SELF-COMPACTING CONCRETE: THE ROLE OF THE PARTICLE SIZE DISTRIBUTION

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Abstract

This paper addresses experiments and theories on Self-Compacting Concrete. The "Chinese Method", as developed by Su et al. [1] and Su and Miao [2] and adapted to European circumstances, serves as a basis for the development of new concrete mixes. Mixes, consisting of slag blended cement, gravel (4-16mm), three types of sand (0-1, 0-2 and 0-4mm) and a polycarboxylic ether type superplasticizer, were developed [3]. These mixes are extensively tested, both in fresh and hardened states, and meet all practical and technical requirements such as a low cement and powder content (medium strength and low cost). It follows that the particle size distribution of all solids in the mix should follow the grading line of the modified Andreasen and Andersen [4] model.

1. INTRODUCTION

Pioneering work in the development of SCC was carried out by Okamura [5] and Okamura and Ouchi [6], which will henceforth be referred to as Japanese Method. The method focuses on the flowability of paste and mortar (paste plus sand), and results in SCC that has a relatively high content of paste. Many SCC mixes therefore attain a higher strength than actually required.

More recently, Su et al. [1] and Su and Miao [2] developed an alternative method for composing SCC, henceforth referred to as Chinese Method. The Chinese Method starts with the packing of the aggregates (sand and gravel), and later with the filling of the aggregate voids with paste. The method is easier to carry out, and results in less paste. This saves the most expensive constituents, namely cement and filler, and concrete of "normal" strength is obtained. This will also favour the technical performance of the concrete, as the largest possible volume of aggregate is advantageous in regard to strength, stiffness, permeability, creep and drying shrinkage.

Though with both methods SCC can be composed, a thorough theoretical background is still lacking, which is addressed in this paper. Starting point of this analysis is the packing theory. SCC is treated as a mix of water and solids, whereby the solids consist (from coarse to fine) of gravel, sand, filler (stone powder, fly ash) and cement. In regard the packing of granular materials, Andreasen and Andersen [4] presented a semi-empirical study of the packing of continuous particle size distributions (PSD), and determined the PSD with the densest packing. Funk and Dinger [7] modified this PSD to account for the smallest particle

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size (modified A&A model). It will be demonstrated that the aggregate packing as applied by Su et al. [1] and Su and Miao [2] appears to follow the grading curve of the modified A&A model. Finally, mixes are designed that follow the modified A&A model, including all particles. Mixes are composed using GGBS cement and gravel, and investigating the role of the three types of sand. It appears that the fine sand is a useful component in optimizing the PSD, and thereby increasing the stability and flowability of the concrete mix. It is also a major source of reducing the costs of the mix.

2. PACKING THEORY

The Japanese and Chinese Methods do not pay attention to the PSD of the aggregates. It is however known that the viscosity of slurry becomes minimal (at constant water content) when the solids have tighter packing [7]. When particles are better packed (less voids), more water is available to act as a lubricant between the particles. Therefore, first the densities and other relevant properties of the materials used in this study are summarized in Table 1.

Table 1: Properties of materials used

Material	Type	ρ [kg/m^3]	ρ_l [kg/m^3]	Blaine [cm^2/g]	S [cm^2/cm^3]
Cement	CEM III/B 42.5 N LH/HS	2950	1100	4700	13865
Filler	Limestone powder	2740	1110	4600	12604
Filler	Fly ash	2250	1000	3900	8775
Coarse sand	Rhine sand 0–4 mm	2650	1631	-	-
Medium sand	Rhine sand 0–2 mm	2650	1619	-	-
Fine sand	Sand 0–1 mm	2650	1511	-	-
Gravel	Rhine gravel 4–16 mm	2650	1604	-	-
Superplasticizer	Glenium 27	1045	-	-	-

In Figure 1 the particle distribution (PSD) of the materials used is presented (cumulative finer fraction). The PSD of the sands and gravel is determined by sieving, the PSD of cement and limestone powder by laser granulometry.

For "normal concrete", most design codes require continuous grading to achieve tight packing. Continuous grading curves range from 250μm to a maximum particle size and are S-shaped in a single-logarithmic graph (Fuller curve). For modern concretes, such as High Strength Concrete and SCC this Fuller curve is less suited. This curve is applicable to materials with a particle size larger than 500μm. Applying this grading curve to materials with fine constituents results in mixes that are poor in cement and that are less workable. Standards therefore require a minimum content of fine materials (< 250μm) in normal concrete. As the content and PSD of fine materials (powder) cannot be determined properly with the Fuller curve, it is less suited for SCC as a large part of the solids consist of powder.

Actually, the packing theory of Fuller and Thompson represents a special case within the more general packing equations derived by Andreasen and Andersen [4]. According to their theory, optimum packing can be achieved when the cumulative PSD obeys the following equation:

$$P(D) = \left(\frac{D}{D_{min}} \right)^q \quad (1)$$

P is the fraction that can pass the sieve with opening D, Dmax is maximum particle size of the mix. The parameter q has a value between 0 and 1, and Andreasen and Andersen [4] found that optimum packing is obtained when q ≈ 0.37.

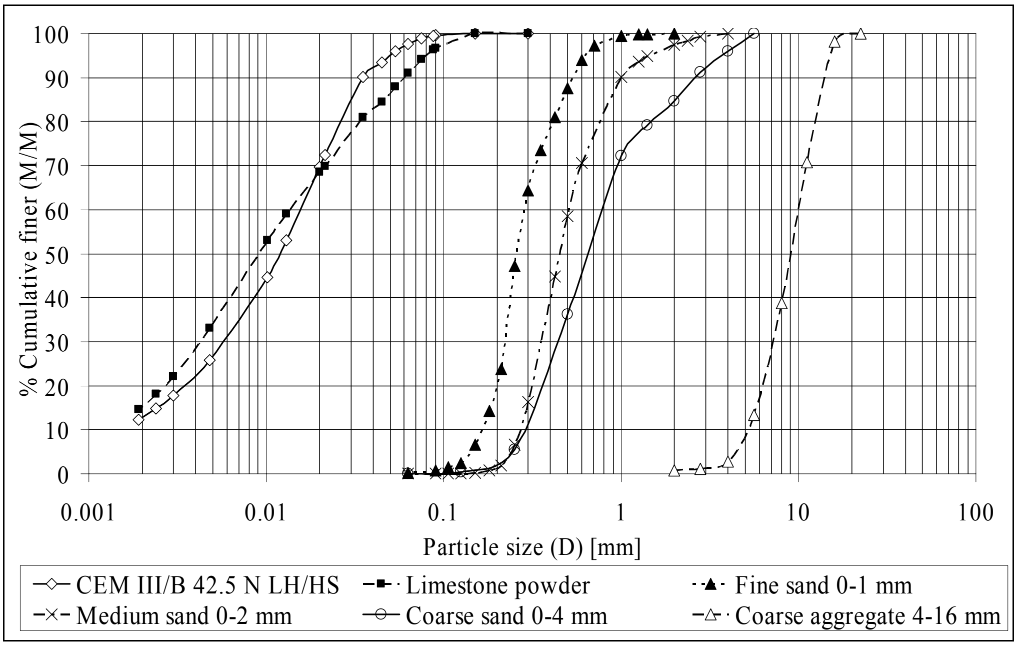


Figure 1: PSD of aggregates and powders used (cumulative finer mass fraction)

The grading by Fuller is obtained when q = 0.5. The variable q renders the A&A model suitable for particle sizes smaller than 500μm. In general, the more powders (< 250μm) in a mix, the smaller the q that best characterizes the PSD of the mix. To validate the hypothesis of tight packing and the application of the A&A model, the PSD of the Chinese Method is analysed. In Figure 2 the PSD of the aggregates are graphically depicted, based on the sieving data given by Su et al. [1] and Su and Miao [2]. As no sieve information is provided for the powders, it is not possible to depict the PSD down to 1μm. But the PSD of the entire solid mix is corrected for this powder content, which is known. In Figure 2 also the grading curves of Fuller and A&A (with q = 0.3) are depicted.

Figure 2 reveals that the Chinese Method seems to follow the grading curve of the A&A theory with q = 0.3. The figure confirms that the grading curve of A&A better accounts for powders than the grading curve of Fuller. From the curves in Figure 2 it furthermore follows that about 20% of the particles are finer than 75μm, whereas, according to Fuller, only 5.5% are smaller than 75μm. As the A&A model accounts for powders (< 250μm) better, it is better suited for designing SCC. A continuous grading of all solids (aggregate and powders) will result in a better workability and stability of the concrete mix.

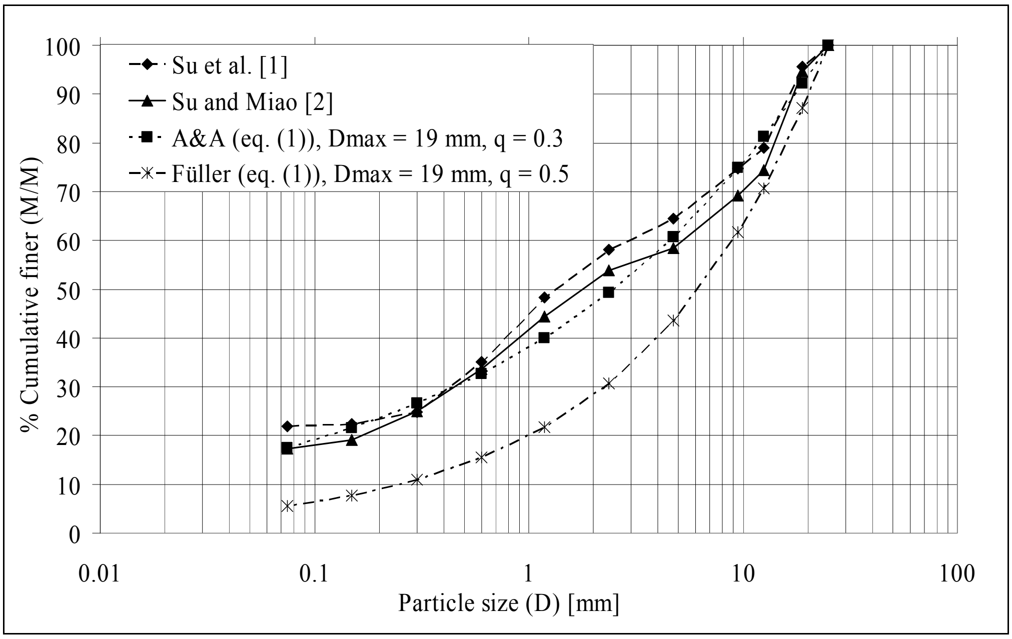


Figure 2: Analysis of actual PSD by Su et al. [1] and Su and Miao [2]

The A&A model prescribes a grading down to a particle diameter of zero. In practice, there will be a minimum diameter in the mix. Accordingly, a modified version of the model is applied that accounts for the minimum particle size in the mix [7]. This modified PSD (cumulative finer fraction) reads:

$$P(D) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \tag{2}$$

Whereby Dmin is the minimum particle size in the mix. For many years the same equation is also used in mining industry for describing the PSD of crushed rocks [8].

In a 'double–logarithmic' graph, the A&A model results in a straight line, whereas the modified A&A model results in a curve that bends downward when the minimum diameter is approached. In the next Sections, for the design of the SCC mixes, use will be made of the modified A&A model.

3. GRADING

Table 2 contains the final mix compositions of the developed SCC, based on packing theory and some mortar tests [3]. The total powder content (cement plus limestone powder) amounts 473 kg/m^3 to 499 kg/m^3 only. In Figures 3 and 4 the PSD (cumulative finer) of the three mixes are given. In both figures also the curves following the A&A grading, the modified A&A grading and the Fuller grading are included.

Figures 3 and 4 reveal that the PSD of the three mixes does not follow the Fuller curve, which is used for "normal" concrete. The designed three mixes follow as much as possible the PSD from the modified A&A grading (with q = 0.25). However, the PSD from the three mixes cannot follow the A&A curve perfectly, as the PSDs of the constituents used are S-shaped (Figure 1). Especially, between 100µm and 4mm one can see a disturbance, which can be explained by the fact that in this particle range the sand contributes significantly to the PSD. The S-shaped pattern corresponds to the pattern of the sand (Figure 1). In order to avoid this deviation, more constituents with overlap in their particle sizes should be used. One can think on the application of sand 2-4mm and gravel 4–8mm.

Table 2: Dosages of mixes

Material	Mix A [kg/m^3]	Mix B [kg/m^3]	Mix C [kg/m^3]
Cement	310	315	320
Limestone powder	189	164	153
Sand 0-1 mm	-	-	388
Sand 0–2 mm	-	306	-
Sand 0–4 mm	1018	719	628
Gravel 4–16 mm	667	673	687
Water	170	173	174
Superplasticizer	6.0	5.51	5.21
Water/cement ratio	0.55	0.55	0.55
Water/powder ratio	0.34	0.36	0.37
Mass fraction < 250 µm	554	538	687

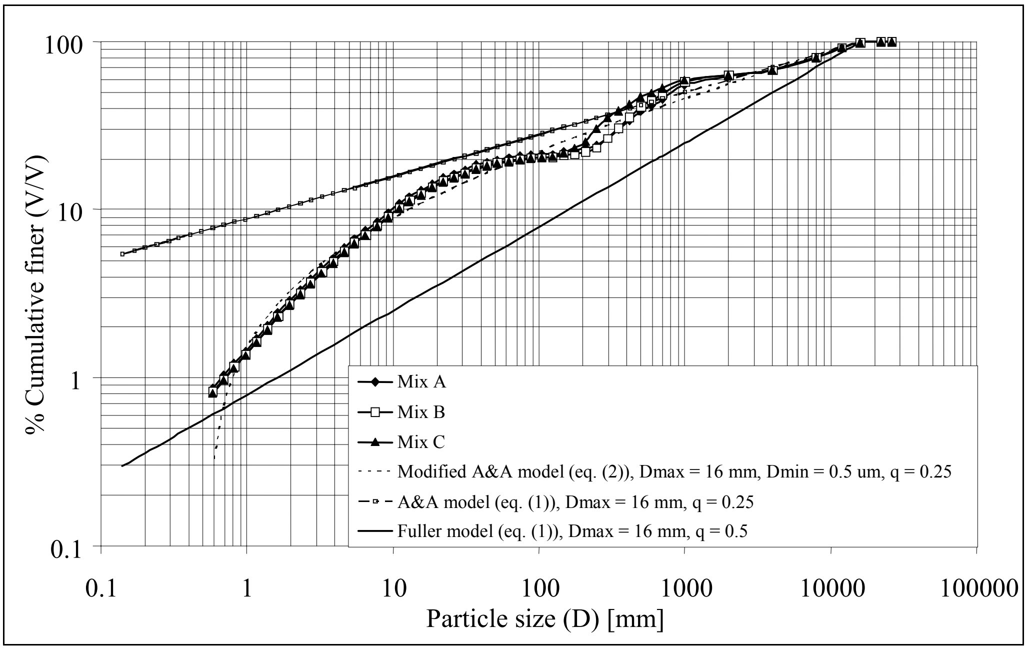


Figure 3: Cumulative finer mass fraction of Mixes A, B and C in double-logarithmic graph

Using the A&A grading curve, the part of fine materials (< 250µm) is about three times higher than with the application of the Fuller curve. Table 2 lists the amount of fine materials in the three mixes. Table 2 shows that Mix C contains much more fine material than Mixes A and B, and that the quantity of the stone powder is least in Mix C. Hence, by application of fine sand (0–1mm) it is possible to increase the amount of fine materials, while at the same time reducing the quantity of cement and filler. The corresponding volume of fine material in

Mix C amounts to about 0.245m^3 per m^3 of concrete, which is about two times the minimum amount prescribed by NEN 5950 (1995) for concrete with a maximum particle size of 16mm. This reduction of powders and superplasticizer in case of fine sand application can also be explained by comparing the PSDs of the three mixes. The PSD of Mix C follows best the modified A&A curve, especially between 100μm and 1mm (Figures 3 and 4). In the next Section the fresh concrete mixes will be tested.

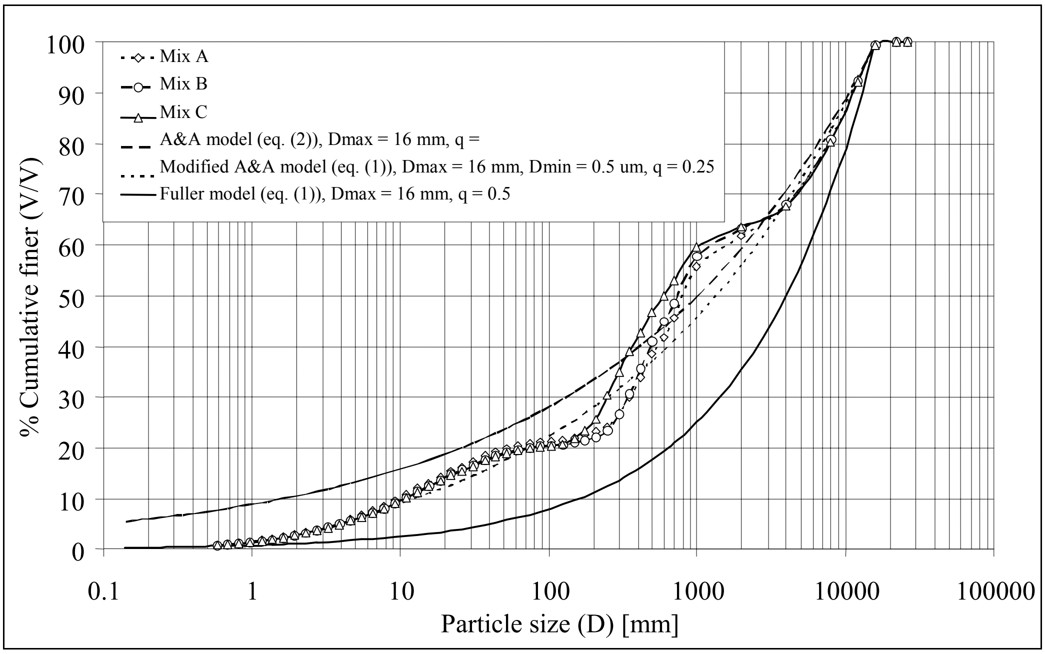


Figure 4: Cumulative finer mass fraction of Mixes A, B and C in single-logarithmic graph

4. CONCRETE MIX EVALUATION

The three mixes will be examined in detail here. In The Netherlands, basic evaluation tests for SCC have been developed which can also be executed on site. A number of these test are described in CUR [9] and BMC [10], being in line with current international methods [11].

The consistence of the concrete mix is assessed by the slump and the time needed to attain a slump of 500 (t_{500}), using the Abrams cone. The final slump should range from 630mm – 800mm (CUR [9]). The target flow time, t_{500}, amounts to 2 a 5s (CUR [9]). A visual inspection also gives an indication of the degree of segregation. The test is executed according to BMC [10] and CUR [9].

With the help of a V-funnel, the flowing time is determined 2 times (t_1 and t_2), the arithmetic mean being the mean flow time ($\bar{t}$). This mean time gives an indication of the viscosity and filling time of the mix. The sizes of the funnel depend on the maximum aggregate size, here 16mm. The V-funnel test is executed according to the guidelines given by CUR [9]. According to CUR [9], $\bar{t}$ should range from 5 to 15s, BMC [10] prescribes $\bar{t}$ to lie between 5 and 15s. The segregation resistance is determined by measuring the flow out time 5 minutes after the funnel has been filled (t_5). The stability time (t_S) is defined as:

$$t_s = t_5 - \bar{t} \quad (3)$$

whereby $t_S = 0$ if $t_5 < \bar{t}$. BMC [10] prescribes that t_S should be smaller than 3s.

The passing ability of the mixes is tested with the help of the J-ring. The J-ring is an open rectangular steel ring, thickness 25mm, inner diameter 260mm and outer diameter 324mm. Vertical holes are drilled (72), which can accept vertical bars that can be spaced at different intervals. The diameter of the bars is 16mm, and their height 100mm. The number and spacing of the bars is in accordance with reinforcement considerations: when the largest aggregate size is below 12mm, 24 bars are used, below 20mm, 18 bars, and below 32mm, 12 bars (CUR [9]). As the largest grain size is 16mm, 18 bars are used. This implies that the gap between the bars is about 37mm, corresponding to about 2.3 maximum grain sizes.

The J-ring is placed in conjunction with the Abrams cone, which is placed centrally inside the J-ring. After the concrete has flown out freely, the extent of blocking is measured (CUR [9]). The blocking factor (B) is computed with:

$$B = 2\,(h_{in} - h_{ex}) - (h_c - h_{in}) \qquad (4)$$

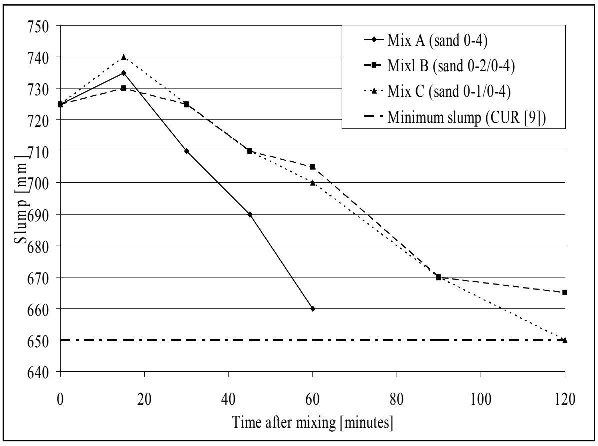
whereby h_c, h_{in} are h_{ex} the height of the mix in the centre, just inside the bars and just outside the bars, respectively, measured at four locations and averaged. The blocking factor B should be smaller than 15mm (CUR [9]). The concrete is also inspected visually to evaluate segregation and blocking.

It is known that the performance of superplasticizers decays with time. In particular, for the ready-mixed concrete industry, the workability should not reduce too much with time and a constant (or minimum preserved) workability is of major importance. To assess the preservation of the workability, the Slump-flow and J-ring tests are also measured at 15, 30, 45, 60, 90 and 120 minutes after preparation of the mixes. Ready-mixed concrete is slowly stirred upon transport in the truck-mixer. To simulate this truck mixing, the concrete was also stirred; after each 4 minutes of rest, the concrete was rotated for 1 minute in the mixer. Finally, also the air content of the fresh concrete is measured. Composing the three mixes, it was assumed that they would have an air content of 1.5% (by volume).

Table 3 reveals that all three mixes meet the set requirements discussed above. Figures 5 and 6 depict the slump flow and blocking factor with time, respectively. Figure 5 shows that the slump flow decreases linearly with time, after an increase during the first 15 minutes. A possible explanation for this increase is that the SP needs some time to become active. In particular, the slump loss of Mix A is most pronounced in time. On the other hand, Mixes B and C follow a similar line and after 2 hours they still meet the minimum slump flow of 650 mm.

Table 3: Results of fresh concrete tests

Result	Mix A	Mix B	Mix C
Slump [mm]	720	745	730
Slump flow time t_{500} [s]	3	3	3
Blocking factor [mm]	14.50	4	12.50
Mean funnel time [s]	12	11.5	12
Funnel time after 5 minutes t_5 [s]	15	14	15
Air content [V/V %]	2.6	1.7	2.5
Density [kg/m^3]	2220	2200	2200



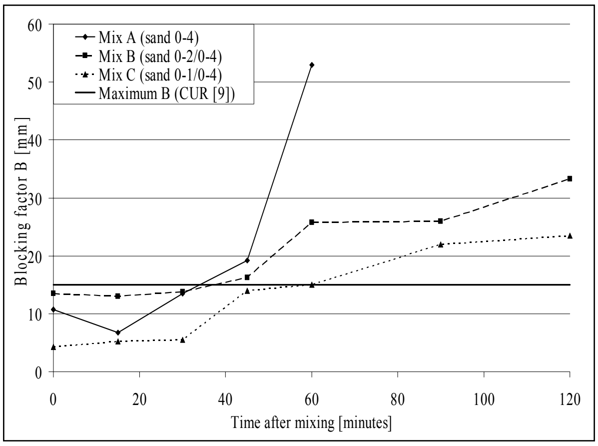


Figure 5: Slump flow reduction with time

Figure 6: Blocking factor increase with time

Figure 6 reveals that after 45 minutes Mix A exceeds the maximum blocking factor of 15 mm. After 60 minutes Mix A clearly exhibits substantial blocking. Mix B is performing better than Mix A, but after 45 minutes it does not meet the maximum allowable blocking factor either. Mix C meets the requirements during 60 minutes and exceeds the maximum blocking factor only slightly. It should be noted that the blocking of Mixes B and C are very minor, only a slight difference in height is noticeable across the J-ring. The concrete still flows easily along the bars and does not show any sign of segregation. It was expected that a grading that more closely follows the modified A&A curve will result in a mix with a better workability and stability. The concrete mixes reveal indeed that Mix C exhibits a better resistance to segregation and workability. The required amount of SP in this mix is also lower than in the two other mixes, whereas their slump flows and funnel times are almost equal. The addition of fine sand (0–1mm) has improved the flowing properties of the mix, so that the amount of powders and SP can be reduced.

Actually, a reading off error from about 1mm will already result in a blocking factor that is too large. The maximum value set by CUR [9] is quite severe, and is only realistic when the mix height can be measured with an accuracy of 0.1mm (e.g. with laser). That is the reason that in Germany the difference in Slump-flow with and without J-ring is considered, whereby the difference should be smaller than 50mm [12]. This difference is easier to measure, and all three mixes meet this requirement. The high retention of filling and passing abilities is most probably owed to the type of plasticizer used. Hanehara and Yamada [13] also observed a longer workability when using a polycarboxylate type admixture.

Table 3 also contains the measured air content and density of the concrete. The air content is higher than 1.5% as assumed during the mix computations. As possible explanation is that the concrete did not have enough time to de-air (5 minutes) after filling the air-pressure container. But all values are well within the maximum air content of 3% (NEN 5962 (1988)). The densities of all three mixes are close. Mix A possesses a slightly higher density as it contains more powder (Table 2). Mixes B and C have the same density, although Mix C contains less powder than Mix B. But Mix C contains 5 kg/m^3 cement more, which has a higher specific density than all other constituents (Tables 1-3).

The concrete mix tests therefore yield the conclusion that the PSDs and the content of fine materials (< 250μm) greatly influence the stability and workability of the mix. The application of fine sand helps to optimize both content and PSD in the fine particle range, so that the amount of required SP can be reduced. This application of fine sand also reduces the ingredient costs of the mix. Fine sand is relatively cheap; it is cheaper than the two other sands and than gravel, and replaces the most expensive constituents: cement and stone powder (the powders). Furthermore, composing a mix with a PSD that closely follows the modified A&A model reduces another expensive ingredient, namely the SP. It could be expected that if one would optimize the PSD down in the nanometre range, the workability and stability could be maintained while further reducing the necessary SP content.

5. CONCLUSIONS

In the present paper the Chinese Method is investigated and applied. A theoretical analysis reveals that the packing of all solids in the mix (gravel, sand, filler and cement) is of major importance. Ideally, the grading curve of all solids should follow the modified Andreasen and Andersen curve. Indeed, it followed that the aggregate used by Su et al. [1] and Su and Miao [2] followed this curve (eq. (2), q = 0.30). Furthermore, combining the solids, the quantity of paste (water, cement and filler) should be reduced as much as possible. In this paper, it is analysed which combinations of 3 sands, gravel, SP and slag blended cement result in the lowest powder (cement, limestone powder) content.

Based on these considerations, three mixes have been composed and tested [3]. Another objective was to meet these theoretical requirements while using the most economical ingredients. This has resulted in three mixes with a low content of powder, ± 480 kg/m^3 of concrete. The fresh concrete has been evaluated with the Slump-flow, V-funnel and J-ring tests, and its air content has been measured. All mixes meet the criteria set by these tests, whereby the use of superplasticizer could be limited to 1% of the powder content, and the use of a viscosity modifying agent can be avoided.

Using the packing theory of Andreasen and Andersen [4], and its modifications by Funk and Dinger [7], cheap SCC mixes can be composed that meet the standards and requirements in fresh state. Furthermore, a carboxylic polymer type superplasticizer is employed as sole admixture; an auxiliary viscosity enhancing admixture is not needed to obtain the required properties.

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