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Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-compacting concrete

Steffen Grünewald*, Joost C. Walraven

Stevin Laboratory, Concrete Structures Group, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands

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Abstract

Self-compacting concrete (SCC) offers several economic and technical benefits; the use of steel fibers extends its possibilities. Steel fibers bridge cracks, retard their propagation, and improve several characteristics and properties of the concrete. Fibers are known to significantly affect the workability of concrete. Therefore, an investigation was performed to compare the properties of plain SCC and SCC reinforced with steel fibers. Two mixtures of SCC with different aggregate contents were used as reference. Each of the concretes was tested with four types of steel fibers at different contents in order to answer the question to what extent the workability of SCC is influenced. The slump flow, a fiber funnel and the J-ring test were used to evaluate the material characteristics of the fresh concrete. This paper discusses the suitability of the applied test methods and the effect of the coarse aggregate content, the content and type of steel fibers on the workability of SCC.

Keywords: Self-compacting concrete; Fiber reinforcement; Mix proportioning; Workability

1. Introduction

Self-compacting concrete (SCC) has a high flowability and a moderate viscosity, and no blocking may occur during flow; the concrete has to de-air by itself during casting. Several mix design methods for SCC were proposed by Okamura and Ouchi [1], Petersson and Billberg [2], and Sedran and De Larrard [3].

The use of fibers might extend the possible fields of application of SCC. Fibers are produced in a wide range of materials, at different shapes, with divergent properties concerning their affinity to paste or water. Some types of fibers are fragile, flexible or stiff, cylindrically, rectangularly or irregularly shaped. They are known to affect the workability and the flow characteristics of plain concrete essentially. Fibers have a long shape and compared with aggregate of the same volume a higher specific surface. The degree to which workability decreases does depend on the type and content of fibers used, on the matrix in which they are embedded and the properties of the constituents of the matrix on their own. A high content of fibers is difficult to distribute uniformly; a good distribution, however, is required to achieve optimum benefits of the fibers. Manufactures try to improve the pull-out resistance of the fibers by deforming or crimping them, giving them a surface texture that increases the roughness, and bend or enlarge the ends to improve the anchorage capacity.

Edington et al. [4] investigated the effect of the aspect ratio and volume content on the VEBE-time of fiber-reinforced mortars. The aspect ratio describes the length of the fiber divided by its diameter. The higher the aspect ratio was, the fewer fibers could be added to surpass the critical fiber content. For the same fiber content, better workability was achieved at lower aspect ratios. The higher the aspect ratio and the volume concentration of the fibers, the better is the performance in the hardened state. Unfortunately, the higher the product of these two parameters [$V_f L/D$] the more difficult the concrete becomes to mix. Therefore, the reinforcement index [5] or the so-called 'fiber factor' was proposed for steel fibers to characterize and compare the properties of different fiber-reinforced mixtures. The aggregate content influences the workability [6,7]. More fibers can be added as the fine aggregate content of the total

* Corresponding author. Tel.: +31-15-278-4580; fax: +31-15-278-5895.

E-mail address: s.grunewald@citg.tudelft.nl (S. Grünewald).

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Table 1
Mixture composition of both the reference mixtures

Component	Series 1 [kg/m^3]	Series 2 [kg/m^3]
CEM III/B 42.5 LH HS	362	386
Fly ash	191	204
Water	164	171
Superplasticizer CUGLA LR	(2.09)	(2.19)
Superplasticizer CUGLA HR	(0.84)	(0.87)
Fine aggregate (0.125–4 mm)	641	676
Coarse aggregate (4–16 mm)	942	855

aggregate is increased. The less aggregate was present in the mixture, the higher was the possible fiber content [8]. Rossi and Harrouche [9] proposed a mix design method for fiber-reinforced concrete that was based on the method of Baron–Lesage. First, their assumption was that the most workable concrete would be achieved if its granular skeleton would be optimized. They found that the optimum aggregate proportions were independent of the volume and properties of the paste. After varying the ratio of the sand to aggregate by trial and error, an optimum content of sand was found to achieve the best workability. This ratio depended on the type and amount of fibers. Next, an adjustment of the water, cement and superplasticizer has to be performed to attain the desired workability. Usually, the cement content has to be adjusted if a higher sand content was applied.

Because fibers are known to affect the workability of concrete, the question arises whether the fibers are detrimental to the workability of SCC. Therefore, an experimental study was performed on the effect of four types of steel fibers at different contents on the workability of two SCCs with different compositions. The feasibility of the applied test methods was investigated. This paper summarizes the results of an ongoing experimental parameter-study.

2. Materials and methods

2.1. Experimental method

Two self-compacting reference mixtures with different compositions were developed. Table 1 shows their mixture composition. The mixtures differed in their content and composition of paste, coarse aggregate content and ratio fine to coarse aggregate. The content of sand in the mortar was kept constant at 40 vol.% of the mortar. The compressive strength of 150-mm cubes after 28 days was 55.9 and 56.9 MPa for Series 1 and 2, respectively.

First, it was assumed that the fibers would lower the workability of the mixtures: for this reason the reference mixtures were proportioned at the upper level of self-compactability, in order to remain within the given limits after the addition of the fibers. Therefore, the contents of water and superplasticizer of the reference mixtures were adjusted to obtain a high slump flow of about 700 mm and a V-funnel time of 10 s. The porosity of the granular skeleton of the solids increases with increasing fiber factor: to take this into account a slightly increased content of paste compared with that of plain SCC was used. Next, to keep the changes of the mixtures as small as possible, it was decided to exchange coarse aggregate (4–16 mm) against the same volume of the fibers. Finally, the maximum possible fiber content for each reference mixture was determined. Table 2 lists all experiments that were performed as a part of this parameter-study. Two SCC and 20 fiber-reinforced mixtures were tested. Only the characteristics in the fresh state were considered.

2.2. Materials

Blast furnace slag cement (CEM III/B 42.5 LH HS) and fly ash were the only powder materials used for these experiments. The volume ratio of these powders was kept constant at 60:40. A combination of two superplasticizers (CUGLA) based on a polycarboxylic ether complex was applied to achieve a better slump retention ability. The maximum aggregate size was 16 mm. A grading curve was chosen and then combined from fractions. Fig. 1 shows the size distribution of the aggregates and the grading areas A, B and C according to the Dutch recommendation NEN 5950 [10]. The sand (0.125–4 mm) had a specific gravity of 2.60 kg/m^3, an absorption value of 0.52% and a fineness modulus of 2.94, whereas the characteristics of the gravel were 2.58 kg/m^3, 1.12% and 6.65, respectively. Four cylindrical steel fiber types, three with hooked ends (Dra-

Table 2
Experimental program

Steel fiber content	20 [kg/m^3]	40 [kg/m^3]	60 [kg/m^3]	80 [kg/m^3]	100 [kg/m^3]	120 [kg/m^3]
SCC-Series 1						
Dramix-RL 45/30				○	○	
Arbed/Eurosteel 50/50			○	○		
Dramix-RC 65/40		○	○			
Dramix-RC 80/60		○	○			
SCC-Series 2						
Dramix-RL 45/30				○	○	○
Arbed/Eurosteel 50/50			○	○	○	
Dramix-RC 65/40		○	○	○		
Dramix-RC 80/60		○	○	○		

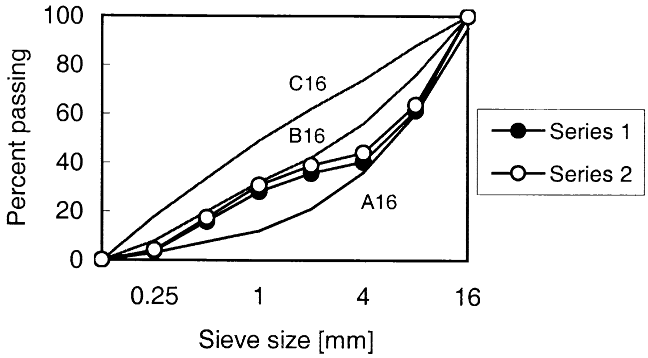

Fig. 1. Grading curves of the aggregates.

mix 45/30 RL, Dramix 65/40 RC, Dramix 80/60 RC) and one crimped type (Arbed/Eurosteel 50/50), were tested throughout the experiments. The first indicium represents the fibers' aspect ratio and the second the length of the fibers in millimeters. The length of the fibers varied between 30 and 60 mm; their aspect ratio was between 45 and 80.

2.3. Mixing procedure

A forced pan mixer was used throughout the experiments. The mixing procedure was the following: Powders and sand were added first, then mixed for 10 s; premixed water with superplasticizer was then introduced and homogenized for 110 s; after throwing in the gravel and mixing for 60 s, a rest was held for 60 s to allow the superplasticizers to initiate. The mixtures without fibers were mixed for a further 30 s, in case of a fiber addition the further mixing time at this stage was 90 s. This extended mixing time was required to dissolve the glue of the fiber bundles.

2.4. Test methods

A combination of qualitative observations and quantitative measurements was applied to characterize this kind of material. The measurement of the slump flow indicates the free deformability of the mixture. The 'slump flow' is the average diameter of the horizontal flow (the largest diameter and the one orthogonal to this) after lifting Abrams' cone. A funnel (Fig. 2a) similar to that proposed in Ref. [1], but at larger dimensions, was applied to achieve an indication of stability, segregation resistance and restricted deformability of the mixtures. In order to study the passing ability of fiber-reinforced mixtures with different types and contents of fibers, different bar spacings must be arranged. The J-ring with variable bar spacings (Fig. 2b) was used during this parameter-study. According to Nemegeer [11], blocking is assumed to occur if the difference between the heights of the concrete inside and outside the J-ring is larger than 10 mm. Additionally, the reference mixtures were tested with the V-funnel, the filling vessel test and the box test [12].

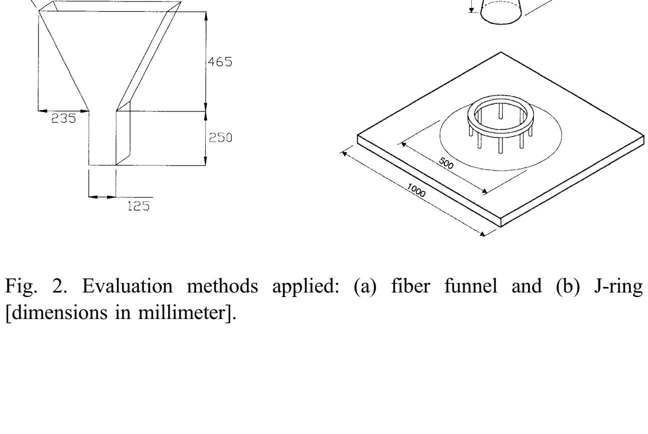

Fig. 2. Evaluation methods applied: (a) fiber funnel and (b) J-ring [dimensions in millimeter].

Table 3
Test results of the reference mixtures

Measurement	Series 1	Series 2
Slump flow [mm]	708	716
V-funnel [s]	10.8	9.5
Fiber funnel [s]	4.5	5.7
Filling vessel test [%]	97.6	97.7
Box test [mm]	335	335
Air content [vol.%]	2.0	2.0

3. Results and discussion

3.1. Results of reference mixtures

Both reference mixtures were self-compacting; a filling degree with the filling vessel test, a transparent box with a grid of transverse bars, of more than 90% (Table 3) was achieved.

3.2. Slump flow

The steel fibers affected the slump flow of both reference mixtures. The more fibers were added, the more the deformability decreased. Fig. 3a–b show the relation between the fiber factor and the slump flow for Series 1 and 2. The reference mixtures had a fiber factor of zero. In spite of the fibers' addition, both series could keep a high deformability. The slope of the regression line indicates the sensitivity to the fiber addition. The ability to keep the workability in time forms another criterion for SCC. Almost

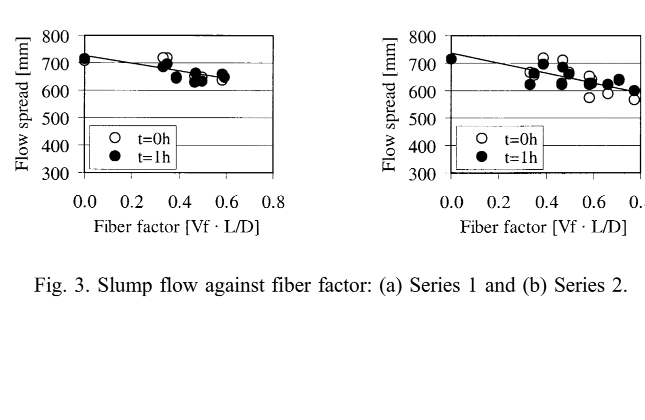

Fig. 3. Slump flow against fiber factor: (a) Series 1 and (b) Series 2.

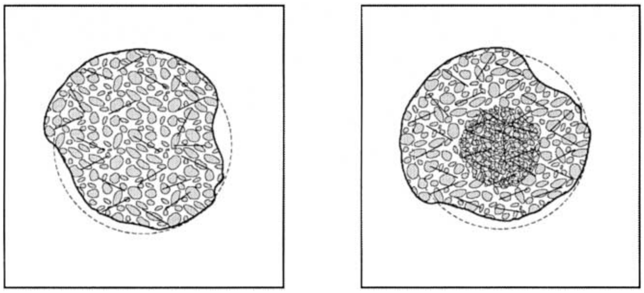

Fig. 4. Nonhomogeneous flow patterns: (a) restricted flow and (b) clustering.

no difference was measured between the measurement directly after mixing and 1 h after mixing.

Two observations indicated that some of the mixtures did not flow homogeneously. First, it was observed that the flow spread of some mixtures was not circular (Fig. 4a). This indicates that the flow had been counteracted in one or more directions. Furthermore, for some mixtures it was observed that a cluster of material remained at the center of the flow spread after the removal of Abrams' cone (Fig. 4b). The longer types of steel fibers tended to entangle after surpassing a critical content.

3.3. Flow-time 'fiber funnel'

The fiber funnel allows measuring the deformation speed of flowing concrete. Fig. 5a–b show the effect of the fibers on the flow-time through the fiber funnel of both reference mixtures. The more fibers were added and the higher the aspect ratio, the more the flow-time increased.

The flow behavior of concrete through the funnel depends not only on the viscosity but also on the ratio between the maximum particle size and the dimensions of the opening gap. If the maximum size of the solids is relatively large compared with the opening of the gap of the funnel, higher contents of them would cause blocking. Then, the measurement of the flow-time does not simply give an indication of viscosity but also of the restricted deformability. The higher the content of longer fibers, the more the passing behavior of the mixture was decisive. All mixtures were stiffening in time, which was indicated by an increased flow-time. At first, paste stuck to the test instruments, while working about 90 min with the mixtures. Therefore, an undefined part of paste was lost. Next, water

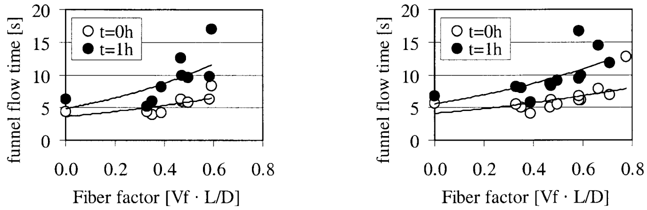

Fig. 5. Flow-time through the fiber funnel as a function of the fiber factor: (a) Series 1 and (b) Series 2.

Table 4
Blocking behavior measured by the J-ring (bar spacing in millimeter)

Steel fiber content	20 [kg/m^3]	40 [kg/m^3]	60 [kg/m^3]	80 [kg/m^3]	100 [kg/m^3]	120 [kg/m^3]
SCC-Series 1						
Dramix 45/30 RL				74 (87)	87 (99)	
Eurosteel 50/50			74 (74)	99 (111)		
Dramix 65/40 RC		74 (87)	99 (111)			
Dramix 80/60 RC		87 (99)	111 (122)			
SCC-Series 2						
Dramix 45/30 RL				62 (74)	74 (87)	87 (99)
Eurosteel 50/50			74 (74)	87 (87)	99 (99)	
Dramix 65/40 RC		74 (87)	87 (99)	99 (99)		
Dramix 80/60 RC		62 (74)	122 (122)	122 (122)		

evaporates under dry laboratory conditions. Possibly, water absorption by aggregate takes place. Furthermore, a slight stiffening of concrete is normal for concrete also during the dormant period. The stiffer a mixture was, the higher was the possibility that blocking was caused. A steep increase of the flow-time at a lower fiber factor was found for the mixtures of Series 1 compared with that of Series 2, the one with a lower content of coarse aggregate.

3.4. Passing ability

It would be a benefit for mix design to know the bar spacing that leads to nonblocking. The relation between the bar distance and mixture parameters was investigated during this study. The passing behavior is affected by the content of mainly coarse particles, the maximum size of aggregate and by the segregation resistance of the mixture [13]. The bar

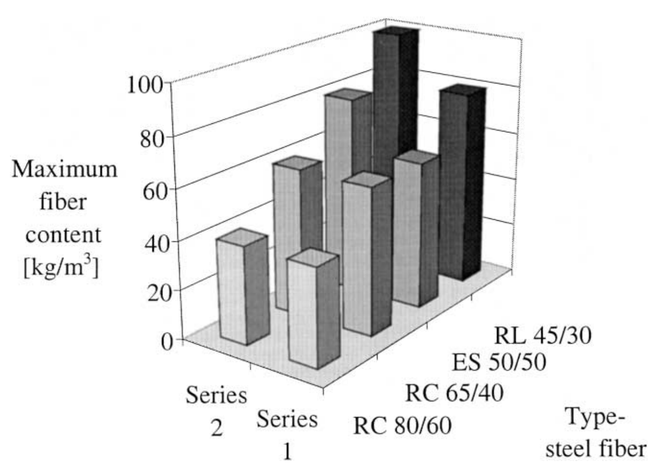

Fig. 6. Maximum fiber content depending on type of fiber and reference mixture.

spacing was varied three times; at least one measurement above and below the blocking criterion according to Nemegeer was required. Both reference mixtures did not cause blocking at a bar spacing of 36 mm. Table 4 shows the required bar spacing for each mixture to remain below a height difference of less than or equal to 10 mm after mixing; the results of the measurements 1 h after mixing are given in parentheses.

A comparison indicated the fiber length, the fiber factor and the stiffening of the mixture in time as affecting factors. A minimum required bar spacing of 62 mm to achieve nonblocking was found. A maximum of 122 mm was found for mixtures of both series at a fiber content of 60 or 80 kg/m^3 (Dramix 80/60 RC). In conclusion, a larger bar spacing compared with normal SCC is required to avoid the risk of blocking of fiber-reinforced mixtures.

3.5. Maximum fiber content

Fig. 6 shows a ranking to summarize the results of the experimental study concerning the aspect of the maximum fiber content for different reference mixtures and different types of fibers. The criteria to judge about the self-compactability were a slump flow over 600 mm, a round shape of the outflow and a homogenous distribution of the solids. No segregation might occur.

Both reference mixtures remained self-compacting even after the addition of a considerable amount of steel fibers. With decreasing aspect ratio, more fibers can be added to SCC without a problematic loss of workability. The maximum fiber content is not a single value; it depends on the mixture composition as well. A difference was found for the steel fiber types of Dramix 45/30 RL and Eurosteel 50/50. Compared with the reference mixture of Series 1, the one at a lower paste and higher coarse aggregate content, 20 kg/m^3 more fibers of both of these types could be added to the mixture of Series 2.

4. Conclusions

This paper describes the results of an experimental study performed to gain insight into the parameters that influence the flow mechanisms of self-compacting fiber-reinforced concrete. During this parameter-study two reference mixtures and 20 steel fiber-reinforced mixtures were tested. High deformability, segregation resistance and passing ability are characteristics that define the quality of SCC. Fibers do affect the workability of plain concrete; this study was performed to answer the question to what extent they affect the properties of SCC in the fresh state. The major findings of the study are:

First, a method was proposed to design SCC reinforced with steel fibers. It was experienced that it was useful throughout the experiments.

Second, it was found that the flow behavior of fiber-reinforced mixtures differs from that of plain SCC. Qualitative observations indicated if a homogenous distribution was given; if a critical fiber content was surpassed, a stiff structure of the granular skeleton makes flow under concretes' own weight impossible.

Next, the combination of test devices and observations that was applied during these experiments can be regarded as an appropriate tool to describe the properties of SCFRC. The slump flow test detected the clustering of coarse particles.

In addition, to avoid the risk of blocking a larger free bar spacing compared with plain SCC appears to be necessary if steel fibers are applied.

Finally, it was found that a considerable amount of fibers allowed self-compacting behavior. The mixture composition of the reference mixture influences the maximum possible fiber content.

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