

Flow Characteristics of Macro-Synthetic Fiber-Reinforced Self-Consolidating Concrete

by D. Forgeron and A. Omer

Synopsis: To evaluate the flow characteristics of macro-synthetic fiber-reinforced self consolidating concrete (MSFRSCC), a total of 20 non-air entrainment self-consolidating concrete (SCC) mixtures with varying w/c ratios, macro-synthetic fiber lengths, and fiber dosages rates were evaluated. The flow characteristics of each mixture were evaluated using four typical SCC workability test methods: slump flow, filling capacity, L-box, and V-funnel tests. The plastic shrinkage cracking resistance, compressive strength and flexural strength of each mixture were also evaluated. The objective was to develop an understanding of the factors that influence the flow characteristics of MSFRSCC and determine if criteria set for conventional SCC can be applied to MSFRSCC.

The testing results demonstrated that fiber lengths of 50 mm cause significant internal friction leading to mixture stability issues when attempting to increase the volume of high range water reducer to produce acceptable slump flow values without viscosity modifying admixtures. Reducing fiber length to 38mm led to reduction in the internal friction allowing satisfactory slump flow, filling capacity, and V-funnel flow time to be achieved with slight mixture modifications and no viscosity modifying admixtures were required. The addition of fibers did cause lower than acceptable L-Box test results where mixtures were made to change direction and flow between closely spaced bars. It was concluded that the slight increase in internal friction produced by the addition of fibers caused the low L-Box results and not any form of blockage. The plastic shrinkage test results showed that the addition of 0.40% fibers by volume led to as much as 70 % reduction in total crack area and up to 50% reduction in maximum crack width as compared to plain concrete. The results obtained from this research clearly shows that it is possible to develop highly crack resistant MSFRSCC mixtures for concrete structures.

Keywords: flowability; internal friction; macro-synthetic fiber reinforcement; mixture stability; passability; plastic shrinkage cracking resistance; self-consolidating concrete; self leveling concrete

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Dr. Dean Forgeron is the assistant Director of the Center for Innovation in Infrastructure and an assistant professor in the department of Civil and Resource Engineering at Dalhousie University, Nova Scotia, Canada. He is a member of ACI Committee 544, Fiber-reinforced Concrete and chairman of ACI 544 subcommittee on testing of fiber-reinforced concrete. His research interests include specifically the development of macro-synthetic fiber reinforcement, material characterization of fiber-reinforced concrete, self-consolidating, self leveling fiber-reinforced concrete and structural applications incorporating fiber-reinforced concrete

Mr. Alkilani Omer currently works as a project manager for the Libyan government. Mr. Alkilani completed his M.A.Sc in 2006 where he developed macro-synthetic fiber-reinforced self-consolidating concrete for marine structures in hot climates. Mr. Alkilani will begin his Ph.D studies in 2010 researching the structural response of macro-synthetic self-consolidating fiber reinforcement at Dalhousie University, Nova Scotia Canada. His research interests include self-consolidating concrete, fiber-reinforced-self-consolidating concrete, fiber-reinforced concrete.

INTRODUCTION

During the construction of conventional concrete structures many factors, such as improper or inadequate placement and consolidation techniques as well as inadequate curing regimes, can lead to poor compaction and surface cracking which, when combined, results in high concrete permeability. The aforementioned consolidation, compaction and curing issues reduce the ability for concrete resistance to the ingress of aggressive agents (chloride ions, moisture, oxygen, etc) and can lead to the corrosion of reinforcing steel. Corrosion leads to serviceability issues and, in extreme cases, can cause large reductions in overall structural capacity or even failure of the member or structure. Ultimately, a mixture that possesses both a high cracking resistance and the ability to self consolidate would mitigate against many of these “serviceability” problems.

The addition of macro-synthetic fiber reinforcement has been shown to improve cracking resistance of normal concrete while self-consolidating concrete has been used extensively to reduce the occurrence of improper consolidation and placement methods (Trottier et al. 2002, Khayat 1999). It follows that the combination of these two technologies would eliminate many of the issues mentioned above.

It has been shown that the addition of macro-fibers leads to a reduction in workability of concrete mixtures due to the additional surface area and the internal friction produced by the addition of fibers (Balaguru and Shah 1992). Most of the research that has been conducted on fiber-reinforced concrete has been focused on the effect of steel fibers on the rheology of SCC mixtures and the development of steel fiber-reinforced self-consolidating concrete mixture design procedures (Khayat and Roussel 2000, Grunewald 2004, Bui et al 2003, De Larrard 1999, Ferrara et al. 2007).

Fewer studies have been conducted on macro-synthetic fiber reinforcement and its effect on the flow characteristics of SCC. One study in the literature details an invention into the potential synergistic effects of incorporating steel and synthetic macro-fibers in various hybrid (single, binary, and ternary) combinations into SCC. They noted that the addition of 40 and 50mm macro-synthetic fibers caused a significant reduction of slump flow and blockage in the L-Box test (Moncef and Ladanchuck, 2004). Others noted that SCC can be achieved when macro-synthetic fibers are used but total fiber volume fractions must be less than 0.4% by volume. They also suggested that reduced fiber length as well as size and content of coarse aggregates are necessary to maintain adequate flow properties of FRSCC (Grunewald and Walraven 2001).

Recent advancements have lead to development of an innovative self-fibrillating macro-synthetic fibers that partially fibrillate upon mixing. This increased the surface area in contact with the cement matrix and improved the resulting mechanical properties (Trottier and Mahoney 2001). These fibers

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become flexible after mixing and therefore will not behave like steel or conventional macro-synthetic fibers when introduced into self-consolidating concrete mixtures. It is therefore important to study the flow characteristics of self-consolidating concrete mixtures that incorporate this type of macro-synthetic fiber reinforcement in order to identify and characterise the main factors affecting its flow. The information garnered from this study can then be used in the development of macro-synthetic fiber-reinforced self-consolidating (MSFRSCC) mixtures and mixture design procedures.

Overall it is important to provide sufficient cement paste to allow free movement of the coarse aggregate particles past one another as the mixture flows. The paste must also be sufficiently fluid to allow movement in a relatively rapid manner while possessing adequate yield stress to prevent segregation of the mixture while at rest. It follows that the addition of fiber reinforcement will not only require additional paste to coat the fibers but the paste fluidity will also need to be increased in order to allow movement of the aggregate through a paste that contains fiber reinforcement. The balance comes in attempting to maintain the stability of the mixture (ensuring no segregation) while increasing fluidity. One option is to reduce the coarse aggregate content of the mixture in order to compensate for the additional fiber induced friction and surface area. This will lead to less volumetric stability and higher potential for cracking. The key is to ensure that the mixture adjustment required to produce acceptable flow characteristics does not cause more cracking potential than the added fibers can prevent.

A total of 20 non-air entrainment self-consolidating concrete (SCC) mixtures with varying w/c ratios, self-fibrillating macro-synthetic fiber lengths and dosage rates plus one normal concrete control mixture (NC) were evaluated. The flow characteristics of each mixture were evaluated using four typical SCC workability test methods: slump flow, filling capacity, L-box, and V-funnel flow time tests. The cracking resistance, compressive strength and flexural strength of each mixture were also evaluated to determine the influence of various mixture adjustments on the engineering properties of each mixture. Ultimately, this research was conducted to further develop an understanding of the factors that influence the flow characteristics of MSFRSCC.

TESTING PROGRAM

In this study, a total of 21 non-air-entrained mixtures were investigated; one normal concrete mixture (NC), shown in [Table 1](#) and 20 SCC mixtures, shown in [Table 2](#). The aggregate grading for the normal concrete mixture and SCC mixtures are shown in [Figure 1](#). The coarse to fine aggregate volume ratio was maintained at 50/50 therefore one curve describes the combined aggregate grading for all 20 SCC mixtures in this study.

Table 1. Reference Normal Concrete Mixture Composition

Mix No.	Cement* Kg/m ³ (lbs/yd ³)	Coarse Agg.** Kg/m ³ (lbs/yd ³)	Fine Agg.+ Kg/m ³ (lbs/yd ³)	Water L/m ³ (gal/yd ³)	Super-Plasticizer++ L/m ³ (oz/yd ³)
NC	440 (741.6)	970 (1635)	760 (1281)	175 (35.3)	0.85 (22)

* Type GU (St. Lawrence Cement)

** 19mm max. Crushed rock (SG= 2.72, abs = 0.9 %)

+ Natural sand (FM = 3.0, SG = 2.6, abs = 1.5%)

++ Superplasticizer = Euclid Chemical (Plastol 5000 SCC)

The plain SCC mixtures were proportioned with w/c ratios of 0.40, 0.42, and 0.45 and constant water contents (190L/m³) labelled as SCC1, SCC2, and SCC3, respectively. The SCC mixture designs were created to evaluate the effect of volume of paste contents, V_p , while also changing compressive strength of the resulting mixtures. The normal concrete reference mixture had a w/c ratio of 0.4 and was labelled NC.

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All 20 SCC and MSFRSCC mixtures (0.15m^3 each) were prepared in a 0.25 m^3 (9.5 ft^3) laboratory drum mixer. The batch sequence used for all SCC mixtures was as follows:

- Add the sand to the mixer and mix for 30 seconds (moisture content evaluation and correction, as established by ACI recommended practices 211.1)
- Add the coarse aggregate to the mixer and mix for 30 seconds
- Add the fibers and mix for 3 minutes (not conducted for the plain SCC)
- Add 50% of the adjusted water and mix for 30 seconds
- Add all the cement to the mixer and mix for 30 seconds
- Add HRWR and the balance of the water and mix for 4 minutes
- Let stand for 2 minutes and then mix for 4 additional minutes

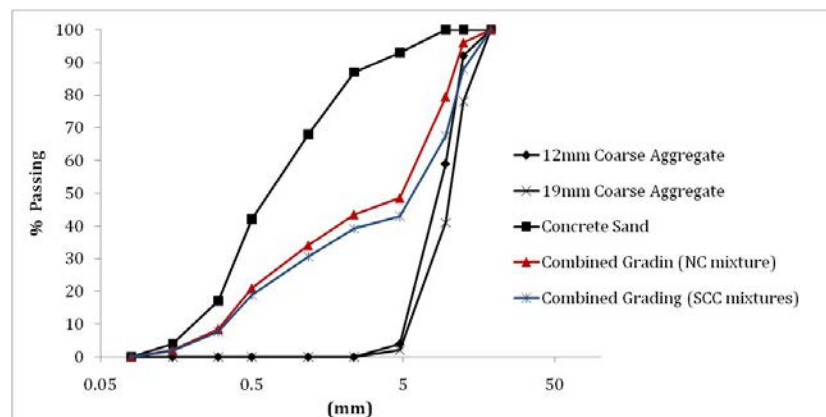


Figure 1. Concrete Aggregate Grading Curves

A commercially available self-fibrillating macro-synthetic fiber was selected for this study. This fiber is unique in that it is a monofilament fiber that partially fibrillates when mixed in concrete. The cross sectional geometry, specific gravity, tensile strength and modulus of elasticity of the fiber are given in [Table 2](#). Two fiber lengths (38 mm and 50 mm) were used in this study to investigate the effects of fiber length on the flow characteristics of SCC.

To evaluate the influence of fiber length on the flow characteristics of SCC, two separate self-fibrillating macro-synthetic fiber lengths (38 mm and 50 mm) were evaluated in mixture SCC2. Initially, the influence of 50mm fibers on the flow characteristics of SCC was evaluated in mixture SCC2. Two fiber volume fractions 0.20% and 0.50% were used and labelled as MSFRSCC2-6 and MSFRSCC2-7 as shown in [Table 3](#). Acceptable flow characteristics without the use of viscosity modifying admixtures could not be achieved therefore a shorter 38 mm self-fibrillating macro-synthetic fiber was used for the balance of the study. The influence of the 38 mm self-fibrillating macro-synthetic fibers on each of the SCC mixtures (SCC1, SCC2, SCC3) was then evaluated at five different fiber volume fractions ranging from 0.2% to 0.4%. The MSFRSCC mixtures were labelled as MSFRSCC#-1, MSFRSCC#-2, MSFRSCC#-3, MSFRSCC#-4, and MSFRSCC#-5, which contained the 38mm long fiber at fiber volume fractions of 0.20%, 0.25%, 0.30%, 0.35%, and 0.40% respectively. The volume fractions of 0.20%, 0.25%, 0.30%, 0.35%, 0.40%, and 0.5% correspond to fiber addition rates of 1.8kg/m^3 (3.0lbs/yd^3), 2.3kg/m^3 (3.9lbs/yd^3), 2.8kg/m^3 (4.7lbs/yd^3), 3.2kg/m^3 (5.4lbs/yd^3), 3.7kg/m^3 (6.2lbs/yd^3), and 4.6kg/m^3 (7.75lbs/yd^3), respectively.

Table 2. Self-Fibrillating Macro-Synthetic Fiber

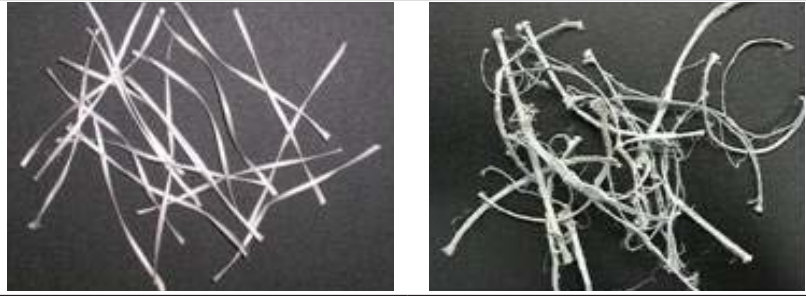
Specific Gravity	0.92		
Material	Polypropylene/ Polyethylene Blend		
Surface Area of Fiber	0.3 x 1.1 mm (0.012" x 0.043")		
Modulus of Elasticity	9.5 GPa (1378ksi)		
Tensile Strength	670 MPa (97.1ksi)		
		Before Mixing	After Mixing

Table 3. Self-consolidating Concrete Mixture Composition

Mix No.	Fiber Volume Fraction (%)	Fiber Length mm (in)	Blended Cement* Kg/m ³ (lbs/yd ³)	Coarse Agg.** Kg/m ³ (lbs/yd ³)	Fine Agg.+ Kg/m ³ (lbs/yd ³)	Water L/m ³ (gal/yd ³)	Super-Plasticizer** L/m ³ (oz/yd ³)
SCC1	-	-	475 (801)	800 (1348)	843 (1421)	190 (38.3)	3.2 (82.7)
MSFRSCC 1-1	0.20	38					3.5 (90.5)
MSFRSCC 1-2	0.25	38					3.5 (90.5)
MSFRSCC 1-3	0.30	38					3.75 (97)
MSFRSCC 1-4	0.35	38					4.0 (103.4)
MSFRSCC 1-5	0.40	38					4.25 (110)
SCC2	-	-	450 (758)	810 (1365)	854 (1439)	190 (38.3)	3.0 (77.6)
MSFRSCC 2-1	0.20	38					3.25 (84)
MSFRSCC 2-2	0.25	38					3.5 (90.5)
MSFRSCC 2-3	0.30	38					3.75 (97)
MSFRSCC 2-4	0.35	38					4.2 (108.6)
MSFRSCC 2-5	0.40	38					4.0 (103.4)
MSFRSCC 2-6	0.20	50					4.0 (108.6)
MSFRSCC 2-7	0.50	50					4.25 (110)
SCC3	-	-	423 (713)	825 (1391)	869 (1465)	190 (38.3)	2.88 (74.5)
MSFRSCC 3-1	0.20	38					2.9 (75.0)
MSFRSCC 3-2	0.25	38					3.0 (77.6)
MSFRSCC 3-3	0.30	38					3.25 (84)
MSFRSCC 3-4	0.35	38					3.4 (87.9)
MSFRSCC 3-5	0.40	38					3.5 (90.5)

* St. Lawrence Cement = 69% Type GU, 25% Flyash, 6% Silica Fume

** 12mm Coarse aggregate (SG= 2.74, abs = 1.0%)

+ Natural sand (FM = 3.0, SG = 2.6, abs = 1.5%)

++ Superplasticizer = Euclid Chemical (Plastol 5000 SCC)

After batching and mixing, the various workability tests used to characterize the flow characteristics of each SCC mixture were conducted in the following sequence: slump flow test, filling capacity test (34mm between bars), L-box test (34mm spacing between bars, as the most common arrangement of reinforcing bars) then V-funnel test. A photo of each test is shown in [Figure 2](#).



Figure 2. From left to right (Slump Flow, Filling Capacity, L-Box and V-Funnel)

To evaluate and compare the shrinkage potential of each mixture, plastic shrinkage cracking tests were conducted immediately after the fresh properties were evaluated. Two identical concrete slab specimens were cast in plywood moulds 610 mm x 915 mm x 50 mm (24" x 36" x 2") with uniformly distributed internal and side restraints. The specimens were finished and immediately exposed to a uniform drying condition for 24 hours. The temperature during testing ranged from 21 °C to 23 °C (70°F -73°F). The relative humidity in the concrete laboratory testing room was monitored during all tests and ranged from 65% to 75% during the period of testing. Two fans were used to generate a constant air speed of approximately 4 m/s (13.1fps) over the surface of the specimens. The fans were placed at the short edge of each plate as shown in [Figure 3](#). Plastic shrinkage testing was not conducted on mixture MSFRSCC2-6 and MSFRSCC2-7 because acceptable flow characteristics could not be achieved.

After 24 hours of exposure, the total area of cracking, total number of cracks, and the average crack widths were measured and the results were averaged. The total area of cracking of each specimen was calculated by summing up the product of the length and average width of each crack on the surface of the specimen.

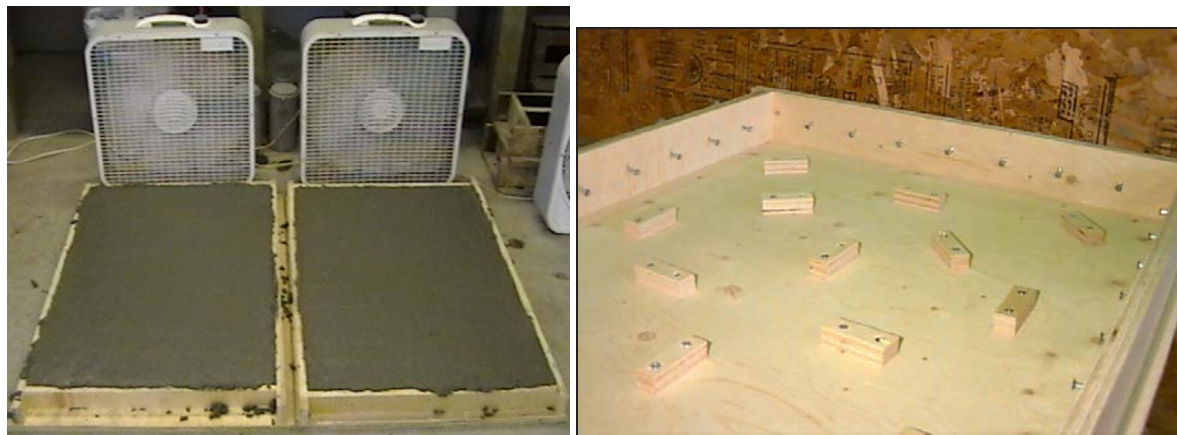


Figure 3. Plastic Shrinkage Panel Configuration and Internal Restraints

In addition to fresh properties and plastic shrinkage potential, test specimens were cast from each batch for compressive strength (ASTM C39) and flexural strength (ASTM C78) testing. All specimens were demolded at 24 hours and stored in the 20 ° lime water bath, as specified in ASTM C31, until the day of testing. Compressive and flexural strength tests were not conducted on mixture MSFRSCC2-6 and MSFRSCC2-7 because acceptable flow characteristics could not be achieved.

RESULTS

The slump flow, filling capacity, L-Box blockage ratio and V-funnel time test results for the 38 and 50mm fiber-reinforced mixtures are presented in Table 4. Comparing the flow characteristics of MSFRSCC2-1 (38mm fiber @ 0.2% by volume) to MSFRSCC2-6 (50mm fiber @ 0.2% by volume) it is clear that acceptable slump flows can be achieved for both fiber lengths. However, when filling capacity, L-Box, and V-funnel test are performed on both mixtures, the effect of fiber length became clear. It was clearly evidenced that fiber length plays a very important role in the flow characteristics of SCC when moving around, over or through obstacles. It is important to reiterate that the same fiber cross section was used in the 38mm and 50mm fiber therefore the surface area of the fibers in both mixtures is almost identical. The number of fibers for a given fiber volume fraction is 31% higher for the 38mm compared to the 50mm fiber. This indicates that fiber length has a stronger influence on flow characteristics than the number of synthetic fibers in a mixture.

Table 4. Fresh Properties

Mix No.	Slump Flow mm/(in)	Filling Capacity %	L-Box Blockage Ratio H2/H1	V-Funnel Time Sec
SCC1	637/ (25.1)	85.1	0.74	2.3
MSFRSCC 1-1	705/ (27.8)	86.8	0.67	2.9
MSFRSCC 1-2	628/ (24.7)	79.6	0.70	2.9
MSFRSCC 1-3	665/ (26.2)	82.6	0.67	3.0
MSFRSCC 1-4	715/ (28.1)	89	0.67	3.0
MSFRSCC 1-5	700/ (27.6)	93.9	0.70	2.8
SCC2	625/ (24.6)	78.4	0.70	2.9
MSFRSCC 2-1	640 / (25.2)	82.6	0.74	2.8
MSFRSCC 2-2	625/ (24.6)	82.7	0.67	2.6
MSFRSCC 2-3	680/ (26.8)	90.5	0.73	2.4
MSFRSCC 2-4	700/ (27.6)	91.7	0.67	2.6
MSFRSCC 2-5	668/ (26.3)	82.6	0.60	3.0
MSFRSCC 2-6	680/ (26.8)	72	0.6	10
MSFRSCC 2-7	550/ (21.6)	65	0	Blockage
SCC3	675/ (26.6)	84.7	0.86	2.0
MSFRSCC 3-1	635/ (25.0)	76.8	0.63	2.5
MSFRSCC 3-2	667/ (26.3)	79	0.63	2.6
MSFRSCC 2-3	632/ (24.9)	79.7	0.60	2.8
MSFRSCC 3-4	640/ (25.2)	82	0.53	2.7
MSFRSCC 3-5	655/ (25.8)	76.1	0.53	2.7
Coefficient of Correlation		0.749	0.147	0.086

50mm long self-fibrillating macro-synthetic fiber

Figure 4 shows the slump flow versus filling capacity and L-Box results. The graph includes trendlines for each parameter and the associated coefficient of determination, R^2 and the 70% limit for acceptable L-Box and Filling Capacity.

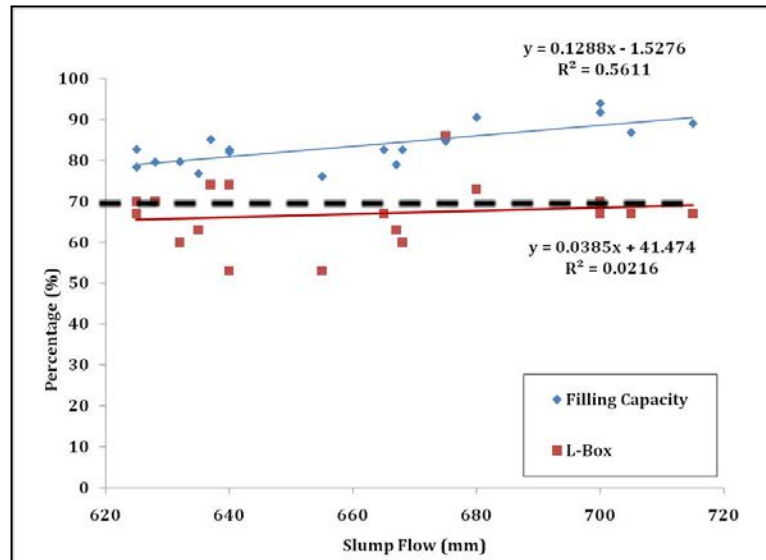


Figure 4. Relationship between Slump Flow, Filling Capacity and L-Box Ratio

To evaluate the correlation between slump flow and the other parameters, the coefficient of correlation between slump flow and filling capacity was evaluated for the 38mm fiber mixtures and it was found to be 0.75 indicating a strong correlation between these two variables. When evaluated for slump flow versus L-Box and versus V-Funnel the correlation coefficients were calculated as 0.147 and 0.086 which indicated very weak correlation between these variables. The correlation between slump flow and filling capacity is clear while the L-Box results are scattered and do not show any strong

The nature of the flow in a slump flow test and filling capacity test is similar in that the concrete moves horizontally driven by gravity or the energy induced during the filling process. It appears that the movement over horizontal obstructions, as is found in the filling capacity test, is very different than movement through narrowly spaced vertical obstructions as is the case in the L-Box test. It is also important to note that the movement of concrete in the L-Box test is very different from the slump flow and filling capacity tests. In the L-Box test the vertical chamber of the apparatus is filled and then the gate opened and the concrete is forced to move down and then change direction while being forced around closely spaced reinforcements. Figures 5 and 6 show that with the addition of fibers, the L-Box ratio is decreased due to the presence of a small shelf of concrete behind the reinforcing bars. Within the horizontal portion of the L-Box, the FRSCC remains almost horizontal as was the case in the slump flow and filling capacity tests. To determine if the concrete in the shelf was being held due to some sort of blockage a small amount of additional concrete was poured into the vertical chamber of L-box apparatus and the shelf of concrete was pushed through the reinforcing bar however the additional poured concrete remained behind the bars. This is attributed to the additional internal friction provided by the fiber reinforcement.

Table 4 shows that the macro-synthetic fiber-reinforced mixtures performed better in the L-Box test when lower water to cement ratios were used. To illustrate the difference, compare the photos in Figure 5 (series 2, w/c = 0.42) to those in Figure 6 (series 3, w/c = 0.45). It is clear that the additional paste content in Series 2 produced lower internal friction and better L-Box test results.

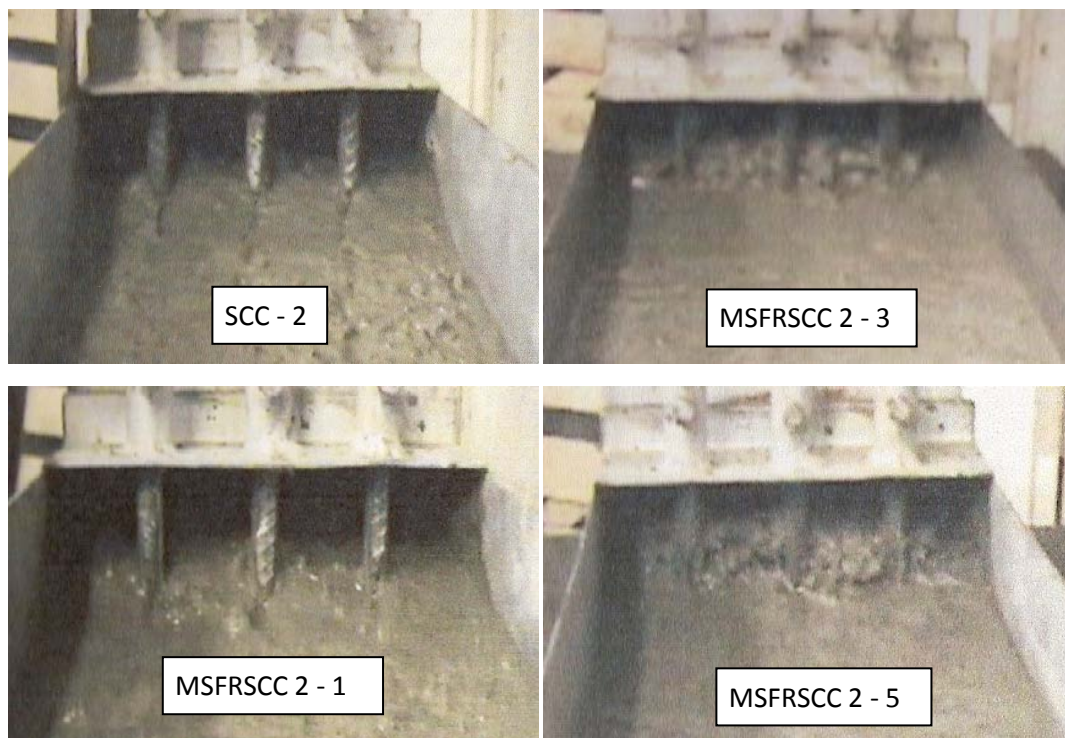


Figure 5. L-Box Test (Series 2)

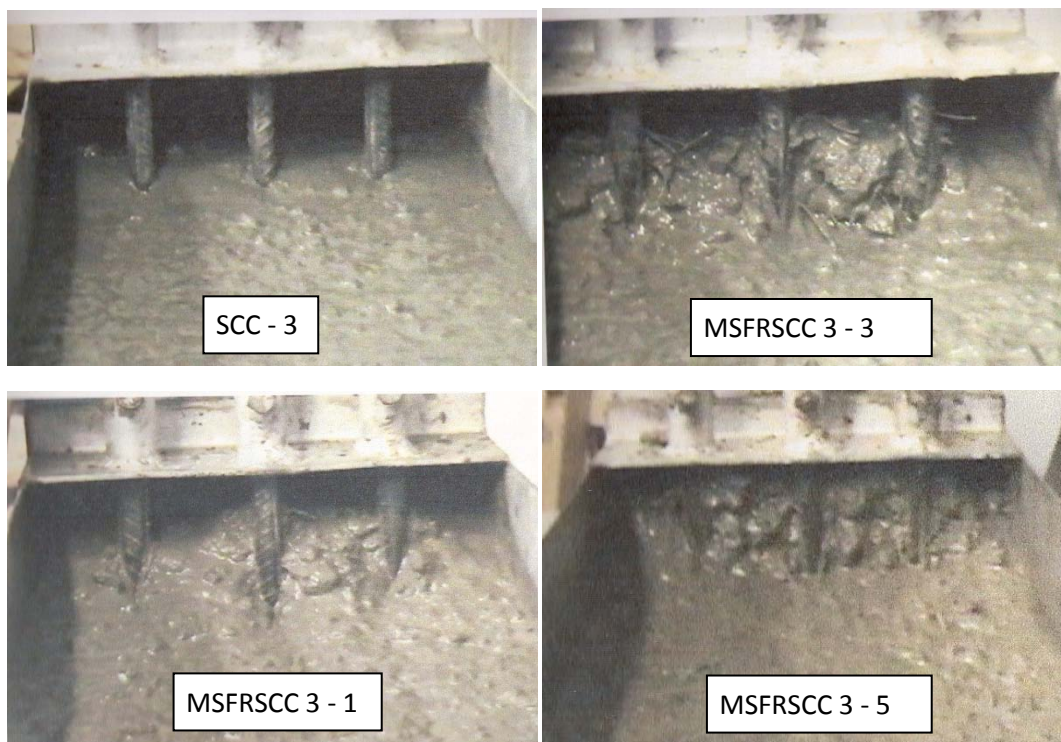


Figure 6. L-Box Test (Series 3)

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The total cracking area, average crack widths and maximum crack widths are presented in [Table 5](#). The total area of cracking of each specimen was calculated by summing up the product of the length and average width of each crack on the surface of the specimen. Plastic shrinkage testing was not conducted on mixture MSFRSCC2-6 and MSFRSCC2-7.

The relationship between fiber content and total cracking area for each mixture type used in this study is shown in [Figure 7](#). The average crack width versus fiber volume fraction was also evaluated and is shown in [Figure 8](#). It is clear that there is a strong correlation between total cracking area and fiber volume fraction in each mixture type (correlation coefficient from -0.94 to -0.97) as well as between average crack width and fiber volume fractions in each mixture type (correlation coefficient from -0.84 to -0.93). The correlation can be evaluated visually in [Figure 7](#) and [Figure 8](#).

Table 5. Plastic Shrinkage Test Results

Mix No.	W/C	Total Cracking Area mm ² /(in ²)	Average Crack Width mm/ (in)	Reduction in Crack Area %	Max Crack Width mm / (in)
NC	0.40	318/(0.49)	0.35/(0.138)	-	0.50/(0.02)
SCC1	0.40	490/(0.76)	0.31/(0.012)	-	0.40/(0.016)
MSFRSCC 1-1		387/(0.60)	0.27/(0.0106)	21.0	0.30/(0.012)
MSFRSCC 1-2		308/(0.48)	0.25/(0.010)	37.1	0.30/(0.012)
MSFRSCC 1-3		220/(0.34)	0.20/(0.008)	55.0	0.20/(0.008)
MSFRSCC 1-4		176/(0.27)	0.15/(0.006)	64.0	0.20/(0.008)
MSFRSCC 1-5		145/(0.22)	0.15/(0.006)	70.4	0.20/(0.008)
SCC2	0.422	287/(0.44)	0.25/(0.010)	-	0.40/(0.016)
MSFRSCC 2-1		159/(0.25)	0.18/(0.007)	44.6	0.30/(0.012)
MSFRSCC 2-2		150/(0.23)	0.15/(0.006)	47.7	0.20/(0.008)
MSFRSCC 2-3		123/(0.19)	0.18/(0.007)	57.1	0.20/(0.008)
MSFRSCC 2-4		122/(0.19)	0.15/(0.006)	57.5	0.20/(0.008)
MSFRSCC 2-5		117/(0.18)	0.18/(0.007)	59.2	0.15/(0.006)
SCC3	0.45	123/(0.19)	0.15/(0.006)	-	0.35/(0.014)
MSFRSCC 3-1		81/(0.13)	0.13/(0.005)	34.1	0.20/(0.008)
MSFRSCC 3-2		74/(0.11)	0.13/(0.005)	40.0	0.20/(0.008)
MSFRSCC 2-3		71/(0.11)	0.13/(0.005)	42.3	0.20/(0.008)
MSFRSCC 3-4		66/(0.10)	0.13/(0.005)	46.3	0.20/(0.008)
MSFRSCC 3-5		70/(0.11)	0.10/(0.004)	43.1	0.15/(0.006)

By comparing the total cracking area of mixture NC (490mm²) and mixture SCC1(318mm²), both having a w/c ratio of 0.4, the effect of paste content on the cracking resistance is evident. The higher cement paste volume (V_p) of SCC1(166L/m³) vs NC (V_p =139L/m³) and therefore the lower volume stabilizing coarse aggregate content results in a 54% greater crack area on the surface of the panel. It is important to note that slabs with a high number of cracks will have a lower average and maximum crack width due to the configuration of this testing procedure. In effect, as a particular crack increases due to internal shrinkage induced strain, mixtures with higher cracking potential will tend to form another crack nearby causing the first crack to contract. For this reason mixture SCC1, which has a higher cracking potential has an average and maximum crack widths lower than those of NC mixture. Within the same mixture design, the effect of fiber addition can be compared by looking at total crack area, average crack width and maximum crack width in a similar way. As the fiber dosage rate is increased, a marked reduction in all three parameters is noted in all mixtures.

To determine how mixture design and cracking potential are affected by the addition of self-fibrillating macro-synthetic fiber reinforcement, the total cracking area is plotted against the fiber volume fraction in [Figure 7](#) and average crack width is plotted against fiber volume fraction in [Figure 8](#). It is clear from these graphs that the addition of fibers increases the cracking resistance (total crack area, average crack width and maximum crack width) of all mixtures, however the effectiveness (slope of the curves

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in Figure 7 and Figure 8) of this fiber decreases as the paste content (V_p) and therefore cracking resistance of the mixture increases. In practical terms, an additional 0.1% by volume will have more of an effect in a mixture with high paste volume than one of low cracking potential. Figures 7 and 8 illustrate the large impact that relatively low fiber dosage rates of 0.4% by vol. (3.7kg/m^3 (6.2lbs/yd^3)) can have on SCC mixtures reducing the cracking area by 70% and average crack width by 50%.

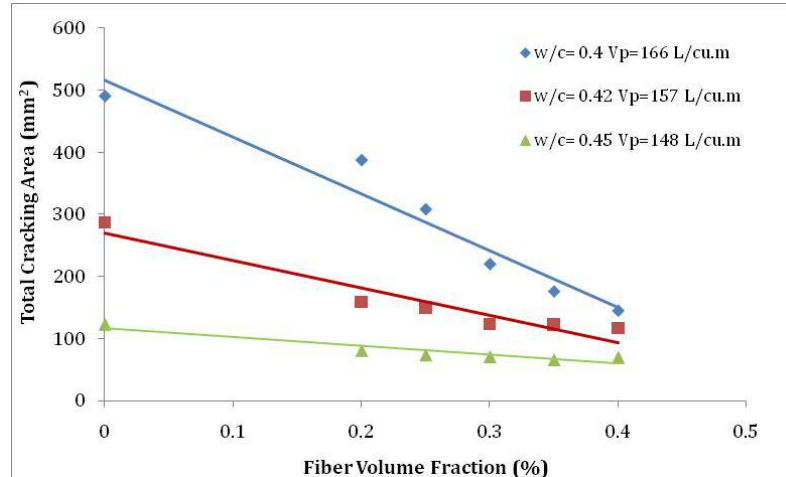


Figure 7. Fiber Volume Fraction versus Total Cracking Area

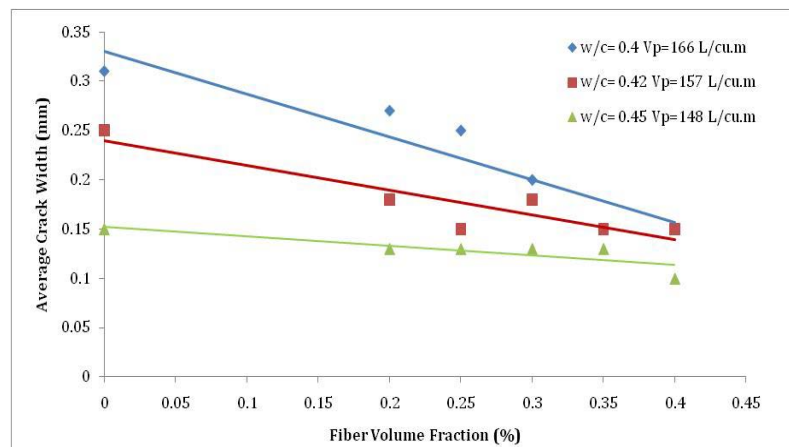


Figure 8. Fiber Volume Fraction versus Average Crack Width

The addition of a modest 0.3% by volume (2.8kg/m^3 (4.7lbs/yd^3)), of self-fibrillating macro-synthetic fiber reinforcement to the mixture reduced the cracking area to 220mm^2 (0.34in^2) and the average crack and maximum crack width to 0.20mm (0.008in). Comparing this to the NC mixture we observe a total cracking area of 318mm^2 (0.49in^2), an average crack width of 0.35mm (0.138in) and a maximum crack width of 0.50mm (0.02in). Therefore it is clear that a MSFRSCC mixture can be produced with superior cracking resistance to a comparable normal concrete mixture and still maintain adequate flow characteristics.

The compressive strength and flexural strength of all mixtures, except MSFRSCC2-6 and MSFRSCC2-7, are shown in Table 6. The consistency in both compressive strength and flexural strength between all SCC mixtures confirms that the control measure put in place to accurately batch each mixture was successful. Comparing the NC mixture and SCC1 mixture shows that the alternate SCC mixture designed

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in this study produced a very similar compressive strength to lab consolidated cylinders. In the field, the self compacting nature of the SCC mixture will ensure relatively uniform compressive strengths in a structure while the normal concrete mixtures “in place” compressive strength will depend on the quality of compaction achieved.

The slight reduction in flexural strength of all MSFRSCC mixtures compared to their respective control mixture could be attributed to the slight change in compaction of the granular skeleton caused by the presence of the macro-synthetic fiber reinforcement.

Table 6. Compressive Strength and Flexural Strength Results at 28 days

Mix No.	Compressive Strength MPa/(psi)	Flexural Strength MPa / (psi)
NC	49.8/(7223)	N/A
SCC1	48.2/(6991)	7.50/(1088)
MSFRSCC 1-1	48.2/(6991)	7.35/(1066)
MSFRSCC 1-2	49.4/(7165)	7.20/(1044)
MSFRSCC 1-3	49.4/(7165)	7.12/(1033)
MSFRSCC 1-4	52.7/(7644)	7.15/(1037)
MSFRSCC 1-5	50.5/(7325)	7.20/(1044)
SCC2	44.1/(6396)	7.00/(1015)
MSFRSCC 2-1	44.6/(6469)	6.90/(1001)
MSFRSCC 2-2	44.5/(6454)	6.80/(986)
MSFRSCC 2-3	45.3/(6570)	6.85/(994)
MSFRSCC 2-4	46.6/(6759)	6.82/(989)
MSFRSCC 2-5	45.6/(6614)	6.90/(1001)
SCC3	42.0/(6092)	6.45/(936)
MSFRSCC 3-1	42.7/(6193)	6.17/(895)
MSFRSCC 3-2	42.5/(6164)	6.53/(947)
MSFRSCC 3-3	45.0/(6527)	6.21/(901)
MSFRSCC 3-4	42.6/(6179)	6.13/(889)
MSFRSCC 3-5	43.7/(6338)	6.13/(889)

CONCLUSIONS

Macro-synthetic self-fibrillating self-consolidating concrete mixtures can be designed with 38mm self fibrillating macro synthetic fibers with dosage rated up to 0.4% by volume with only ternary blend cement and high range water reducing admixtures. A strong correlation was found between slump flow and Filling capacity while the L-Box results do not correlated well with slump flow indicating that the movement of MSFRSCC in the L-Box test is very different from the slump flow and filling capacity tests. Mixtures with lower water to cement ratios (higher cement contents) performed much better in the L-Box test. Interestingly, fiber length was found to have a stronger influence on flow characteristics of SCC than the number of fibers in a mixture. If unrestricted flow is desired, as seen in the slump flow and filling capacity tests, fiber volume fractions can be increased up to 0.5%.

The addition of modest dosage rates (<0.4%) of self-fibrillating macro-synthetic fiber reinforcement can significantly reduce the cracking area, the average crack and maximum crack width of SCC. MSFRSCC mixture can be produced with superior cracking resistance to a comparable strength normal concrete mixture and still maintain adequate flow characteristics.

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Maximum Fiber Content and Passing Ability of Self-Consolidating Fiber-Reinforced Concrete

by S. Grünewald and J. C. Walraven

Synopsis: Self-consolidating fiber-reinforced concrete (SCFRC) combines the benefits of self-consolidating concrete (SCC) in the fresh state and an enhanced performance of fiber reinforced concrete (FRC) in the hardened state. The application of SCC improves the efficiency at building sites, allows rationally producing prefabricated concrete elements and improves the working conditions, the quality and the aesthetical appearance of concrete structures. By adding fibers to SCC bar reinforcement can be replaced, crack widths reduced, the durability improved and the load bearing capacity of a structure increased.

An extensive research study¹ was carried out on the characteristics and the mix design of SCFRC that consisted of three parts: the fresh as well as the hardened state of SCFRC and the influence of the production process determined in three full-scale studies. This paper discusses two aspects of the mix design of SCFRC: the maximum fiber content and the required spacing of reinforcement at which blocking does not occur. Based on the analysis of experimental results mix design tools are proposed that allow predicting the maximum fiber content and the passing ability of SCFRC, which is essential information to obtain a homogeneous distribution of the fibers in a structure.

Keywords: flow behavior; maximum fiber content; mixture composition; passing ability; self-consolidating concrete; steel fibers

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Steffen Grünewald is an Assistant Professor at the Delft University of Technology in The Netherlands (Section of Structural and Building Engineering). He completed his PhD-study on 'Performance-based design of self-compacting fibre reinforced concrete' at the Delft University of Technology. He is also Manager of the Quality and Material Department of Hurks Beton, a Dutch producer of prefabricated concrete elements and Convener of fib Task Group 8.8 'Structural Design with Flowable Concrete'.

Joost C. Walraven is Professor of Concrete Structures at the Delft University of Technology in the Netherlands. His main areas of research are the development and application of new types of concrete and the determination of the residual strength of existing concrete structures. He is honorary president of fib, the international concrete federation. He was chairman of the Project Team producing Eurocode 2 "Concrete Structures."

RESEARCH SIGNIFICANCE

Optimized SCFRC is a tailor-made concrete that might be an alternative for either typical SCC- or FRC-applications. Due to the special characteristics of SCFRC new fields of application can be explored. SCFRC can be optimized for various purposes: to apply the highest possible fiber content, to obtain the highest performance-cost ratio, to design the granular skeleton for the highest packing density or to produce with the lowest possible material costs. The knowledge about the fiber percent addition to SCC at a given mixture composition and how the fibers perform in the hardened state allows composing economical and performance-based mixtures. Tools to predict design characteristics and to optimize the mixture composition of SCFRC reduce the number of 'trial and error' experiments and indicate possibilities and limits.

INTRODUCTION

Fibers are known to affect characteristics of concrete in the fresh and the hardened state. Fibers bridge cracks and restrict their propagation. They contribute to an increased energy absorption compared to plain concrete^{2,3}. Steel and plastic fibers are the most common fiber types in the building industry; other fiber types like glass and carbon fibers contribute with a smaller part to the market.

Fibers and workability

Fibers affect the characteristics of concrete in the fresh state. They are needle-like particles that increase the resistance to flow and contribute to the formation of an internal structure of aggregate grains and fibers. In order to optimize the performance of each fiber, the fibers need to be homogeneously distributed and clustering of fibers has to be counteracted. The size of the fibers relative to the aggregates determines their distribution.⁴ To be effective in the hardened state it is recommended to choose fibers not shorter than the maximum aggregate size.^{4,5} Usually, the fiber length is 2-4 times that of the maximum aggregate size. The effect of fibers on the workability is mainly due to four reasons: First, the shape of the fibers is more elongated compared to the aggregates; the surface area at the same volume is higher. Second, stiff fibers change the structure of the granular skeleton, whereas flexible fibers fill the space between them. Stiff fibers push apart particles that are relatively large compared to the fiber length, which increases the porosity of the granular skeleton. Third, the surface characteristics of fibers differ from that of cement and aggregates, e.g. plastic fibers might be hydrophilic or hydrophobic. Finally, fibers can be deformed (i.e. have hooked ends or are wave-shaped) to improve the anchorage between them and the surrounding matrix.

Maximum fiber content

The maximum fiber content is the critical fiber dosage at which the compactability drastically decreases. The size, the shape and the content of the coarse aggregates as well as the geometry and the volume fraction of steel fibers affect the workability of concrete⁶. The relative fiber to coarse aggregate volume and the 'balling up' phenomenon govern the maximum possible content of steel fibers⁷. The

more fibers the mixture contains the more likely the occurrence of fiber balling; a maximum of 2 Vol.-% of steel fibers (1 Vol.-% at a high aspect ratio) is considered as a maximum⁸. Narayanan & Kareem-Palanjian⁹ found that the 'optimum fiber content' increased at increasing percentage sand of total aggregate; both parameters were linearly correlated. The 'optimum fiber content' was defined as the content of the steel fibers beyond which fiber balling took place. SCFRC can maintain self-compactability in spite of the addition of fibers. Groth & Nemegeer¹⁰ performed parameter-studies on the effect of steel fibers on the characteristics of SCC in the fresh state (slump flow, flow-time T_{50} and J-ring test). Khayat & Roussel¹¹ tested SCFRC with the IBB-Rheometer; the applied fiber contents were 0.5 and 1.0 Vol.-%. Higher contents of short steel fibers have been added to self-consolidating mortar.¹²

Passing ability

Passing ability is the ability of the concrete to pass narrow gaps between reinforcement bars without blocking. Passing ability of SCFRC is required to guarantee a homogeneous distribution of the components during the flow in the vicinity of obstacles. The minimum bar distance to avoid blocking depends on the flowability of the concrete, on the maximum aggregate size, the paste content and the distribution and the shape of the aggregates. The size of the components of SCFRC relative to the bar spacing affects the passing ability; the fibers usually are the largest components.

The passing ability of SCC can be predicted by calculating the risk of blocking^{13,14}, which takes into account the size, the shape (nature or crushed) and the distribution of the aggregates. The risk of blocking calculated with the CBI-model¹⁴ is used as an input parameter to predict the minimum bar spacing for SCC with steel fibers. **Figure 1** shows the relative effect of the aggregates on the passing ability of SCC (n_{abi}) related to the ratio of the bar spacing c divided by the diameter of the equivalent aggregate particle diameter D_{af} . The bar spacing c is the opening between the rebars of the L-box, which is a test method to determine the passing ability of SCC¹⁵. The equivalent diameter D_{af} of an aggregate fraction can be calculated with Equation 1.

$$\text{Fraction diameter: } D_{af} = M_{i-1} + \frac{3}{4} (M_i - M_{i-1}) \quad (1)$$

in which

M_i upper sieve dimension of aggregate [mm]
 M_{i-1} lower sieve dimension of aggregate [mm]; 1 inch = 25.40 mm

The points of **Figure 1** were obtained by an inverse analysis performed with experimental results and can be applied to calculate the risk of blocking according to Equation 2; blocking occurred in the experiments when the risk of blocking was higher than 1. Similar to the Miner-rule on fatigue, the contribution of each aggregate fraction is accumulated with Equation 2. The 'risk of blocking' has to be smaller than or equal to one.¹⁴

$$\text{Risk of blocking: } \sum_{i=1}^n \frac{n_{ai}}{n_{abi}} = \sum_{i=1}^n \frac{V_{ai}}{V_{abi}} \leq 1 \quad (2)$$

in which

n_{ai} aggregate contribution of group i to blocking [-]
 n_{abi} blocking volume ratio of group i [-]; $n_{abi} = V_{abi} / V_t$
 V_t total volume of the concrete mix [m³]
 V_{ai} aggregate volume of group i [m³]
 V_{abi} blocking volume of aggregate group i [m³]

Filling and passing ability are interrelated. Tests on the slump flow and the blocking ratio (L-Box) were carried out in the European 'Testing SCC'-project.¹⁶ The blocking ratio increased at a given risk of blocking at increasing slump flow. Nemegeer¹⁷ reported on a study on the passing ability of SCFRC; the J-ring in combination with the slump flow test was used to determine the bar spacing required to avoid blocking. A bar spacing of about two times the fiber length was found to prevent blocking. Groth¹⁸

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proposed a guideline (Table 1) for hooked-end steel fibers with circular cross-sections to counteract blocking of SCFRC, which is independent of the mixture composition of SCFRC. Groth normalized the bar spacing (bar spacing c divided by the fiber length L_f) to take into account the effect of different types of the steel fibers on the passing ability.

EXPERIMENTAL SET UP

Sixteen SCCs were composed as a reference to study the effect of the type and the content of the steel fibers. The maximum aggregate size was 4 mm/0.16 inch, 8 mm/0.31 inch or 16 mm/0.63 in. The applied aggregates of the mixtures of Series 1-16 were round and are assumed to be 'natural' aggregates according to Figure 1. The mixtures also differed in the content and the composition of the paste and the distribution of the aggregates. Table 2 shows the mixture compositions (in Vol.-%) and the characteristics in the fresh state (slump flow, T50 and filling degree Kajima test). The applied test methods for SCC are described in detail by Bartos et al.¹⁵. The air content of mixtures 1-13 was assumed for the mix design to be 2.0 Vol.-%. The target slump flow of mixtures 1-13 was 710 mm/27.95 inch $\pm$ 20 mm/0.79 inch, whereas it was a mortar flow of 245 mm/9.65 inch $\pm$ 20 mm/0.79 inch for mixtures with a maximum aggregate size of 4 mm/0.16 inch. The filling degree (Kajima test¹⁹) of the reference mixtures was higher than 90% in each case. The Kajima test was not carried out for mixtures 14-16, since the prepared volume of concrete was not sufficient. Due to the smaller aggregate size and the high filling ability a very high filling degree can be assumed.

Fiber types with lengths between 6 mm/0.24 inch and 60 mm/2.36 inch (mixtures 1-13: 20-60 mm (0.79-2.36 inch), mixtures 14-16: 6-13 mm (0.24-0.51 inch)) were tested. The content of the fibers was varied in order to determine the maximum fiber content and to determine the passing ability of SCFRC. The fiber contents were increased stepwise, which allowed studying the change in flow patterns at increasing fiber content. The volume of the aggregates was decreased by the fiber volume compared to the reference mixture (Series 1-4: against coarse aggregates, other series: the ratio sand to coarse aggregate was kept constant). Table 3 summarizes the tested fiber amounts and the maximum fiber contents of different reference mixtures (Dramix: D, Eurosteel: E, Harex: H). The first fiber index is the aspect ratio (L_f/d_f); the second index is the fiber length. The study consisted of 121 mixtures (including 16 mixtures without fibres). The effect of filling ability on the prediction of passing ability of SCFRC is considered small in this study; the slump flow of all self-consolidating mixtures with steel fibers (Series 1-13) was in a small range of 600-660 mm (23.62-25.98 inch).

The mixtures in parenthesis (Table 3) were not self-consolidating; to be considered 'self-consolidating' SCFRC had to meet the following criteria:

- Slump flow > 600 mm (23.62 inch)
- No segregation of the fibers
 - judged by their distribution in the mixer
- Homogeneous distribution of SCFRC on the flow table
 - uniform distribution of the fibers/aggregates/cement paste
 - a round shape of the flow spread

A forced pan type of mixer (Zyklos) with a maximum capacity of 120 liters/0.157 yd³ was used (Series 1-13). The volume of a batch with fibers was kept constant at 40 liters /0.052 yd³. A smaller forced pan type of mixer (Zyklos) with a maximum capacity of 25 liters/0.033 yd³ was used to prepare mixtures of Series 14-16. The volume of each batch was 16 liters/0.021 yd³. Figure 2 shows the mixing procedure.

Besides the slump flow test, the slump flow test with J-ring¹⁵ was carried out to evaluate the passing ability of SCFRC. A J-ring with seventy-two drilled holes was used to vary the distance of the bars. The diameter of the J-ring was 300 mm/11.81 inch (distance of the center of the holes). The applied bars ($d=16$ mm/0.63 inch) were smooth and made of stainless steel. Blocking is defined to occur in case the difference of the heights of the concrete in- and outside the J-ring was more than 10 mm/0.39 inch. The height difference was measured at four positions (rotation of 90°); the smallest and the largest differences were omitted. The bar spacing of the J-ring was varied three times in order to obtain one

height difference above and one below the blocking criterion (blocking: $\Delta h > 10$ mm/0.39 inch). The applied bar spacings of the J-ring were 36, 49, 62, 74, 87, 99, 111 and 122 mm (1.42, 1.93, 2.44, 2.91, 3.43, 3.90, 4.37, and 4.80 inch).

MAXIMUM FIBER CONTENT

Up to a defined fiber content, which depends on the fiber type and the mixture composition, a homogeneous distribution of the fibers was observed. However, the steel fibers affect the filling ability of SCC. The more fibers are added and the higher their aspect ratio, the more the slump flow decreased compared to a reference SCC without fibers. Dependent on the type and the content of the fibers, the slump flow decreases and the flow-time T50 increases compared to plain SCC. The fiber factor ($V_f \cdot L_f/d_f$) is the product of the volume of the steel fibers times the aspect ratio and can be applied to compare the effect of different types and contents of the steel fibers on the slump flow. Three deviating flow patterns were observed when the fiber dosage exceeded the “maximum fiber content.” The types of flow pattern (A, B and C) depend on the fiber type and are shown by [Figures 3-5](#).

- **Flow pattern A:** Fiber types having a large surface area have a pronounced effect on the filling ability of SCC. The fibers are homogeneously distributed but the shape of the concrete flow is not round. This flow pattern often coincided with a flow spread smaller than 600 mm/23.62 inch (example: Dramix 80/30 BP).
- **Flow pattern B:** This flow pattern can be observed in two cases: First, the mixture is not stable, the fibers segregate or second, the maximum content of long fibers is surpassed. In the latter case, this flow pattern was observed even when the fibers did not segregate in the mixer. This flow pattern coincided with a larger slump flow, since the flow was barely obstructed by the fibers (Example: Dramix 80/60 BN).
- **Flow pattern C:** Fiber types of intermediate aspect ratios (L_f/d_f : 45-65) often showed a combination of flow patterns A and B. The free flow is obstructed and a cluster of fibers and/or aggregates remains in the centre of the flow table (Example: Dramix 65/40 BN).

The ‘maximum fiber content’ is defined to be the highest possible amount of steel fibers, which can be added to SCC; SCFRC is self-consolidating below this fiber dosage. Below the maximum fiber content, the effect of different types and contents of the steel fibres can be described by the fiber factor ($V_f \cdot L_f/d_f$). For example, the fiber factor is 1.6 with an aspect ratio of 80 and 2 Vol.-% steel fibers ($80 \cdot 0.02 = 1.6$). The design of SCFRC at high fiber dosages requires to compensate for the effect of the fibers while keeping the fibers homogeneously distributed. High filling ability and sufficient segregation resistance often are irreconcilable demands for SCC, which only leaves a small range within which SCFRC is self-consolidating. At a very high filling ability the fibers might segregate. At too low a filling ability already low fiber contents counteract the flow. In this study, the reference mixtures had an intermediate filling ability (mixtures 1-13: slump flow ± 710 mm/27.95 inch), which balanced the contrary demands for SCFRC. The degree to which the slump flow spread is affected might range from almost no effect compared to the reference mixture (flow pattern B) to a significant decrease of the slump flow (flow pattern A). [Figures 3-5](#) can be applied to decide whether SCC with fibers is self-consolidating or not.

In order to predict the maximum content of the steel fibers, the characteristics of the aggregates have to be taken into account. The bar spacing to aggregate fraction diameter ratio (c/D_{af}) of the ‘risk of blocking’-approach ([Fig. 1](#)) was replaced by the ratio of the fiber length to aggregate fraction diameter (L_f/D_{af}) in order to take into account the relative size of aggregate fraction i . The influence factor n_{abi} of the CBI-model was replaced by the MFC-ratio $n_{a,mfi}$; MFC stands for the maximum fiber content (the MFC-ratio describes the relative effect ($n_{a,mfi}$) of aggregates on the maximum fiber content). Similar with the risk of blocking of the CBI-model, the MFC-volume can be calculated with Equation 2. The MFC-volume is the sum for all aggregate fractions of the volume of each aggregate fraction i (V_{ai}) divided by the MFC-ratio ($n_{a,mfi}$), which is equal to the influence factor $n_{a,mfi}$; [Figure 6](#) shows the relation between the ratio fiber length to aggregate diameter and $n_{a,mfi}$. The characteristic points of $n_{a,mfi}$ ([Fig. 6](#)) were varied to obtain the best correlation of experimental results and the maximum fiber factor. Relatively large

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aggregates ($L_f/D_{af} < 1.8$) result in a lower MFC-ratio; $n_{a,mf}$ is approximately constant at higher ratios of L_f/D_{af} .

Figure 7 compares the maximum fiber factor of mixtures of different series with the maximum fiber content volume (MFC) of the aggregates. The fiber length is the weighted average in case a hybrid mixture of short fibers (6 mm/0.24 inch and 13 mm/0.51 inch) was added. The maximum fiber factor ($V_f L_f / d_p$) can be determined with the MFC-volume as the intersection of the regression line (Equation 3). SCC is self-consolidating at a given fiber factor in case the MFC-volume is equal to or lower than the corresponding value on the regression line of Figure 7.

$$\text{Maximum fiber factor} = \frac{0.781 - \text{MFC}}{0.211} \quad (3)$$

in which

MFC maximum fiber content volume [-]

The analysis was performed with experimental results of mixtures with steel fibers and fiber lengths in the range of 6 mm/0.24 inch to 60 mm/2.36 inch. The mixture which was optimized for the production of slender prestressed sheet piles²⁰, is also included in Figure 7; its maximum aggregate size was 1 mm. The free spacing between the mould and the strands of the sheet piles was 16 mm/0.63 inch; 125 kg/m³/210.8 lb/yd³ of Dramix OL 13/0.16 steel fibers ($L_f=13$ mm/0.51 inch) were added. In order to increase the maximum fiber content the following parameters might be altered: to apply fibers with a lower aspect ratio, to increase the content of cement paste and/or to replace coarse with finer aggregates. Once aggregate fractions with a ratio L_f/D_{af} smaller than 1.8 are excluded, the paste content becomes the governing parameter. The model on the maximum fiber content was calibrated with mixtures that contained round aggregates. A single mixture was tested, which contained crushed aggregates. The content of the aggregates was the same as for mixture 8 (Table 2); crushed instead of round coarse aggregates were applied. In spite of the elongated shape and a rough surface of the coarse aggregates the mixture was self-consolidating. An upper limit (the fibers cluster no matter what the composition of SCC is) fiber content was found for Dramix 80/60 BP; 80 kg/m³/134.9 lb/yd³ of this fiber type caused fiber clustering without any interaction of the aggregates. The maximum fiber content depends on the mixture composition, whereas the upper limit is a characteristic of the fiber type.

PASSING ABILITY OF SCFRC

The minimum bar spacing required to avoid blocking is essential information to optimize the mixture composition of SCFRC. Table 4 summarizes test results concerning the non-blocking bar spacing for Series 1-4; some mixtures (with fiber dosages in parenthesis) were not self-consolidating. Only mixtures were considered that were self-consolidating according to the criteria presented before, which excludes the effect of fiber clustering on the passing ability. The experiments showed that the presence of the fibers increased the bar spacing for non-blocking compared to the reference SCC. The type and the content of the fibers mainly determine the required bar spacing. However, different bar spacings for non-blocking were found for different reference mixtures in spite of the same fiber type and fiber content. The mixture composition (the paste content, the distribution and the maximum size of the aggregates) also determines the required bar spacing. The bar spacing required to avoid blocking of mixtures with long steel fibers might be 99 mm/3.90 inch or larger. According to Table 1, the bar spacing for 30 kg/m³/50.6 lb/yd³ of 60 mm/2.36 inch steel fibers has to be 180 mm/7.09 inch. The bar spacings found in the tests for 60 mm fibers were smaller. For example, the required bar spacing at a fiber content of 40 kg/m³/67.5 lb/yd³ ($L_f=60$ mm/2.36 inch) was 87 mm/3.43 inch (Table 4: Mixture 2). The blocking factor (Equation 4) was calculated and is the product of three parameters that affect the passing ability of SCFRC. These parameters are the risk of blocking (Equation 2), the fiber content and the blocking diameter (Equation 5).

$$\text{Blocking factor (BF)} = BD \cdot V_f \cdot ROB_{(BS)} \quad (4)$$

in which

$ROB_{(BS)}$ risk of blocking (depends on the chosen bar spacing) [-]
 V_f fiber content (volume) [Vol.-%, for example 2 Vol.-%: 0.02]
 BD blocking diameter (depends on fibers' diameter) [-]

The higher the risk of blocking (effect of the aggregates) the larger the required bar spacing has to be to counteract blocking for a given type and content of the steel fibers. Higher contents of sand and paste were applied for SCFRC in order to provide 'space' for the fibers. The use of round aggregates also contributed to a low risk of blocking, which was typically lower than 0.90. The parameter BD (Equation 5 relates the dimensionless parameter BD and d_f) was applied to characterize different fiber types having the same length and their effect on the passing ability. The effect of the fibers on the passing ability increased at decreasing diameter. **Figure 8** shows the relation between the diameter of the steel fibers and the factor BD.

$$\text{Blocking diameter (BD)} = 0.553 \cdot d_f^{-1.51} \quad (5)$$

in which

d_f fiber diameter [mm]; 1 inch = 25.40 mm

In order to predict the 'non-blocking' bar spacing of SCFRC, the free opening c of the J-ring was normalized to the fiber length. A good correlation between the normalized bar spacing and the blocking factor was obtained (linear regression line: $R^2 = 0.89$). The actual bar spacing for 'blocking' is not exactly known since the bar spacing of the J-ring had to be increased in predefined steps. It is between the bar spacing for 'blocking' and 'non-blocking'. The predictions are on the safe side in case none of the data points is lower than Equation 6 predicts. The models' line was shifted parallel to the original regression line; Equation 6 was obtained as the intersection with the data point at the largest distance from the regression line.

$$BF = 0.607 \cdot \frac{c}{L_f} - 0.857 \quad (6)$$

in which

BF blocking factor of SCFRC [-]
 c clear spacing between reinforcement [mm]
 L_f fiber length [mm]; 1 inch = 25.40 mm

Figure 9 compares the regression line (Equation 6) with experimental results (mixtures with $D_{\max} \geq 8$ mm/0.31 inch); the model predicts 'non-blocking' in each case. The required bar spacing of most of the tested mixtures (Series 1-13) was between 1.5 to 3 times the fiber length (**Fig. 9**), which is in agreement with the findings of Groth (**Table 1**). It should be mentioned that often higher fiber contents were applied in this study compared to the maximum fiber contents of **Table 1**. Most self-consolidating mortars (Series 14-16) with short steel fibers (6 mm/0.24 inch and/or 13 mm/0.51 inch) below the maximum fiber content were able to pass the J-ring test at a bar spacing of 36 mm without blocking¹. Equation 6 was also applied to analyze the results of Series 14-16. **Figure 10** summarizes experimental results and predictions of Series 1-16. A correction (0.25 times the blocking factor) had to be applied to obtain results for Series 14-16, which were comparable with the results of mixtures containing longer steel fibres ($L_f \geq 20$ mm/0.79 inch). The effect of very short steel fibres on the passing ability was relatively small (a reduction factor of 0.25 indicates a small influence on passing ability). Blocking was measured in one case only, when non-blocking was predicted.

The optimization of the mixture composition with the normalized bar spacing and the blocking factor is an iterative process, since the risk of blocking ($ROB_{(BS)}$) depends on the actual bar spacing (Equation 2). The Blocking-Factor approach can be applied in two cases: First, in case the design bar spacing is known, the blocking factor can be calculated under consideration of the chosen fiber length (Equation 4). The fiber diameter can be calculated from the aspect ratio. The remaining parameters, the fiber volume and the ROB 'Risk of Blocking' (Equation 2), might be chosen. The fiber content has to remain below the maximum fiber content (Equation 3). The content, the shape and the grading of the aggregates determine the ROB at this bar spacing. The actual blocking factor has to be smaller than the predicted blocking factor. Second, the model can be applied to calculate the bar spacing required for non-blocking. The blocking factor has to be determined from the mixture composition. In order to calculate the ROB, the required bar spacing needs to be estimated. A comparison between the estimated and calculated bar spacings is necessary to control the assumed bar spacing.

FULL-SCALE APPLICATION: SHEET-PILE

Flowable mixtures are preferred in production in order to minimize the effort to compact the concrete. The applicability of SCFRC in practice and the influence of the casting method was determined in a case-study with sheet piles (developed by SPANBETON, a Dutch producer of prefabricated concrete elements)²¹. **Figure 11** shows the innovative sheet pile in comparison with a conventional concrete sheet pile; the length of the sheet piles is 12.5 m/41 feet. Sheet piles are ground- and water-retaining structures, which are usually made of steel. Prestressed sheet piles produced with SCFRC have several advantages compared to a standard concrete sheet pile: the placement of the concrete is easier (no rebars have to be placed), the storage of the segments requires less space, more sheet piles can be transported with one truck (they are lighter and occupy less space) and the placement in the ground is easier (less resistance).¹⁹

With the earlier discussed mix design tools an optimized mixture was developed at the Delft University of Technology that fulfilled all design criteria, i.e. a 1-day compressive strength of at least 60 MPa/8700 psi (28 days: C90/105). The mixture was self-consolidating and contained 125 kg/m³/210.8 lb/yd³ Dramix OL13/0.16 ($L_f=13$ mm/0.51 inch, $d_f=0.16$ mm/0.0063 inch) steel fibers. The free opening between the strands and the mould was 16 mm/0.63 inch. **Table 5** shows the mixture composition; the volume of the superplasticizer is subtracted from the content of free water. The applied mixture is more expensive than the conventional concrete; due to the more slender shape of the sheet pile (less material) and other savings (production, placement of bar reinforcement, transport and faster construction) these costs are compensated. The fibers oriented along the flow due to the effect of the walls and the strands. Especially in the lower flanges the flow distance was rather long. The fibers oriented along the flow in the lower flanges, whereas their orientation was more random in the upper flange. The performance of the sheet piles in the hardened state was according to the expectations, taking into account the orientation of the steel fibers and their effect on the tensile strength.²⁰

CONCLUSIONS

SCFRC is an innovative type of concrete, which combines the advantages and extends the possibilities of both SCC and fiber reinforced concrete. Two tools are discussed that facilitate the mix design of SCFRC concerning the maximum fiber content and the passing ability. An application (sheet piles) with SCFRC is discussed that shows the applicability of the tools. Based on the experimental studies and the analysis of the behavior of SCFRC the following conclusions can be drawn:

- Steel fibers affect the key characteristics filling ability and passing ability of SCC. The applicable range of mixture compositions and characteristics in the fresh state of SCC containing high fiber contents (close to the maximum fiber content) is smaller compared to SCC. By optimizing the mixture composition and balancing filling ability and segregation resistance, SCC can be self-consolidating at relative high fiber contents.

- The effect of the fibers on the maximum fiber content and the passing ability can be predicted with the type and the content of the fibers and the characteristics of the aggregates as input parameters. Visual observations on the slump flow test are proposed to provide information concerning the maximum fiber content.
- Due to an optimized mixture composition of SCFRC the fibers are homogeneously distributed in a structural element (without blocking) and effectively embedded in the matrix (without clustering).

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Table 1—Recommendation¹⁸ on the normalized bar spacing to avoid blocking of SCFRC (fiber dosage: m_f)

c/L_r [-]	L/d_r [-]	Max. m_f [kg/m ³]	Max. m_f [lb/yd ³]
≥ 3	80	30	50.59
	65	60	101.18
≥ 2	65	30	50.59
	45	60	101.18
≥ 1.5	45	30	50.59

Table 2—Mixture composition and characteristics of sixteen self-consolidating reference mixtures

No.	Max. aggregate size	Fine aggregates (0.125-4 mm)	Coarse aggregates (4-16 mm)	Paste content (<0.125 mm)	Slump flow/ Mortar flow	Flow-time T50	Filling vessel test ¹⁹
	[mm]	[Vol.-%]	[Vol.-%]	[Vol.-%]	[mm]	[s]	[%]
1	16	23.40	39.50	35.10	718	2.4	91.1
2	16	24.59	36.52	36.89	708	3.3	97.6
3	16	25.95	33.13	38.92	716	4.2	97.7
4	16	27.31	29.72	40.97	743	3.5	98.9
5	16	35.10	26.40	36.50	703	1.9	93.8
6	16	33.63	25.37	39.00	693	2.1	90.4
7	16	41.82	19.68	36.50	730	2.1	93.0
8	16	40.12	18.88	39.00	725	2.6	93.9
9	16	43.52	20.48	34.00	698	3.3	95.8
10	16	41.82	19.68	36.50	728	3.0	98.8
11	16	40.12	18.88	39.00	720	2.7	97.8
12	8	42.21	18.09	37.70	690	2.0	91.3
13	8	40.60	17.40	40.00	693	2.4	91.3
14	4	40.0	—	60.0	830/265	1.2	—
15	4	50.0	—	50.0	865/266	1.6	—
16	4	55.0	—	45.0	800/244	2.0	—

Note: 1 mm = 0.0394 inch

Table 3—Applied types and contents of steel fibers
(mixtures 1-13: kg/m³ and lb/yd³; mixtures 14-16: Vol.-%; L_f in mm)

<i>Fiber type ($L/d_f; L_f$)</i>	<i>D 45/30 BN</i>	<i>E 50/50</i>	<i>D 65/40 BN</i>	<i>D 80/60 BN</i>	
1 kg/m ³	40/(60)/(80)	-	-	20/(40)	
lb/yd ³	67.5/(101.2)/134.9)	-	-	33.7/(67.5)	
2 kg/m ³	80/(100)	60/(80)	40/60	40/(60)	
lb/yd ³	134.9/(168.6)	101.2/(134.9)	67.5/101.2	67.5/(101.2)	
3 kg/m ³	80/100/(120)	60/80/(100)	40/60/(80)	40/(60)/(80)	
lb/yd ³	134.9/168.6/(202.4)	101.2/134.9/(168.6)	67.5/101.2/(134.9)	67.5/(101.2)/(134.9)	
4 kg/m ³	100/(120)	-	-	-	
lb/yd ³	168.6/(202.4)	-	-	-	
<i>Fiber type ($L/d_f; L_f$)</i>	<i>D 45/30 BN</i>	<i>D 65/40 BN</i>	<i>D 80/30 BP</i>	<i>D 80/60 BP</i>	<i>H 65/20</i>
5 kg/m ³	80/(100)	-	40/(60)	40/(60)	-
lb/yd ³	134.9/(168.6)	-	67.5/(101.2)	67.5/(101.2)	-
6 kg/m ³	120/(140)	-	60/(80)	40/(60)	-
lb/yd ³	202.4/(236.1)	-	101.2/(134.9)	67.5/(101.2)	-
7 kg/m ³	120/(140)	-	40/(60)	40/(60)	-
lb/yd ³	202.4/(236.1)	-	67.5/(101.2)	67.5/(101.2)	-
8 kg/m ³	120/140/(160)	100/(120)	60/(80)	60/(80)	-
lb/yd ³	202.4/236.1/(269.8)	168.6/(236.1)	101.2/(134.9)	101.2/(134.9)	-
9 kg/m ³	100/(120)	-	40/(60)	40/(60)	-
lb/yd ³	168.6/(202.4)	-	67.5/(101.2)	67.5/(101.2)	-
10 kg/m ³	120/(140)	-	60/(80)	40/(60)	-
lb/yd ³	202.4/(236.1)	-	101.2/(134.9)	67.5/(101.2)	-
11 kg/m ³	120/(140)	80/(100)	60/(80)	60/(80)	-
lb/yd ³	202.4/(236.1)	134.9/(168.6)	101.2/(134.9)	101.2/(134.9)	-
12 kg/m ³	-	-	20/(40)	-	40/(60)
lb/yd ³	-	-	33.7/(67.5)	-	67.5/(101.2)
13 kg/m ³	-	-	40/(60)	-	40/60/(80)
lb/yd ³	-	-	67.5/(101.2)	-	67.5/101.2/(134.9)
<i>Fiber type (L_f)</i>	<i>D OL6</i>	<i>D OL13</i>	<i>D OL6+D OL13</i>	<i>D OL6+D OL13</i>	<i>D OL6+D OL13</i>
14	1.0/3.0/4.0/(5.0)	1.5/2.0/(3.0)	(1.5+1.5)	2.0+0.5	2.0+1.0
15	3.0/(4.0)	1.0/1.5/(2.0)	(1.5+1.5)	2.0+0.5	(2.0+1.0)
16	1.5/(3.0)	1.0/(1.5)	-	-	-

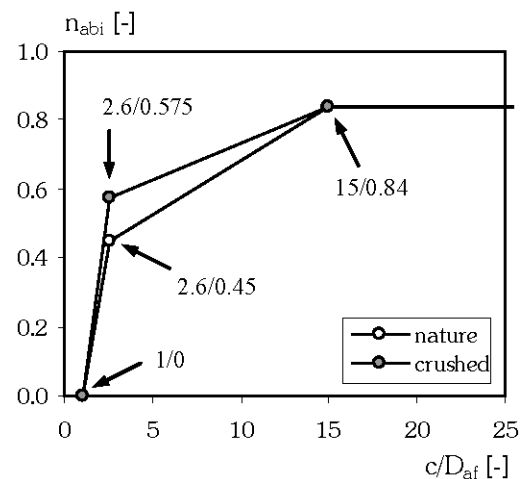
Table 4—Required bar spacings c_{NB} for non-blocking of Series 1-4 (in mm/inch)

Steel fiber content	0	20	40	60	80	100	120
	[kg/m ³]	[kg/m ³]	[kg/m ³]	[kg/m ³]	[kg/m ³]	[kg/m ³]	[kg/m ³]
	0	33.7	67.5	101.2	134.9	168.6	202.4
	[lb/yd ³]	[lb/yd ³]	[lb/yd ³]	[lb/yd ³]	[lb/yd ³]	[lb/yd ³]	[lb/yd ³]
Mixture 1	49/1.93						
Dramix - 45/30 RL	-	-	87/3.43	(99/3.90)	(87/3.43)	-	-
Dramix - 80/60 RC	-	99/3.90	(111/4.37)	-	-	-	-
Mixture 2	36/1.42						
Dramix - 45/30 RL	-	-	-	-	74/2.91	(87/3.43)	-
Eurosteel 50/50	-	-	-	74/2.91	(99/3.90)	-	-
Dramix - 65/40 RC	-	-	74/2.91	99/3.90	-	-	-
Dramix - 80/60 RC	-	-	87/3.43	(111/4.37)	-	-	-
Mixture 3	36/1.42						
Dramix - 45/30 RL	-	-	-	-	62/2.44	74/2.91	(87/3.43)
Eurosteel 50/50	-	-	-	74/2.91	87/3.43	(99/3.90)	-
Dramix - 65/40 RC	-	-	74/2.91	87/3.43	(99/3.90)	-	-
Dramix - 80/60 RC	-	-	62/2.44	(122/4.80)	(122/4.80)	-	-
Mixture 4	36/1.42						
Dramix - 45/30 RL	-	-	-	-	-	74/2.91	(87/3.43)

Table 5—Mixture composition of SCFRC for sheet piles

Mixture composition	[kg/m ³]	[lb/yd ³]
CEM I 52.5 R	358	603,7
CEM III/A 52.5	555	935,9
Silica fume	61	102,9
Sand (0.125-0.5 mm)	549	925,8
Sand (0.5-1.0 mm)	549	925,8
Steel fibers (OL13/0.16)	125	210,8
Superplasticizer	(21)	(35,4)
Total water	226	381,1
w/c-ratio	0.25	0.25

note: 1 mm = 0.0394 inch

Figure 1—Relation between the ratio of the bar spacing c to fraction diameter D_{af} of the aggregates and the blocking volume ratio n_{abi} (numbers: X/Y coordinates)

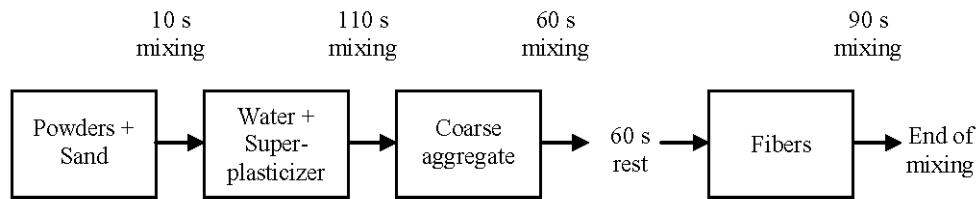


Figure 2—Mixing procedure for SCFRC

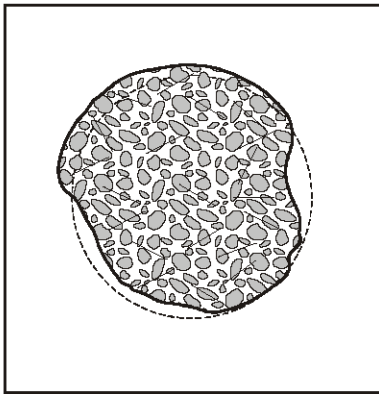


Figure 3 — Flow pattern A

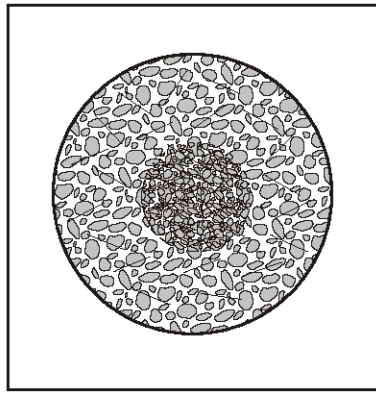


Figure 4 — Flow pattern B

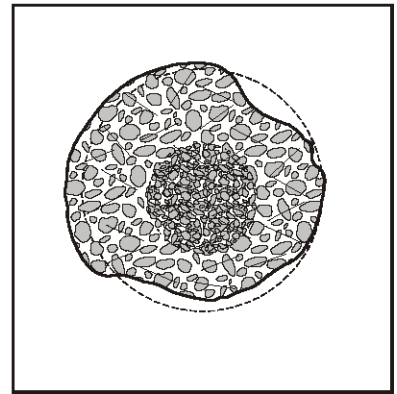
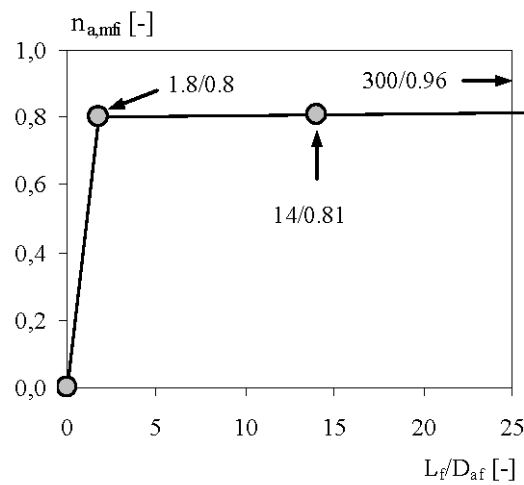


Figure 5 — Flow pattern C


Figure 6—Relation between the ratio fiber length to aggregate diameter and the MFC-ratio ($n_{a,mfi}$)

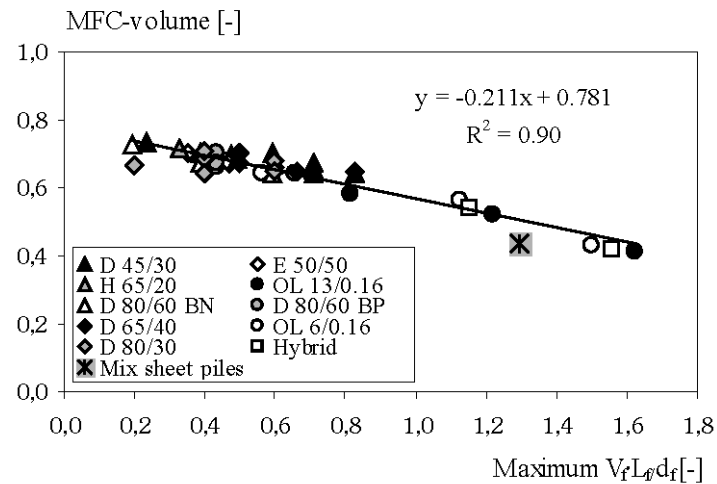


Figure 7—Relation between the maximum fiber factor and the MFC-volume

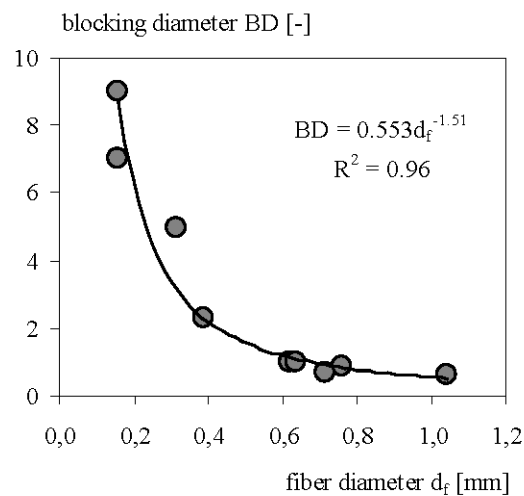


Figure 8—Relation between the diameter of the steel fibers and the blocking diameter (BD); 1 mm = 0.0394 inch

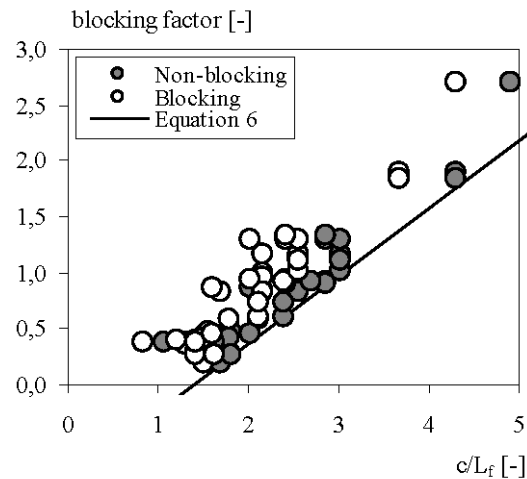


Figure 9—Determination of the bar spacing sufficient for non-blocking compared to the test results of SCFRC (Series 1-13; $L_f \geq 20$ mm; 1 mm = 0.0394 inch)

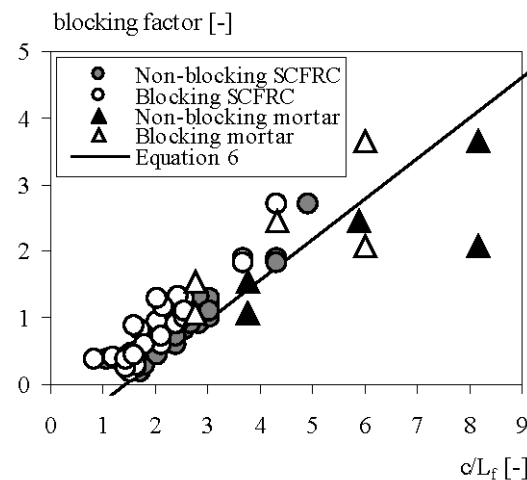


Figure 10—Determination of the bar spacing sufficient for non-blocking compared to the test results of SCFRC (Series 1-16; $L_f \geq 6$ mm; 1 mm = 0.0394 inch)



Figure 11—Prestressed sheet piles cast with SCFRC (left: C90/105) and conventional concrete (right: B55/67 concrete with additional bar reinforcement)

Prediction of Stress Development and Cracking in Steel Fiber-Reinforced Self-Compacting Concrete Overlays Due to Restrained Shrinkage

by J. Carlswärd and M. Emborg

Synopsis: Shrinkage cracking of self-compacting concrete (SCC) overlays with and without steel fibres has been assessed through laboratory testing and theoretical analysis. Test results verified that steel fibre reinforcement has a crack width limiting effect. However, the contribution in case of fibre contents up to 0.75 vol% was not found to be sufficient to distribute cracks in situations where bond to the substrate was nonexistent. Thus, even higher steel fibre contents (or other types of fibres) are required in order to control cracks.

A distributed pattern of fine cracks was however obtained even for unreinforced SCC within bonded areas of the overlays. This implies that steel fibres, or other crack reinforcement, are not required if high bond strength is obtained.

An analytical model, proposed to assess the risk of cracking and to predict crack widths in overlays, was found to give reasonable correlation with experimental results.

Keywords: bond; cracks; overlay; restraint; SCC; shrinkage; steel fibers; theoretical model.

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Jonas Carlswärd is a research engineer at Betongindustri AB, a ready mix concrete supplier within Heidelberg Cement, in Göteborg, Sweden. He received his MSc and PhD in civil engineering from Luleå University of Technology, Sweden, in 1997 and 2006. His research interests include fibre reinforced structures and self-compacting concrete.

Mats Emborg is a Professor and Head of Concrete Structures at the Division of Structural Engineering at Luleå University of Technology, Sweden, and Director of R&D within Heidelberg Cement, Northern Europe. Main research interests include self-compacting concrete, steel fibres and concrete cracking.

INTRODUCTION

Bonded overlays on concrete substrates are applied in a wide range of applications such as for repairs or strengthening of deteriorated bridge and parking decks, damaged industrial floors or as finishing layers on prefabricated elements. In order to ensure that the overlayed system remains durable and fully functioning during the intended service life it is essential to limit crack widths and to prevent delamination.

Many researchers and building clients have pointed out that the single most important factor determining the service life of an overlayed structure is the shrinkage of the newly cast overlay (Granju et al. 2004; Rahman et al. 2000; Weiss et al. 1998; Yuan & Cai 2002). Cracking, delamination and edge lifting (Fig. 1) are typical consequences of the shrinkage, or rather the difference in shrinkage between the overlay and substructure.

Two measures may be undertaken to minimise the negative effects of restrained shrinkage: (1) reduce the shrinkage of the overlay concrete and/or (2) provide reinforcement to distribute and control cracks. Shrinkage reduction may be accomplished for example by adding Shrinkage Reducing Admixture (SRA) to the mix. The effect of SRA has been studied quite extensively over the last 15-20 years (Ohama et al. 1988; Shah et al. 1992; Grzybowski & Ohama 1996; Weiss & Shah 2002; Petersson 2007) and the technique may now be regarded as an accepted method to control concrete shrinkage.

Reinforcement is provided either by welded mesh or steel bars or by mixing fibres into the concrete matrix. An attractive feature of fibre reinforced concrete (FRC) is of course that the demanding handling of traditional reinforcement is eliminated. The improvement in working environment, and possibility to reduce labour intensity, is even more accentuated when fibres are combined with self-compacting concrete (SCC). Experience from real overlay castings has further demonstrated that the use of SCC leads to improved surface finish with regard to flatness demands, thus reducing the need for expensive levelling screeds (Peterson 2008). These factors certainly give the contractor incentives to select FRSCC, both from a productivity perspective as well as from a working environmental and economical point of view.

Despite the fact that fibres, mainly steel, are used on a regular basis to control cracking there is no method available to design overlays, and other structures, on this regard. This means that the steel fibre addition is often selected/designed based on recommendations relying on experience. Several experience based design proposals are available according to Granju & Turatsinze 2005. Although such methods occasionally may prove to result in “crack-free” overlays it is obvious that more reliable approaches need to be developed for the future use of SFRC and SFRSCC in overlays.

Thus, main incentives of the research presented in the article are: (1) to experimentally verify the effect of steel fibres on widths and distribution of shrinkage cracks in thin overlays and (2) to establish a theoretical model for the estimation of crack risk due to restrained shrinkage and to assess the contribution of steel fibres on crack widths.

The work presented in the article summarises previous studies conducted within a doctoral thesis (Carlswärd 2006).

RESEARCH SIGNIFICANCE

The technique of applying thin bonded concrete overlays is widely adopted in the construction industry. Examples of applications are repairs and levelling of floors. Experience shows that cracking

and debonding, caused by the difference in shrinkage between the new overlay and the often old and rigid substructure, are frequent concerns. Despite this fact there are still no reliable design methods or recommendations available to ensure that such harmful damages can be avoided. It is believed that the work presented in this article will provide some useful guidance in the search for a solution to the cracking and debonding problem.

TEST METHODS TO ASSESS THE FIBER EFFECT

Three main categories of test setups are frequently used to study shrinkage cracking: (1) end-restrained, (2) base restrained and (3) ring tests (see Fig. 2). Category (2) tests, overlays cast on a substrate, are clearly the most suitable from the viewpoint that the restraint condition represents the real overlay conditions. A drawback is that it is difficult to control the bond conditions, which means that the cracking response will rely on the particular restraint situation (bond quality) obtained in each test.

From this viewpoint it is favourable to use end-restrained setups or ring tests, as they offer a direct evaluation of the effect of for instance type or amount of fibre. The ring test, in which the shrinkage of an external concrete ring is restrained by an inner steel ring, is certainly the most popular test method. Favourable features are the simplicity of the setup and that the degree of restraint is well defined. A review of test results reported on the ring test method (see Carlswärd 2006) indicates however that the ring test may overestimate the influence of fibres. Multiple cracking is regularly obtained already at steel fibre dosages as low as 0.25 vol%. In fact, more than one crack has even been observed for plain concrete in some investigations (Shah et al. 1992; Petersson 2007; Groth 2000; Bissonnette et al. 2005). As crack distribution would clearly not take place in unreinforced concrete this leads to speculations regarding the validity of the method for assessing the fibre effect.

Thus it was decided to adopt an end-restrained setup in the present study to assess the effect of steel fibres on cracking potential of SCC. The test setup was inspired by a previous test method proposed in Banthia et al. 1996. A series of base restrained tests were also conducted in order to study the effects of restrained shrinkage more realistically in regard to real overlays.

End-restrained test series

A test setup as shown in Fig. 3 was adopted, consisting of an HEA steel beam with a grounded and polished upper flange, giving a smooth and slippery surface to ensure that restraint would only develop at the ends of the concrete specimen. L-shaped supports of steel 80x45 mm (3.15 x 1.77 in.) with 20 mm (0.79 in.) thick legs were bolted to the flange at a distance of 1 m (~40 in.).

A 10 mm (0.39 in.) thick steel platen of 800 mm (31.5 in.) length with oiled and smooth surface was placed at the upper flange to decrease the thickness of the concrete in midsection (100 mm = 4 in. from the end-zones). The ends of the platen were chamfered in order to give a smooth transition between the thick end section and the thinner internal parts of the concrete. The configuration was designed in order to minimize stress concentrations and to ensure that cracking would occur within the internal parts. Furthermore, the platen was divided in two parts by a wedge at mid-section. The wedge was removed the day after casting allowing the steel platen to slide more or less freely underneath the concrete layer. End-restraint was achieved through three 10 mm (0.39 in.) threaded bars at each L-shaped support extending approximately 75 mm (3 in.) into the concrete.

Plastic foil was applied to the concrete surface immediately after casting to allow for a curing period of 24 hours. Testing was initiated by removing the cover, the form along the sides and the wedge in the steel platen underneath the concrete. Furthermore, an air proof tape was put along the concrete sides to prevent drying through the side faces and to ensure one-sided drying, similar to real overlay conditions.

Target points for deformation measurements were glued to the concrete surface at an individual distance of 200 mm (7.9 in.) starting 100 mm (4 in.) from each support, giving four measuring distances along the concrete specimen. Measuring was conducted using a mechanical device of the type Staeger placed in between two successive target points to obtain the deformation.

An experimental program was conducted including reference specimens of plain SCC as well as steel fibre reinforced SCC with fibre contents of 0.25, 0.375 and 0.5 vol% (20 (33.7), 30 (67.4) and 40 (50.5) kg/m³ (lb/yd³)). The basic mix proportions are given in Table 1, corresponding to SCC class C28/35 with maximum aggregate size of 8 mm (0.31 in.). The cement was of the type CEM II/A-L 42.5 R and the sand

was of a natural occurring type. A limestone filler of the type Limus 40 by Nordkalk was added in an amount of 100 kg/m^3 (169 lb/yd^3) in order to enhance the stability of the SCC. Furthermore, a high-range water-reducing admixture of the type Sikament 56 by Sika, a chemical compound based on polycarboxylate ether, was used to obtain the target slump flow of 700 mm (27.5 in.). The fibre type was Dramix RC 65/35 BN, an end-hooked steel fibre with length and aspect ratio of 35 mm (1.38 in.) and 65 respectively.

Two test rigs (Fig. 3) were carried out simultaneously for each type of concrete in order to improve the statistical result basis. The rigs were stored in a climate chamber with temperature and relative humidity of 25°C (77°F) and 50 % respectively. Additional unrestrained specimens for free shrinkage measurement, see Fig. 4, with the same cross section but slightly shorter, width x depth x length = $100 \times 35 \times 500 \text{ mm}$ ($4 \times 1.38 \times 19.7 \text{ in.}$) were stored horizontally aside the test rigs.

Target points for measuring deformation were glued to the surface immediately after demoulding at 24 hours. Shortly after this a zero-reading was recorded on both restrained and unrestrained specimens.

Material properties – Some material properties measured in the test program are given in Table 2. The compressive strength was determined at an age of 28 days while flexural beam tests were conducted after 28 days. Flexural testing was performed in accordance with ASTM C1018-92. The procedure is still rather common in Sweden despite the fact that it was withdrawn in 2006 as a standard test method. Results obtained from the beam tests are the crack strength ($f_{l,cr}$) and residual strength factors ($R_{10,x}$) as shown in the table. Residual strength is obtained by multiplying the crack strength with the residual factor.

Free shrinkage – To simulate a real overlay situation the sides and the bottom face of free shrinkage specimens were covered with air proof material. Thus, drying was only permitted through the upper face as illustrated in Fig. 4. A consequence is that a nonlinear shrinkage distribution developed over the depth initially. The curvature resulting from uneven shrinkage distribution is the explanation as to why the bottom face even expands slightly initially, as observed in the diagram. Note that measurements of free shrinkage deformation at the bottom face, carried out by turning the specimens and measuring between target points, were only conducted for the mixes with 0.25 and 0.375 vol% of steel fibres, denoted SFRSCC 20 and 30.

It can be seen that the response of the unrestrained specimens varied somewhat. In particular it may be observed that SFRSCC 40 had a somewhat slower shrinkage development. The variation is most likely related to a slight change in the relative humidity in the climate chamber during this test rather than to effects of the fibre addition.

It may be noted that despite the rather small size of the free shrinkage specimen, the exact free shrinkage is not obtained due to noneven humidity and eigenstresses within the specimen. These effects, that indeed influence the documented strains, will be studied in a newly initiated Scandinavian research project.

Restrained shrinkage – Deformation results obtained at the upper face of restrained specimens of SCC, SFRSCC 20, 30 and 40 (0.25, 0.375 and 0.5 vol% of steel fibres) are shown in Fig. 5 (a)-(d). It should be pointed out that only one crack developed, in other words crack distribution due to the fibre additions was not observed. Thus, crack strain is the strain measured in the zone where the crack developed while strain in uncracked parts corresponds to the mean strain obtained in uncracked parts. Note that results are given for two specimens in each diagram.

Even though steel fibres did not distribute cracks it is clear when comparing the results shown in Fig. 5 (a) with Figs. 5 (b)-(d) that a positive contribution was obtained due to fibres, resulting in a decreased crack strain and also in lower strain in uncracked parts. It can further be seen that the difference between the free shrinkage strain and the strain in uncracked parts was more significant for fibre reinforced mixes as compared to plain SCC. The reason is that the initially restrained specimens are completely relieved in case of unreinforced SCC, Fig. 5 (a), while some restraint remained after cracking in fibre reinforced specimens, Fig. 5 (b)-(d), due to fibres bridging the crack.

Although it may not be exactly correct to make a direct comparison between SCC and SFRSCC mixes as the free shrinkage development was not identical for the different mixes (Fig. 4) the results indicate that addition of 0.25 vol% of steel fibres (b) did not alter the response very much in comparison to plain SCC. Cracks developed at approximately the same time (prior to 5 days after start of drying) and the crack strains were similar in magnitude.

From Fig. 5 (c) and (d) it may be seen that increased fibre amounts resulted in a more significant influence

on the crack widths. A particularly good response was obtained for SFRSCC 40 (0.5 vol%) where only one of the specimens cracked. It can also be seen when comparing Fig. 5 (d) with (a) that the crack strain was considerably lower and that the difference between strain in uncracked parts and free shrinkage was much higher for the fibre reinforced specimen.

A rather good response was also obtained for one of the specimens of SFRSCC 30 in Fig. 5 (c). The reason as to why the crack width reduction was not as good for the other specimen of the same mix is believed to be due to a lower number of fibres crossing the crack. This was verified by a fibre count, which showed that the number of fibres was 30 % higher in the cracked section of the specimen with the “best” response.

It can further be seen that the time to cracking seems to have been prolonged by increased fibre volume, compare the two specimens of SFRSCC 30. The same situation applies for SFRSCC 40, where the average number of fibres crossing a section in the uncracked SFRSCC 40 specimen was approximately 35% higher than in the cracked specimen. Although not observed within the test period it is believed that a crack would have developed in this specimen as well if testing had been prolonged with a few days.

A prolonged time to cracking for increasing fibre volume fractions has been reported in some previous studies (Shah et al. 2003; Shah et al. 2004; Voigt et al. 2004). This is usually believed to be due to fibres bridging and hindering cracks already at the micro stage.

The fact that the free shrinkage response differed somewhat between the tests (see Fig. 4) makes it difficult to assess the effect of steel fibres on crack widths. In order to make a reasonably fair comparison it was decided to select the measured crack width at the time when a free shrinkage value of 0.6 ‰ was recorded. This value was selected as it corresponded to the maximum shrinkage obtained for SFRSCC 40 within the studied period (see diagram in Fig. 4). Crack width results for the situation are given in Fig. 6. As the actual number of fibres crossing the crack did not always correspond with the amount of fibres added to the mix the volume fraction in the crack zone was determined based on the counted number and by using fibre orientation theory as described by Soroushian & Lee 1990 and Löfgren 2005.

With one exception (one of the specimens of SFRSCC 30) it can be seen in Fig. 6 that crack widths decreased with increasing fibre volume fraction. Addition of 0.4-0.5 vol% of steel fibres reduced the crack width by approximately 50 % compared to plain SCC.

Examples of results from two studies in which ring tests were used to evaluate the effect of steel fibres on cracks are given for comparison. The fibre type used by Voigt et al. 2004 was an end-hooked fibre with length of 50 mm (2 in.) and an aspect ratio of 50 while a crimped fibre with length 25 mm (1 in.) was used in the study of Shah & Weiss 2006. Noticeable is the substantial effect of fibres that was achieved already at dosages as low as 0.25 vol%. This implies that the ring shape gives a somewhat more favourable stress situation as compared to linear specimens. A thorough discussion on possible reasons for the difference can be found in Carlswärd 2006.

Base restrained test series

The base restrained tests consisted of out-stretched overlay strips (50 x 150 x 2500 mm = 2.0 x 5.9 x 98 in.) cast on large concrete bottom slabs (300 x 2000 x 3000 mm = 118 x 79 x 12 in.), see Fig. 7 (a). Four slabs were produced approximately a year in advance to minimise the remaining shrinkage, in order to maximise the differential shrinkage between overlays and slab. Different substrate preparations were applied in order to achieve a variation in bond quality. One of the slabs was grinded and dry at the time of overlaying, one was grinded and wet, one was milled and wet and the last slab was milled and primed with MD 16 from Maxit. Grinding procedure gave a rather smooth texture while milling resulted in a rough texture, see Fig. 7 (b).

The ends of the overlay strips were fastened to the slabs by means of vertical expander bolts in order to avoid complete delamination.

Ten overlay strips were cast on each slab; two strips of plain SCC, two steel bar reinforced strips SBRSCC (a centrally placed 10 mm (0.4 in.) steel bar), two strips with shrinkage reduced SCC (SRASCC with 1.5 % SRA type Sika Control 40) and four SFRSCC strips (two with 0.375 vol% (30 kg/m³ or 50.5 lb/yd³) of fibres and two with 0.75 vol% (60 kg/m³ or 101 lb/yd³)). The steel fibre type was the same as in the end-restrained series (Dramix RC-65/35-BN).

The same basic concrete recipe and materials as for the end-restrained test series was used for all mixes (Table 1), corresponding to SCC of class C28/35 $D_{\max}$ 8 mm (0.31 in.) and a w/c -ratio of 0.58 with a

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target slump flow of 700 mm (27.6 in.).

The overlays were cured underneath plastic coverage for five days before exposed to a rather harsh laboratory environment of 15-20% relative humidity and 20°C (68°F) giving a rapid drying shrinkage development and associated overlay cracking within a rather short period of time (prior to 30 days). Cracking and debonding were followed for a period of approximately 3 months.

Material properties and free shrinkage – The SCC mixes produced in the base restrained test series were only evaluated with respect to the compressive strength. A more thorough analysis was conducted within the end-restrained series (see [Table 2](#)) on identical mixes, although not exactly the same fibre amounts. Results from compressive strength tests gave similar results as in the previous tests, ranging from 35.5 MPa (5149 psi) for SRASCC to 39.5 MPa (5729 psi) for SFRSCC 60.

Free shrinkage was obtained in the same way as for the end-restrained test series described previously, from thin concrete prisms sealed at the bottom and along the sides to allow drying only through the upper face ([Fig. 8](#)). A thickness of 50 mm (2 in.) was adopted in order to simulate the overlay strips. Deformations were measured at the bottom and upper faces of the specimens, using a handheld mechanical measuring device, to capture the shrinkage gradient. The prisms were placed aside the overlays to evaluate the unrestrained deformation under identical drying conditions.

Measured free shrinkage development is shown in [Fig. 8](#). Noticeable is the extensive difference in strain between the top and bottom faces of the specimens, resulting from the one sided drying conditions. It can further be seen that the addition of SRA reduced the average shrinkage by approximately 25%. There were no differences between fibre reinforced and plain SCC, which verifies that the addition of fibres did not influence the shrinkage.

Cracking and debonding – The first visible cracks were observed between 1 and 3 weeks after the start of drying in most of the overlay strips and new cracks were then established until the end of the test period 3-4 months later. From the crack width summary given in [Fig. 9](#) it can be seen that most of the cracks had a width of only between 0.05 and 0.25 mm (0.002-0.01 in.) at the end of the measuring period while a few cracks with more significant widths developed in overlay strips of slabs 2, 3 and 4.

The reason as to why none of the cracks observed in overlays on slab 1 had a width that exceeded 0.15 mm (0.06 in.) is that the bond strength obtained was sufficiently high and evenly distributed to prevent debonding. The result was somewhat unexpected as a smooth and dry substrate is generally believed to be unfavourable from a bond perspective. For slabs 2-4 the bond situation was found to be considerably more varying, ranging from nonexistent to adequately high bond to prevent debonding. This was surprising as the preparations of the substrates of these slabs were intended to provide better bond as compared with slab 1. It is not fully clarified as to why the opposite situation occurred.

Major cracks always coincided with the development of a major, internal debonded zone. A crack mapping of the overlays on slab 3 is given as an example in [Fig. 10](#). For overlays with a major internal debonded zone (shaded area) a single crack developed within this zone for SCC, SRASCC and SFRSCC 30 and 60 (see SCC II, SRASCC II, SFRSCC 30 II and SFRSCC 60 II). This indicates that distribution of cracks, and corresponding crack control, was not achieved for the SFRSCC applied in the tests. It can however be seen that the crack in strip SFRSCC 60 II was only 0.2 mm and did not extend all the way through the width. This implies that the addition of 0.75 vol% of steel fibres was quite effective. For SBRSCC II an additional crack developed within the major debonded zone, which proves that the centrally placed steel bar ($\phi 10$ mm $\approx$ 0.4 in.) did provide some crack distribution.

The reason as to why sufficient bond strength seems to have been obtained for half of the strips (strips denoted I) while the remaining 5 strips (denoted II) seem to have been poorly bonded is unknown. Exactly the same preparation was applied and the strips were cast at the same occasion and cured in the same way. Furthermore, concrete from the same batch was used for the two strips of the same mix, for example SCC I and II. This clearly gives an indication of the sensitiveness of the bond mechanism. The result also clarifies the difficulty in securing high and even bond in real overlay situations.

Effect of steel fibres on cracks – Based on the results presented above it can be concluded that steel fibres, or conventional steel bar reinforcement, are not required in cases when the bond strength is adequate to prevent debonding. In order to validate a possible effect of fibres it is necessary to consider the case where a major debonded area developed.

A summary of crack widths obtained for SCC and SFRSCC overlays in which a major debonded zone was established can be seen in [Fig. 11](#). Observe that the crack widths have been normalised with

respect to the debonded length recorded in the tests in order to enable comparisons. It should also be mentioned that the actual fibre contents were calculated based on the counted number of fibres crossing the crack by using fibre orientation theory as described by Soroushian & Lee 1990 and Löfgren 2005. An interesting observation is that the actual fibre content was lower (3 cases) or equal (1 case) to the expected amount. This shows that the fibre content varied in the SFRSCC overlays and that a major crack is more likely to form in a section with low fibre content.

From the results in Fig. 11 it is quite clear that increased fibre content resulted in a decreased crack width. Based on the trend line it can be seen that a content of 0.5 vol% reduced the crack width by approximately 50 % while 0.75 vol% of steel fibres reduced the crack width to approximately one fourth of the width of cracks in plain SCC. This reduction correlates rather well with the results of the end-restrained test series, see Fig. 6. The reason for this is believed to be that the restraint situations were similar as the overlay strips under consideration were restrained only at the ends of the debonded zones.

Important to recognise is however that as long as only a single crack develops (which was the case for SCC and SFRSCC overlays) the actual crack width will be proportional to the size of the debonded zone, and it is thus not possible to determine a certain content of steel fibres required to limit crack widths. A distributed crack pattern would be required in order to enable crack limitation within a debonded zone.

THEORETICAL MODEL

An analytical model to determine the risk of cracking and the crack width of concrete overlays exposed to shrinkage has been proposed by Carlswärd 2006. The analysis is divided into two stages (Fig. 12); (1) an initial analysis in the uncracked stage, and (2) crack width analysis. In the first stage (1) the tensile stress development is calculated based on beam theory for a composite member, assuming full bond between the two layers. The analysis, which is based on a previous model described in Silfwerbrand 1997, includes the rate of shrinkage and creep, the development of stiffness and tensile strength and the situation of restraint.

Two situations are distinguished in the cracked stage (2), assumed to be reached when the tensile stress exceeds the overlay strength. The first is that an internal debonded area develops and the second that the overlay is still bonded after cracking. In case of debonding it is assumed that just one single crack occurs in the unbonded region while a distributed crack pattern is expected for a bonded overlay. The assumed cracking response is based on observations from the base restrained test series.

(1) Uncracked stage

The stress state in the overlayed structure is evaluated using beam theory for a statically determined system, see (1) in Fig. 12. An incremental procedure is adopted to calculate the shrinkage stress development including the favourable effect of creep, or rather stress relaxation (Fig. 13 (a) and (b)).

Assuming an even shrinkage distribution over the overlay, see $\varepsilon_{cs}(t)$ in Fig. 12, the average stress in the overlay at time t due to the increment of shrinkage strain applied at t_i , $\Delta\varepsilon_{cs}(t_i)$, may be calculated using Eq. (1). For more details on how the expression is actually derived reference is made to Carlswärd 2006.

$$\sigma_c(t, t_i) = \frac{m(t, t_i) \cdot (1 - \alpha) \cdot (m(t, t_i) \cdot (1 - \alpha)^3 + \alpha^3)}{m(t, t_i) + (m(t, t_i) - 1) \cdot (m(t, t_i) \cdot (1 - \alpha)^4 - \alpha^4)} \cdot R_c(t, t_i) \cdot \Delta\varepsilon_{cs}(t_i) \quad (1)$$

α in the above equation corresponds to the relative overlay depth (see Fig. 12 for definition) and $m(t, t_i)$ is the stiffness relation between overlay and substrate calculated as:

$$m(t, t_i) = \frac{E_b}{R_c(t, t_i)} \quad (2)$$

where E_b is the elastic modulus of the substrate concrete and $R_c(t, t_i)$ is the relaxation function corresponding to the shrinkage strain applied at $t = t_i$.

It should be observed that for the situation of an extremely thick overlay in relation to the substrate ($\alpha \rightarrow 1$), the stress in Eq. (1) will equal zero and oppositely, for a very thin overlay ($\alpha \rightarrow 0$), the

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stress will reach the value of $R_c(t, t_i) \cdot \Delta \epsilon_{cs}(t_i)$. At the moment when the increment of shrinkage strain $\Delta \epsilon_{cs}(t_i)$ is applied the relaxation modulus $R_c(t, t_i)$ corresponds to the elastic modulus of the overlay concrete $E_c(t_i)$, implying that the momentary stress at $t = t_i$ ($\Delta \sigma(t_i) = \sigma(t_i, t_i)$) equals the elastic stress $E_c(t_i) \cdot \Delta \epsilon_{cs}(t_i)$. The stress will however successively decrease due to stress relaxation as the relaxation modulus $R_c(t, t_i)$ decreases with time.

Simplifications of the model are that creep and shrinkage of the substrate are neglected and that the influence of selfweight is not considered. It is also assumed that the Poisson's ratio equals zero.

The total stress at any time t is calculated by adding the contribution from each increment as:

$$\sigma(t) = \sum_{i=1}^i \sigma(t, t_i) \quad (3)$$

Verification of stress analysis – The development of stresses and strains was calculated for the overlay strips of the base restrained test series using the methodology outlined above based on measured free shrinkage as shown in Fig. 8. The relative depth α of the overlays were calculated to 0.14 by dividing the overlay depth with the total depth of base slab and overlay. For estimation of the factor $m(t, t_i)$ in Eq. (1) it is necessary to know the relaxation development of the overlay material and the elastic modulus of the base slab according to Eq. (2). The latter property (E_p) was assumed to be 35 GPa (5 076 142 psi). The relaxation functions for different time increments of the overlay $R_c(t, t_i)$ was calculated based on the creep and elastic modulus development as follows:

$$R_c(t, t_i) = \frac{1}{\frac{1}{E_c(t_i)} + \frac{\varphi(t, t_i)}{E_{cm}}} \quad (4)$$

A formulation given in Eurocode 2 was adopted to calculate the elastic modulus at different times from the mean compressive strength (Eq. (5)).

$$E_c(t_i) = (f_{cm}(t_i) / f_{cm})^{0.3} \cdot E_{cm} \quad (5)$$

where f_{cm} and E_{cm} are the mean compressive strength (in MPa) and elastic modulus (in GPa) at an age of 28 days, and $f_{cm}(t_i)$ and $E_c(t_i)$ are the corresponding values at time t_i . The elastic modulus at 28 days and the compressive strength development were calculated according to Eurocode 2 as:

$$E_{cm} = 10 \cdot f_{cm}^{1/3} \quad (6)$$

$$f_{cm}(t) = e^{s \left(1 - \left(\frac{28}{t} \right)^{0.5} \right)} \cdot f_{cm} \quad (7)$$

The factor s in Eq. (7) is a parameter to consider the type of cement used and a value of 0.25 was adopted here. Creep development $\varphi(t, t_i)$ was also calculated in accordance with Eurocode 2. More details can be found in Carlswärd 2006.

A comparison of measured and calculated strains at mid section at the upper face of some of the overlay strips is given in Fig. 14 (a). The response of the overlay strips that were more or less completely debonded (see overlay strips denoted with II in Fig. 10) have been left out as a basic condition for the model is that the overlay is fully bonded to the base.

From the results shown in Fig. 14 (a) it can be concluded that the restraint was not 100% even though the base slabs had a rather significant depth (300 mm or 11.8 in.) in relation to the overlay strips

(50 mm or 2 in.), as such situation would have resulted in a zero strain reading. It can also be seen that the actual strain development was reasonably well captured by the theoretical calculation within the first 25-30 days. At this age however, some major cracks developed in mid section of at least two of the strips (SCC I and SFRSCC 30 I), which resulted in sudden strain changes.

Calculated stress development in reference overlays (SCC) and shrinkage reduced overlays (SRASCC) is shown in Fig. 14 (b). It can be seen that crack initiation (time at which the stress exceeds the strength) was estimated to approximately 20 days for the reference mix SCC and 30 days for the shrinkage reduced mix (SRASCC). The tensile strength development shown in the diagram was calculated from the mean compressive strength (in MPa) using the following relation from Eurocode 2.

$$f_{ctm}(t) = 0,30 \cdot f_{cm}(t)^{2/3} \quad (8)$$

Crack mapping of the overlay strips was only conducted at a few different times including ages 14 and 28 days after casting. Results from the inspections showed that most of the bonded strips were crack-free at the first age (14 days) while quite a number of cracks had developed at 28 days. This verifies that the prediction shown in Fig. 14 (b) is reasonably accurate for the reference concrete (SCC). The prolonged time to cracking predicted for SRASCC was however not verified by experiments. It should also be mentioned that the predicted age of cracking for SCC with steel fibres (SFRSCC 30 and 60) was approximately the same as for the reference concrete (SCC), as the tensile strength as well the shrinkage, creep and elastic modulus development was similar.

(2) Cracked stage

There are two possible situations that need to be considered after crack initiation according to above (see Fig. 12). For the first situation, where the bond strength is sufficient to prevent debonding, it has been proposed in Concrete report 13 2008 to estimate the crack width based on the free shrinkage strain and the depth of the overlay as follows:

$$w_{cr} = \varepsilon_{cs} \cdot 3 \cdot h_o \left(1 - \frac{R_{10,20}}{100}\right) \quad (9)$$

where ε_{cs} is the free shrinkage strain, h_o is the overlay depth and $R_{10,20}$ is the residual strength factor. The equation implies that the crack width will diminish with increasing residual strength factor. For strain hardening fibre concrete ($R_{10,20} \geq 100$ %) the theoretical crack width will be zero, which is of course not true. However, it is believed that multiple cracking will occur for this situation resulting in cracks with insignificant width.

For case 2, where a major debonded area develops after cracking, it was observed in the base restrained tests that crack distribution was not obtained for SFRSCC, that is for the volume fractions and type of steel fibres applied. This means that the crack width will depend on the length of the debonded zone in addition to the reinforcing effect of the fibres. The following formulation to estimate the crack width (Eq. (10)) was proposed in Carlswärd 2006 for this situation.

$$w(t) = (\varepsilon_c(t_{cr}) + \varepsilon_{cs}(t, t_{cr})) \cdot \left(1 - \frac{R_{10,20}}{100}\right) \cdot L_{deb} \quad (10)$$

where $w(t)$ is the crack width at time t after cracking, $\varepsilon_c(t_{cr})$ is the elastic concrete strain at the time of cracking, $\varepsilon_{cs}(t, t_{cr})$ is the shrinkage strain that develops from the age of cracking to time t and L_{deb} is the length of the debonded zone. Time of cracking t_{cr} is obtained from the analysis in the uncracked stage described above.

For plain concrete, for which the residual strength factor $R_{10,20}$ is practically zero, the crack width at the time of cracking $w(t_{cr})$ will be equal to the elastic strain capacity, which is approximately 0.1 ‰, multiplied by L_{deb} . The crack width will then increase in direct proportion to the shrinkage strain that