A MODEL APPROACH TO DESCRIBE THE FRESH PROPERTIES OF SELF-COMPACTING CONCRETE (SCC)

EIN MODELLANSATZ ZUR BESCHREIBUNG DER FRISCHBETON-EIGENSCHAFTEN VON SELBSTVERDICHTENDEM BETON (SVB)

UN MODELE DECRIVANT LES PROPRIETES A L'ETAT FRAIS DES BETONS AUTOPLAÇANTS

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SUMMARY

Within the scope of a parameter study the influence of the mixture composition on the fresh concrete properties of self-compacting concrete was investigated. The concrete was modelled as a two-phase system, consisting of the fluid phase “paste” and the solid phase “aggregates”. Thus the consistency control parameters paste volume, mortar volume and the coarse aggregate volume could be transferred into the model parameter excess paste thickness. By means of this model parameter the characteristic values of the standard tests – such as slump flow test and V-funnel test – and the fundamental rheological parameters yield stress and the plastic viscosity could be described.

ZUSAMMENFASSUNG

Im Rahmen einer Parameterstudie wurde der Einfluss der Betonzusammensetzung auf die Frischbetoneigenschaften von selbstverdichtendem Beton untersucht. Der Beton wurde als Zwei-Phasen-System modelliert, das aus der flüssigen Phase Leim und der festen Phase Gesteinskörnung besteht. Somit konnten die Konsistenzsteuerparameter Leimvolumen, Mörtelvolumen und Grobkornvolumen in den Modellparameter Leimschichtdicke überführt werden. Mit Hilfe dieses Modellparameters ließen sich die Kennwerte der Standprüfverfahren – wie z.B. Setzfließmaß und Trichterauslaufversuch – und die fundamentalen rheologischen Kennwerte Fließgrenze und plastische Viskosität beschreiben.

RESUME

Dans le cadre d'une étude paramétrique, l'influence de la composition sur les propriétés à l'état frais des bétons autoplaçants a été analysée. Le béton a été modélisé par un système bi-phase composé de la phase fluide "pâte pure" et de la phase solide "granulats". Ainsi les paramètres contrôlant la consistance (volume de la pâte pure de ciment, du mortier et des gros granulats) ont pu être convertis en un paramètre épaisseur de pâte. Ce paramètre permet de décrire les valeurs caractéristiques des tests standards – comme par exemple l'essai d'étalement et l'essai d'écoulement – et les paramètres rhéologiques fondamentaux que sont la limite d'écoulement et la viscosité plastique.

KEYWORDS: Self-compacting concrete, SCC, rheological behaviour, model for SCC, excess paste thickness

1. INTRODUCTION

The flow behaviour (rheological behaviour) of self-compacting concrete is mostly characterized by test methods like the slump flow test and the V-funnel test etc. The equipment is inexpensive and the tests are easy in handling and therefore suitable for use on site. But they have one disadvantage: they provide no fundamental physical flow parameters. Fundamental parameters can only be derived from so-called flow curves which are obtained by means of viscometers or rheometers. A flow curve of a fluid describes the relationship between the shear stress τ and the shear rate $\dot{\gamma}$. Many fluids like water or oil behave like a Newtonian fluid where the shear stress is directly proportional to the shear rate. This relationship is expressed by Eq. (1). The characteristic value of such a Newtonian fluid is the viscosity η.

$$\tau = \eta \cdot \dot{\gamma} \tag{1}$$

In contrary to a Newtonian fluid fresh ordinary concrete and also self-compacting concrete starts to flow only if the shear stress exceeds the yield stress τ_0. In the simplest way fresh concrete can be modelled by a Bingham fluid (Eq. (2)). In such a case two characteristic parameters are necessary to describe the flow curve. These are the yield stress τ_0 and the plastic viscosity η_{pl}.

$$\tau = \tau_0 + \eta_{pl} \cdot \dot{\gamma} \tag{2}$$

In the literature papers dealing mostly with the modelling of the rheological parameters τ_0 and η_{pl}. In this article a simple model approach is presented which is also applied to the standard consistency parameters of the slump flow test and the V-funnel test. In this approach the self-compacting concrete is considered as a two phase system which consists of the fluid phase paste and the solid phase aggregates.

2. SCOPE OF INVESTIGATION

2.1 Varied parameters

Three self-compacting concrete mixtures (Table 1) were the backbone of a test programme in which the influence of the concrete composition on the rheological behaviour was investigated. The main differences between these three reference concretes were the type of filler (limestone powder LS respective fly ash FA), the equivalent water-cement ratio $(w/c)_{eq}$ and the particle-size distribution of the aggregates (Fig. 1a).

Table 1: Mixture proportions of the reference concretes; filler types: limestone powder (LS) and fly ash (FA)

Component			**LS (A) Powder Type**	**FA (A) Combination Type**	**FA (B) Combination Type**
Strength class			C30/37	C45/55	C45/55
Cement content (CEM II/A-LL 32.5R)	m_C	[kg/m³]	239	345	311
Equivalent water-cement ratio	$(w/c)_{eq}$ [1)]	[-]	0.70	0.43	0.45
Superplasticizer (Woermann FM/BV 375, type: PCE)	m_{SP}/m_C	[% by mass of cement]	1.00	1.05	1.25
Total water content (inclusive water from superplasticizer)	m_w	[kg/m³]	166.1	169.6	158.0
Viscosity agent (Woermann UW Compound)	m_{VA}/m_C	[% by mass of cement]	0	0.10	0.10
Mass of filler (limestone LS or fly ash FA)	m_F	[kg/m³]	337	194	175
Aggregates (round, river sand and gravel)	m_A	[kg/m³]	1600	1604	1686
Powder content (cement and filler)	m_P	[kg/m³]	576	540	486
Water-powder ratio (by volume)	V_w/V_P	[-]	0.82	0.86	0.89
Paste volume (inclusive 15 litres of air)	V_{Paste}	[litres/m³]	385	383	352
Mortar volume (paste and aggregates < 4 mm)	V_M	[litres/m³]	670	709	648

1) $$(w/c)_{eq} = \frac{m_W}{m_C + 0.4 \cdot m_{FA}}$$

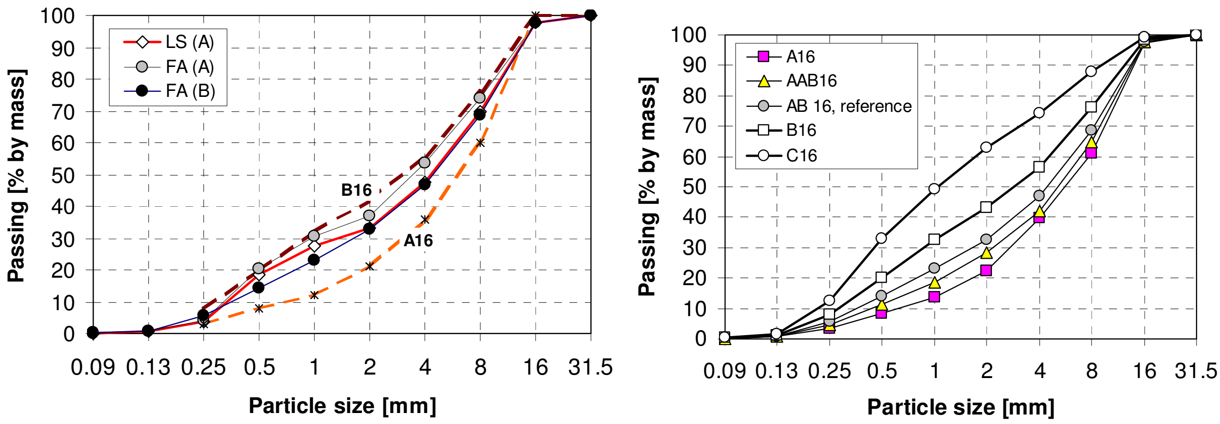
These reference concretes are identified by the filler type followed by “A” or “B”. Table 2 gives a survey of the parameter variations. Based on the reference concretes LS (A) and FA (A) the paste volume V_{Paste}, mortar volume V_M and also the coarse aggregate volume $V_{A>8}$ was changed. The change of the coarse aggregate volume $V_{A>8}$ was controlled by the mass ratio $m_{A,4/8}$: $m_{A,8/16}$ whereas the total volume of aggregates, paste and mortar were held constant. To investigate how the particle-size distribution of the aggregates influences the flow behaviour of SCC a set of different particle-size distributions was chosen

(Fig. 1b) which are lying within the range of the standardized particle-size distributions A16 and C16 according to Appendix L of DIN 1045-2 [1]. For this variation the reference concrete FA (B) has built the base (Table 1). All types of variations are given in Table 2, whereas the italic numbers indicate the reference concrete mixtures. The paste volume V_{Paste} consists of the volume parts of water, cement, filler and admixtures and includes an air content of 15 litres per m³ concrete. All concretes were produced with rounded river sand and gravel. The maximum aggregate diameter was set to 16 mm. The particle-size distributions of the aggregates were characterized by the fineness modulus k (Eq. (3), Table 2). Herein stands p_A for the passed aggregates per sieve, whereas the nine sieves from 0.25 mm up to 63 mm are incorporated. The fineness modulus k increases with an increasing maximum aggregate diameter and an increasing coarse aggregate content from C16 to A16 (Table 2).

$$k = \sum_{i=1}^{9} 1 - \frac{p_{A,i}}{100} \tag{3}$$

Table 2: Parameter variations; reference concretes are indicated by italic numbers

Variation		**Type of filler**	**Nr. 1**	**2**	**3**	**4**	**5**
Paste volume	V_{Paste} [litres/m³]	LS (A)	335	366	385	***396***	-
		FA (A)	340	370	***383***	392	-
Mortar volume	V_M [litres/m³]	LS (A)	604	653	***670***	704	-
		FA (A)	638	691	***709***	730	-
Coarse aggregate volume (mass ratio)	$V_{A>8}$ [litres/m³] ($m_{A,4/8} : m_{A,8/16}$)	LS (A)	294 (0 : 100)	***185 (39 : 61)***	155 (50 : 50)	17 (100 : 0)	-
		FA (A)	210 (20 : 80)	***160 (41 : 59)***	137 (50 : 50)	15 (100 : 0)	-
Fineness modulus of the aggregates (V_{Paste} = constant)	k [-]	FA (B)	A 16 4.54	AAB16 4.33	***AB16 4.12***	B16 3.65	C16 2.81

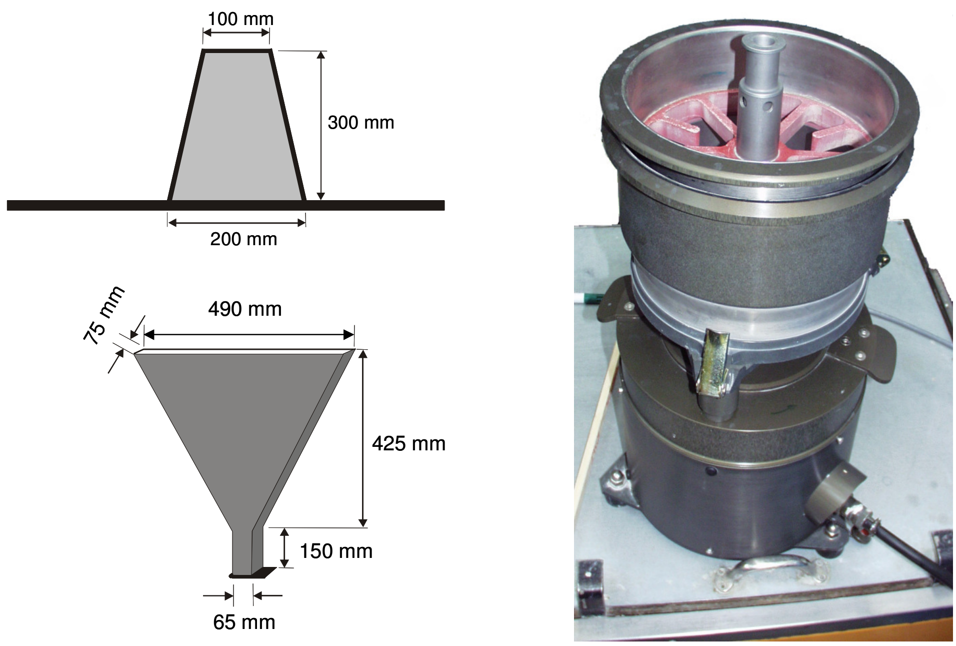


a) b)

Fig. 1: Particle-size distributions of the aggregates; a) reference concretes; A16 and B16 are standing for the standard particle-size distributions according to Appendix L of DIN 1045-2 [1]; b) variations for the concretes including FA (B)

2.2 Rheological investigations

Additionally to the standardized tests like slump flow and V-funnel (dimensions of devices see Fig. 2a) rheological measurements were performed with a concrete rheometer "BTRHEOM" which was developed at LCPC (Laboratoire Central des Ponts et Chaussées Paris, Fig. 2b).



a) **b)**

Fig. 2: a) Dimensions of the slump cone and V-funnel; b) photograph of the "BTRHEOM", inner diameter of the container D = 240 mm, height of the sheared concrete sample h = 100 mm

The BTRHEOM measures the torque which is necessary to shear a concrete sample at a defined number of revolutions. From the measured torque Γ and the number of revolutions n it is possible to derive a Γ-n-curve by a regression analysis (Fig. 3). Such a Γ-n-curve can then transferred into a τ-$\dot{\gamma}$-curve (e.g. Eq.(2)). In the simplest case (Bingham) the measured data can be fitted by a straight line (Eq. (4)). From the torque $\Gamma_{0,B}$ respective the slope of the straight line A_B the yield stress τ_0 respective the plastic viscosity η_{pl} can be calculated. If this linear approach is applied, often negative yield stresses – especially for self-compacting concrete – are calculated. But negative yield stresses are physically not possible. These negative yield stresses have also been described by de Larrard et al. [2] and were confirmed by measurements at the Department of Construction Materials in Stuttgart.

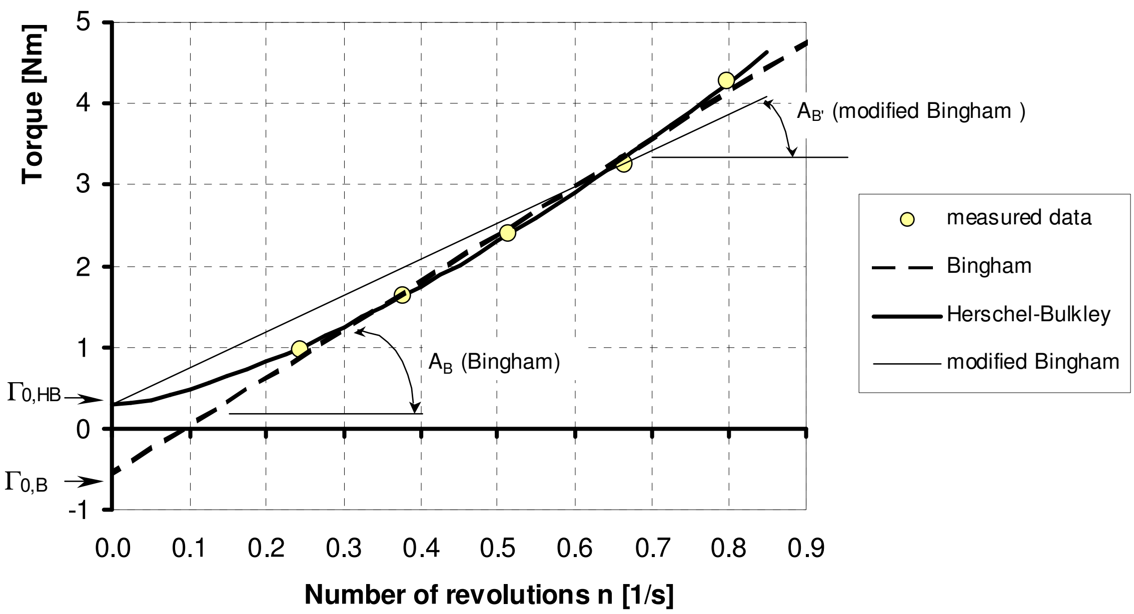


Fig. 3: Examples of different curve fittings

$$\Gamma = \Gamma_{0,B} + A_B \cdot n \tag{4}$$

By means of the application of the so-called Herschel-Bulkley approach (Eq. (5) and (6)) negative yield stresses can be avoided.

$$\Gamma = \Gamma_{0,HB} + A_{HB} \cdot n^b \tag{5}$$

$$\tau = \tau_{0,HB} + a \cdot \dot{\gamma}^{b} \tag{6}$$

However, Eq. (6) implies the disadvantage of three curve parameters, whereas only the yield stress $\tau_{0,HB}$ can physically be interpreted. Hence, a combined method was used in that the Herschel-Bulkley approach was combined with the Bingham approach (modified Bingham method), Eq. (7). The corresponding Γ-n- relationship is given with Eq. (8), see Fig. 3.

$$\tau = \tau_{0,HB} + \eta_{pl,HB} \cdot \dot{\gamma} \tag{7}$$

$$\Gamma = \Gamma_{0,HB} + A_{B'} \cdot n \tag{8}$$

3 RESULTS

3.1 Modelling of the rheological behaviour of SCC

Self-compacting concrete can be considered as a concentrated suspension in that the solids are dispersed in the fluid phase water, de Larrard [3] and Ferraris et al. [4]. Others, Nielsen [5] and Geiker et al. [6], consider self-compacting concrete as a two phase system which consists of the Bingham-phase mortar in that the coarse aggregates are dispersed. The models of these authors are based on the so-called relative solid concentration ϕ/ϕ_{max}.

Generally, the relative viscosity of a suspension, i.e. the ratio between the viscosity of a suspension and the viscosity of the fluid phase, can be traced back to the so-called relative solid concentration of the particles ϕ/ϕ_{max}. Whereas ϕ stands for the volume concentration of the solids in a suspension, ϕ_{max} represents the maximum volume concentration of the particles in the state of the maximum packing and is called maximum packing fraction [7]. The maximum packing fraction ϕ_{max}, being controlled by the type of packing, is very sensitive to particle-size distribution and particle shape [7]. In this context the models for concentrated suspension of Mooney [8] and Krieger and Dougherty [9] have to be mentioned which are both based on the well-known model of Einstein [10] that is only valid for dilute dispersed suspensions [7].

The model presented in this article assumes that SCC consists of the fluid phase paste and the solid phase aggregates, this stands in contrast to models of [3], [4], [5], [6]. The solid-fluid interactions respective the solid-solid interactions are controlled by the so-called excess paste thickness $t_{Paste,ex}$ which is equivalent to the half distance of two neighbouring aggregates if the distance is assumed to be independent of the aggregate size (Fig. 4). The excess paste thickness $t_{Paste,ex}$ can be determined if the excess paste volume $V_{Paste,ex}$, that remains after the voids between the aggregates $V_{A,void}$ are filled with paste, is uniformly layered on the surface of the aggregates. Another approach with a particle-size dependent paste thickness is described by Oh et al. [12]. Krell [11] showed that the consistency of ordinary concrete can be expressed as a function of the thickness of excess paste.

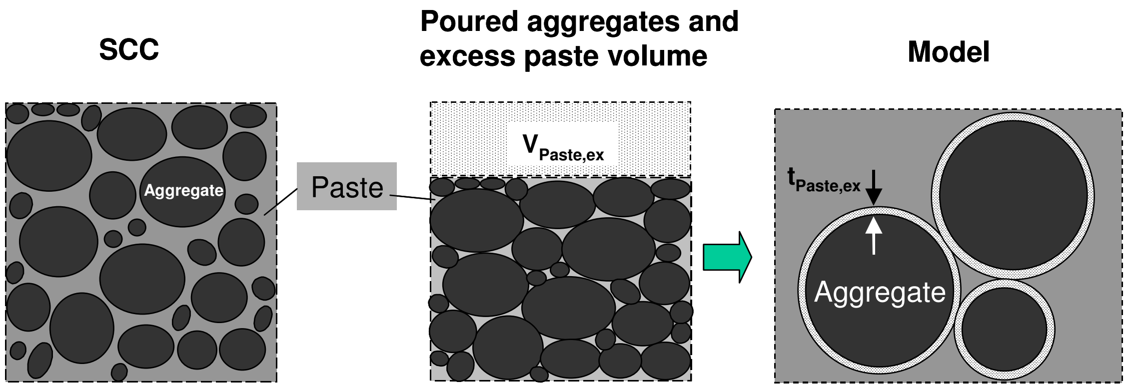


Fig. 4: Model of SCC

The excess paste volume $V_{Paste,ex}$ can be calculated with Eq. (9) where m_A respective ρ_A stands for the mass respective the density of the aggregates. Further is the loose bulk density $\rho_{A,bulk}$ of the aggregates required.

$$V_{Paste,ex} = V_{Paste} - V_{A,void} = V_{Paste} - \frac{m_A}{\rho_A}\left(\frac{\rho_A}{\rho_{A,bulk}} - 1\right) \qquad (9)$$

In this study the loose bulk density was calculated using a 10 litre container according to DIN EN 1097-3 [13]. For this purpose a mass of about 20 kg of dry aggregates 0/16 was first homogenized in the concrete mixer and then filled into the container without any additional compaction as described in [13]. To calculate the excess paste thickness the surface area of the aggregates is required. The aggregates were thereby idealized as spheres. The particle-size distribution of the aggregates is divided into 9 classes according to the sieves of DIN 1045-2

Appendix L [1], see also Table 3. Each class i is represented by the mean particle diameter d_i between two subsequent sieves. Aggregate particles with a diameter < 0.125 mm are ignored. However, they are not part of the paste volume V_{Paste} in Eq. (9), since the powder content of the aggregates is indirectly incorporated in the volume of voids $V_{A,void}$ that is derived from the loose bulk density test.

The results in Table 3 show that the particle fraction 0.25/0.5 mm is dominating with about 48% of the total surface area. This is an evidence for the importance of the fine sand fraction with regard to the workability of concrete respective the flow behaviour of SCC.

Table 3: An example of the calculation of the aggregate surface area per m³ concrete, aggregate particles are considered to be spheres

Particle-size distribution		**Calculation of the surface area S_A**					
Diameter (sieve opening)	Passed aggregates	Class	Representative particle diameter d_i	fraction	Number n_i of particles per m³ concrete	Surface area $S_{A.i}$ (per m³ concrete)	Part of the total surface area
[mm]	[% by mass]	[mm]	[mm]	[% by mass]	[1/m³]	[cm²/m³]	[%]
0.125	0.86	0.09/0.125	0.1075	0.75	-	-	-
0.25	3.72	0.125/0.25	0.1875	2.86	5.096E+09	5659618.7	18.7
0.5	18.42	0.25/0.5	0.375	14.70	3.274E+09	14544824.3	48.2
1	27.63	0.5/1	0.75	9.21	2.564E+08	4556388.9	15.1
2	33.25	1/2	1.5	5.62	1.956E+07	1390168.6	4.6
4	47.56	2/4	3.0	14.31	6.225E+06	1769867.7	5.9
8	69.95	4/8	6.0	22.39	1.218E+06	1384603.0	4.6
16	97.56	8/16	12.0	27.61	1.877E+05	853704.5	2.8
31.5	100.00	16/31.5	23.75	2.44	2.139E+03	38119.6	0.1
				100.00		S_A = 30197295.3	100.0

For a comparison of different particle-size distributions of aggregates the specific surface area $S_{A,spec}$ can be calculated as the ratio between the surface area S_A related to the mass of the aggregates m_A (Eq. (10)):

$$S_{A,spec} = \frac{S_A}{m_A} \tag{10}$$

If a spherical paste layer on the aggregates is assumed (Fig. 4), the excess paste thickness $t_{Paste,ex}$ can be calculated using Eq. (11), whereas r_i is the radius of a particle of class i, n_i is the number of particles per class and $t_{Paste,ex}$ is the thickness of the paste layer.

$$V_{Paste,ex} = \frac{4}{3}\pi \sum_i n_i \left(\left(r_i + t_{Paste,ex} \right)^3 - r_i^3 \right) \tag{11}$$

In a simplified way, the excess paste thickness can directly calculated with Eq. (12). This assumes that the thickness of the paste layer is small compared to particle size, because Eq. (12) is only valid for a planar paste layer.

$$t_{Paste,ex,plan} = \frac{V_{Paste,ex}}{S_A} \tag{12}$$

For small paste thicknesses both methods coincide. The deviation between both methods is increasing with an increasing paste thickness (Fig. 5).

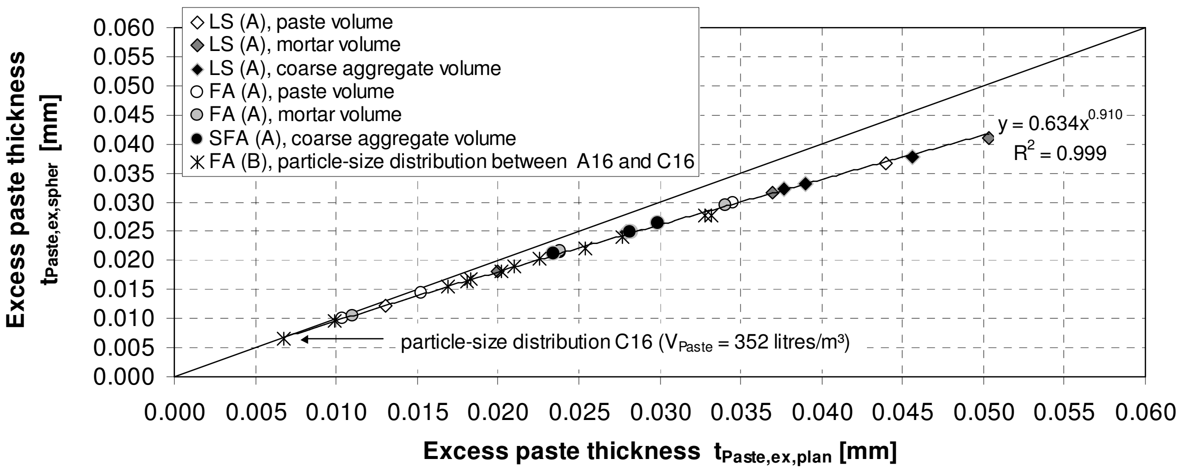


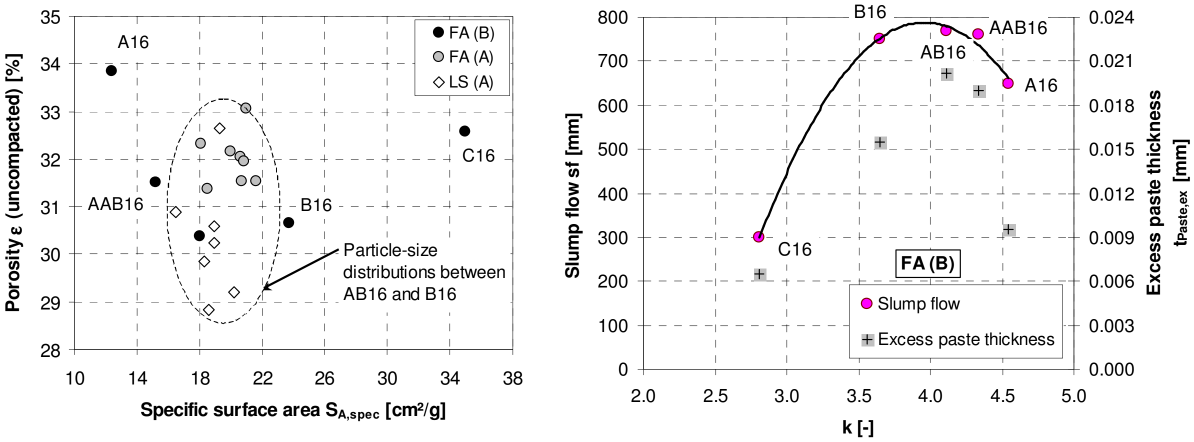
Fig. 5: Comparison of both methods for calculation of the excess paste thickness after Eq. (11) and Eq. (12)

It is possible that the calculated excess paste thickness lies below the median particle diameter[1] of the powder which was determined about 10 μm for all investigated SCC mixtures. Two reasons are responsible for this: 1) The void volume was determined in an uncompacted state by filling the aggregates in a container according to DIN EN 1097-3 [13]. 2) The excess paste thickness was assumed to be independent of the aggregate particle size (Fig. 4). Based on a two-dimensional imagination the thickness of the excess paste should be greater than half of the maximum diameter of the particles in the paste. But in reality a three-dimensional aggregate skeleton exists with sufficiently sized voids between the aggregates. Furthermore, also the particles of the paste as well as the

[1] 50 % (by volume) of the paste particles are below this diameter

voids between the aggregates are continuously distributed. The calculated excess paste thickness is – despite of a partially small value – a suitable parameter for the evaluation of different aggregate particle-size distributions, this will be shown later. The excess paste thickness, which is given in the following figures, was calculated after the spherical method of Eq. (11).

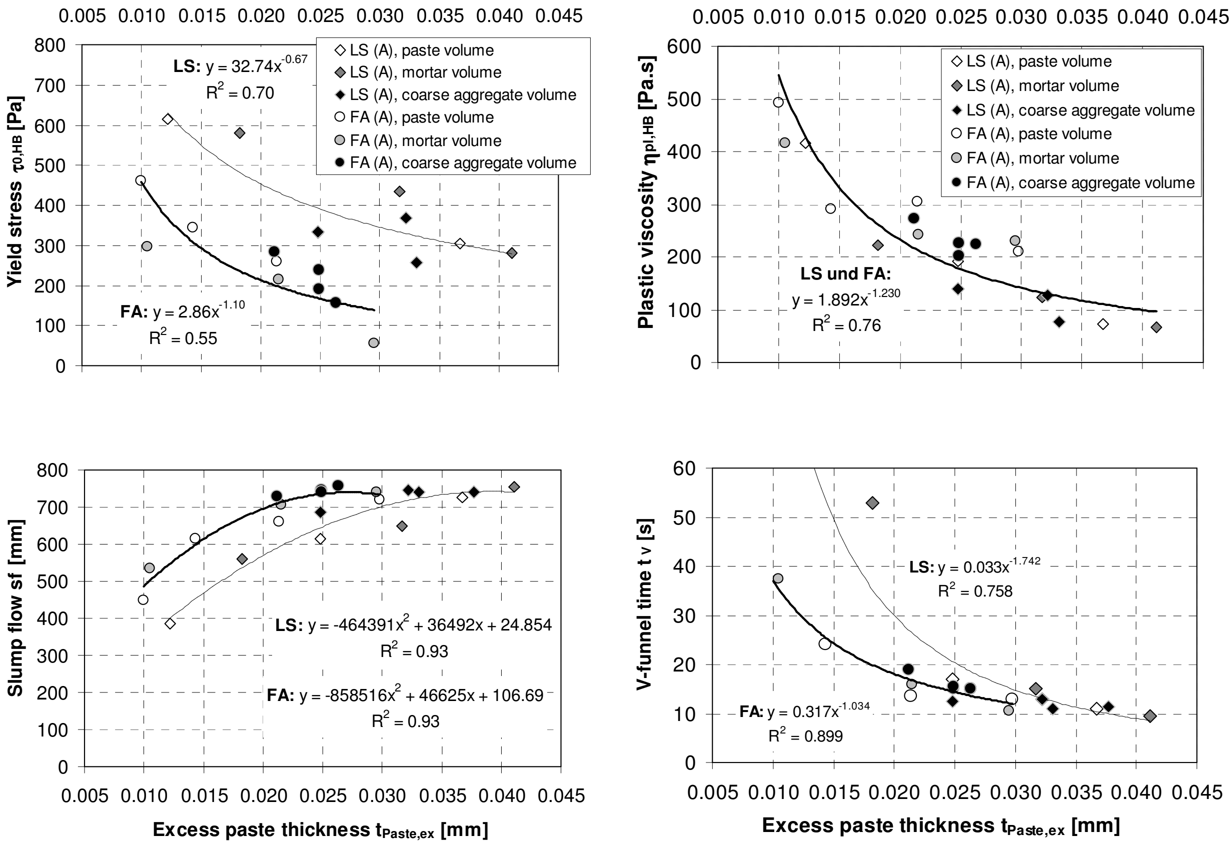
It can be seen from Eq. (9) and (12) that (for a constant paste volume) both, the void volume $V_{A,void}$ of the poured aggregates (respective the porosity $\varepsilon = V_{A,void} / \left(V_A + V_{A,void}\right)$) and the specific surface area $S_{A,spec}$ are controlling the thickness of the paste layer $t_{Paste,ex}$. Hence, particle-size distributions of aggregates have to be preferred which possess a small specific surface area and a small porosity. Both criteria are fulfilled by particle-size distributions which are lying approximately in the range between AB16 and B16 (Fig. 6a). These particle-size distributions have of a reduced coarse aggregate content, which reduces also the risk of blocking. Fig. 6b) shows the influence of the aggregate particle-size distribution (expressed by the fineness modulus k, Table 2) on the slump flow and on the excess paste thickness for a constant paste volume of 352 litres/m³. The maximum paste thickness was calculated for the mixture containing the particle-size distribution AB16. This concrete reached also the maximum slump flow value. It has to be mentioned that the origin of the sand fraction of the aggregates of the SCC mixtures produced with limestone powder LS (A) and fly ash FA (A) differed from those aggregates which were used for the concretes including fly ash FA (B). This is probably one reason for the differences in the porosity shown in Fig. 6a).



a) b)

Fig. 6: a) Porosity versus specific surface area of poured aggregates with different particle-size distributions; b) slump flow and excess paste thickness versus the fineness modulus k

Fig. 7 shows the fresh concrete parameters yield stress $\tau_{0,HB}$, slump flow sf, plastic viscosity $\eta_{pl,HB}$ and the V-funnel flow time t_V as function of the excess paste thickness $t_{Paste,ex}$. The different symbols stand for the variation of the paste volume, mortar volume and the coarse aggregate volume (see Table 2). It can be seen from Fig. 7 that the excess paste thickness is a suitable parameter to describe the consistency of SCC.



a) b)

Fig. 7: Fresh concrete parameters as function of the excess paste thickness

The differences regarding the filler type and the paste compositions (see Table 1) are leading to a different flow behaviour. The given functions were derived from a regression analysis. The deviations of the yield stresses are greater than those of the plastic viscosities, which can be traced back to the measurement procedure and the method of calculating the yield stresses by an extrapolation. The higher yield stresses of the concretes made of limestone powder compared to the fly ash concretes are also indicated by the reduced slump flow values of the concretes containing limestone powder (Fig. 7a). If greater deviations between model and measured data are accepted it is sufficient to use only one function to describe the relationship between the plastic viscosity and the model parameter excess paste thickness (Fig. 7b).

In the slump flow test the flow time t_{500} is normally recorded to get an indication of the apparent viscosity of a SCC mixture. The t_{500}-value is equivalent to the time that is measured from the start of the upward movement of the cone until the concrete spread has reached a diameter of 500 mm. The relationship between the flow time t_{500} and the model parameter excess paste thickness (Fig. 8) can be described – independently of the filler type – by one function.

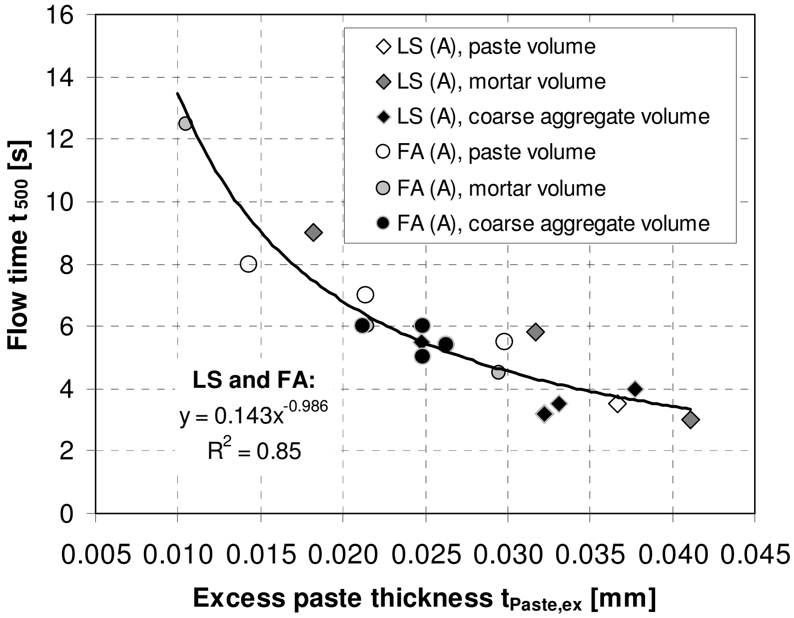


Fig. 8: Flow time t_{500} (slump flow test) as a function of the excess paste thickness $t_{Paste,ex}$

The similar relationships between the model parameter excess paste thickness $t_{Paste,ex}$ and the plastic viscosity $\eta_{pl,HB}$ (Fig. 7b) respective the flow time t_{500} (Fig. 8) denote that a relationship exists between the plastic viscosity $\eta_{pl,HB}$ and the flow time t_{500}. In fact it was found in [14] that the plastic viscosity can be estimated based on the flow time t_{500}, independently of the concrete composition. However, the V-funnel flow time t_V could not be described (independently of the concrete composition) as a function of the plastic viscosity $\eta_{pl,HB}$. Probably blocking effects in the vicinity of the V-funnel orifice played a role, see also [16]. Hence, it is better to use the flow time t_{500} to get an indication of the plastic viscosity.

4. CONCLUSION

The flow properties of different self-compacting concretes including fly ash respective limestone powder were investigated by means of standard tests and a fresh concrete rheometer. It was shown that the influence of the content and composition of the aggregates on the flow properties can be described by means of the model parameter excess paste thickness.

The flow parameters yield stress, slump flow and V-funnel flow time depended – beside the model parameter excess paste thickness – also on the paste composition which was different for the concretes including fly ash and limestone powder. The plastic viscosity and the flow time t_{500} from the slump flow test could be described independently of the filler type only as function of the excess paste thickness.

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