{aggr} - V_{air} - V_{add} \quad (5.5)$$

where the left side expresses the paste volume and the right side expresses the cavity between the aggregate with deductions for air and additives. After a slight rearrangement the following expression can be arrived at:

$$\frac{m_v}{\rho_v} + \frac{m_c}{\rho_c} + \frac{m_{fa}}{\rho_{fa}} = 1 - V_{aggr} - V_{air} - V_{add} \quad (5.6)$$

Now, enter (5.2) and (5.3) on the left side of (5.6) and the only unknown will be the cement content, which afterwards can be expressed as:

$$m_c = \frac{1 - V_{aggr} - V_{air} - V_{add}}{\left(\frac{v}{c}\right)_{eqv} \frac{(1 + K_{fa} \cdot x_{fa})}{\rho_v} + \frac{1}{\rho_c} + \frac{x_{fa}}{\rho_{fa}}} \quad (5.7)$$

from which the cement content can be determined, assuming that air content and additives content are known parameters. Thus, once the cement content is determined, the water and fly ash content can also be determined using (5.2 and 5.3) under Item 3.

6. The resulting concrete composition will be a good starting point for the trial mixing that always has to be performed in order to determine the needed content of additives that can vary considerably depending upon a number of factors, such as e.g. the additive itself, the cement, and the mixing procedure.

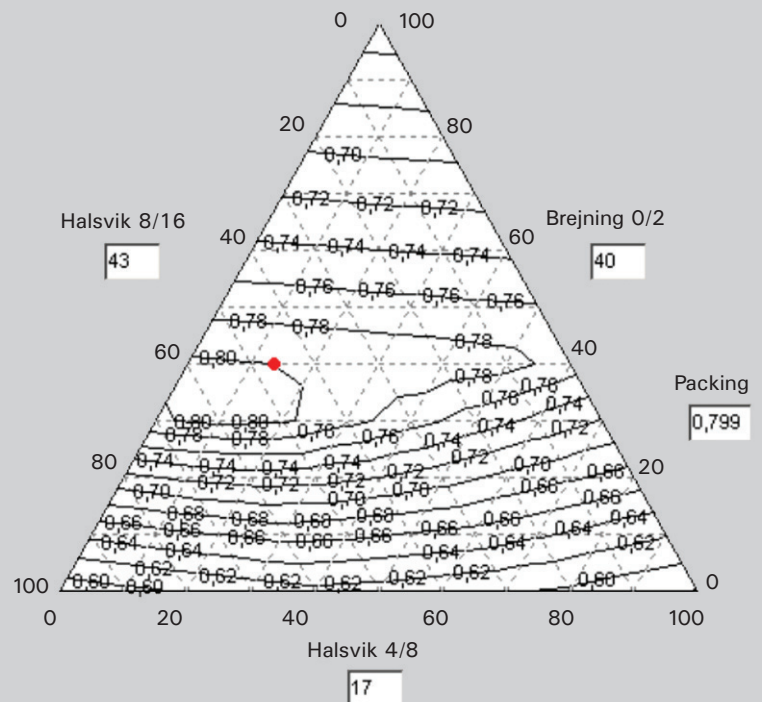


Figure 5.1. Packing triangle for typical Danish Class E aggregate materials. The red dot represents a good combination of aggregate materials with a 0.799 (ϕ') packing degree.

Example

A SCC concrete must be proportioned based on the following prerequisites:

- Strength Class C25
 - Water/cement ratio = 0.59
 - Cement, CEM I ($\rho_c = 3160 \text{ kg/m}^3$)
 - Fly ash is used ($\rho_{fa} = 2300 \text{ kg/m}^3$ og $K_{fa} = 0.5$)
 - $x_{fa} = 0.667$, i.e. a 2:3 ratio between fly ash and cement based on weight
- Slump flow = 550 mm
- Air content in the fresh concrete = 1.5 %, i.e. no air entrainment
- Aggregate materials (rounded shape): 0/4 (density_{SSD} = 2643 kg/m³), 4/8 (density_{SSD} = 2682 kg/m³), 8/16 (density_{SSD} = 2648 kg/m³)

Step 1:

The packing degree of the three aggregate fractions was determined to be 0.700 (0/4 fraction), 0.663 (4/8 fraction) and 0.643 (8/16 fraction). Figure 5.2 shows the packing diagram for the three fractions. The selected aggregate composition on a volume basis is 40% 0/4, 20% 4/8 and 40% 8/16 with a packing degree of 0.828.

Step 2:

The mix design's content of aggregate can now be calculated using (5.4):

$$V_{\text{aggr}} = (1 - V_{\text{excess paste}}) \cdot \phi^* = (1 - 0.140) \cdot 0.828 = 0.712 = 712 \text{ l/m}^3$$

As the aggregate materials are rounded, an excess paste content of 140 l/m³ is selected. The aggregate volume will thus be 712 l/m³ and divided into the three fractions equal to 284.8, 142.4 and 284.8 l/m³ for fractions 0/4, 4/8 and 8/16 respectively. These volumes can naturally be converted to kg/m³ based on the knowledge of the density of the aggregate materials.

Step 3:

The total amount of paste, including air and additives, comes to 1,000 l/m³ – 712 l/m³ = 288 l/m³. The air content is 15 l/m³ and the additives (dry matter) are estimated to be 0.5 l/m³, thus there should be a total of 272.5 l/m³ cement, fly ashes and water in the concrete.

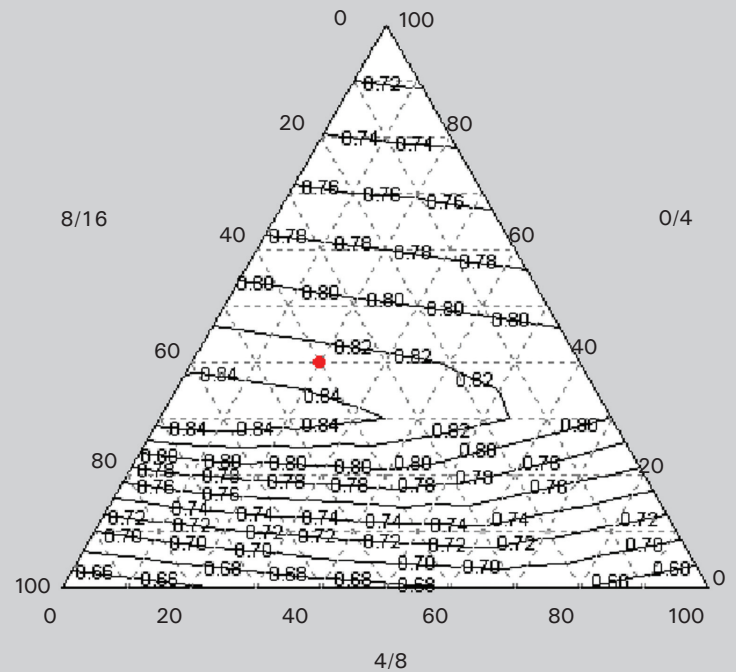


Figure 5.2. Packing diagram calculated using 4C-Packing for the 0/4, 4/8 and 8/16 fractions used in the example. The selected combination of aggregate symbolized by the red dot (40% 0/4, 20% 4/8 and 40% 8/16) has a packing degree, ϕ^* , of 0.828.

The cement content is calculated by entering into (5.7):

$$m_{\text{cement}} = \frac{1 - 0.712 - 0.015 - 0.0005}{\frac{0.59 \cdot (1 + 0.5 \cdot 0.667)}{1000} + \frac{1}{3160} + \frac{0.667}{2300}} \left(\frac{\text{m}^3}{\text{m}^3} \right)$$

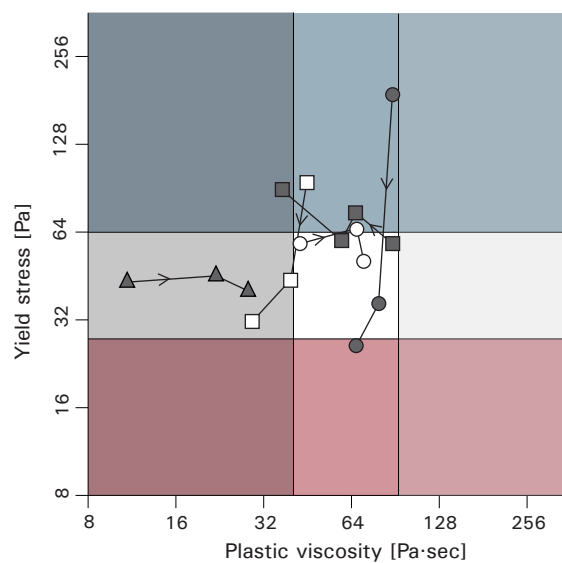
$$= \frac{0.2725}{0.001393} = 195.6 \frac{\text{kg}}{\text{m}^3}$$

By inserting into (5.2) and (5.3) it is found that the concrete should contain 130.4 kg fly ash and 153.8 kg water per m³.

Step 4:

An appropriate SP dosage was found based on a test mixing, and the final mix composition is shown below:

Material	SSD [kg/m ³]
Cement	195.6
Fly ash	130.4
Water	153.8
Fine aggregate 0/4 mm	754
Coarse aggregate 4/8 mm	382
Coarse aggregate 8/16 mm	753
Superplasticizing additive	2.0
Air (l/m ³)	15
Water/cement ratio	0.59
Slump flow (mm)	550
Yield stress (Pa), 4C-Rheometer	57
Plastic viscosity (Pa·sec), 4C-Rheometer	37



● SP, increased dosage – w/c and paste content remain constant.

■ Silica fume, increasing content - Equivalent w/c and yield stress remain almost constant by varying the dosage of superplasticizer.

▲ Fly ash, increasing content - Equivalent w/c and yield stress remain almost constant by varying the dosage of superplasticizer.

○ Equivalent w/c, decreasing value – Paste content remains constant and yield stress almost remains constant by varying the dosage of superplasticizer.

□ Paste, increasing content – Equivalent w/c and dosage of superplasticizer remain constant.