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 is it 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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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 aforenoted 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 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/m³ (lbs/yd³)	Coarse Agg.** Kg/m³ (lbs/yd³)	Fine Agg.+ Kg/m³ (lbs/yd³)	Water L/m³ (gal/yd³)	Super-Plasticizer++ L/m³ (oz/yd³)
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.

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

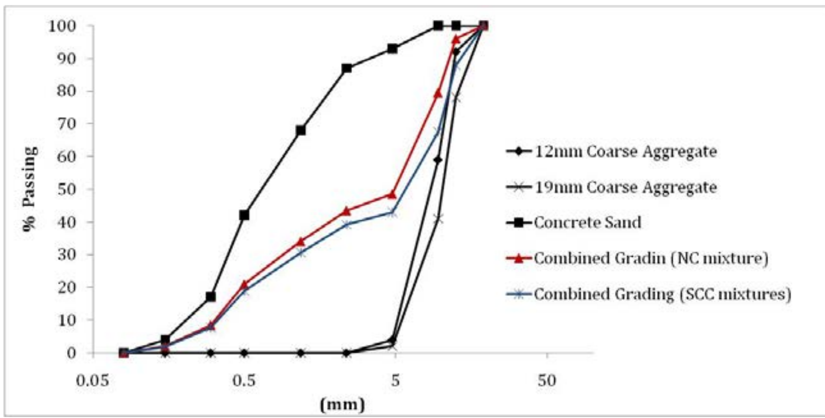


Figure 1. Concrete Aggregate Grading Curves

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

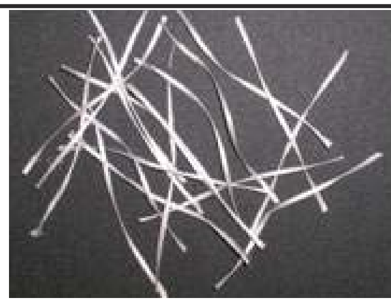
Specific Gravity	0.92		
Material	Polypropylene/ Polyethylene Blend		
Surface Area of Fiber	0.3 x 1.1 mm (0.012” x 0.043“)		
Modulus of Elasticity	9.5 GPa (1378ksi)		
Tensile Strength	670 MPa (97.1ksi)	Before Mixing	After Mixing

Table 3. Self-consolidating Concrete Mixture Composition

Mix No.	Fiber Volume Fraction (%)	Fiber Length mm (in)	Blended Cement* Kg/m³ (lbs/yd³)	Coarse Agg.** Kg/m³ (lbs/yd³)	Fine Agg.+ Kg/m³ (lbs/yd³)	Water L/m³ (gal/yd³)	Super-Plasticizer++ L/m³ (oz/yd³)
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 2-3	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.

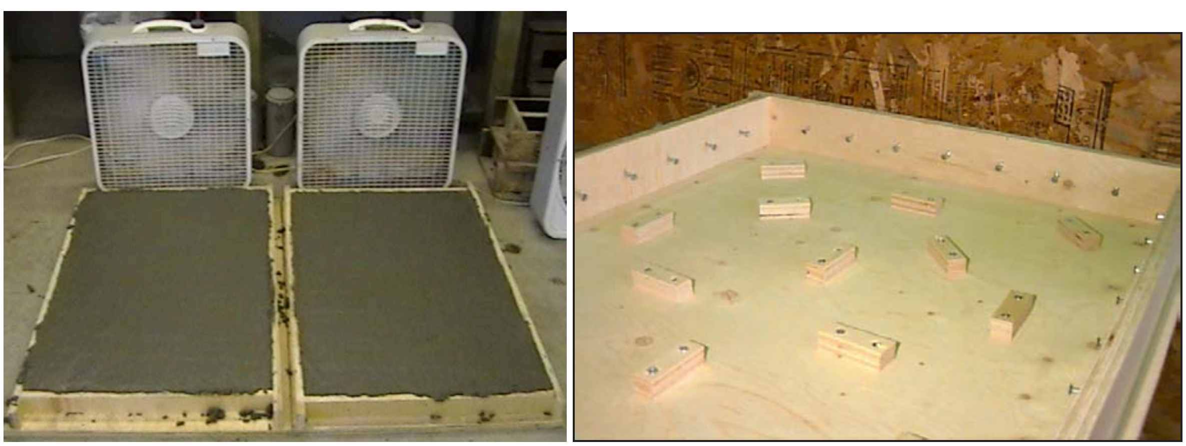


Figure 3. Plastic Shrinkage Panel Configuration and Internal Restraints

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.

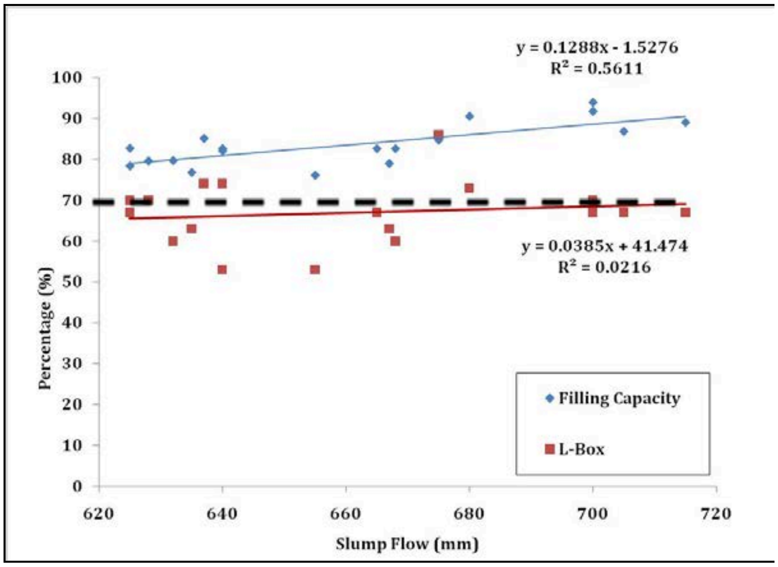


Figure 4. Relationship between Slump Flow, Filling Capacity and L-Box Ratio

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.

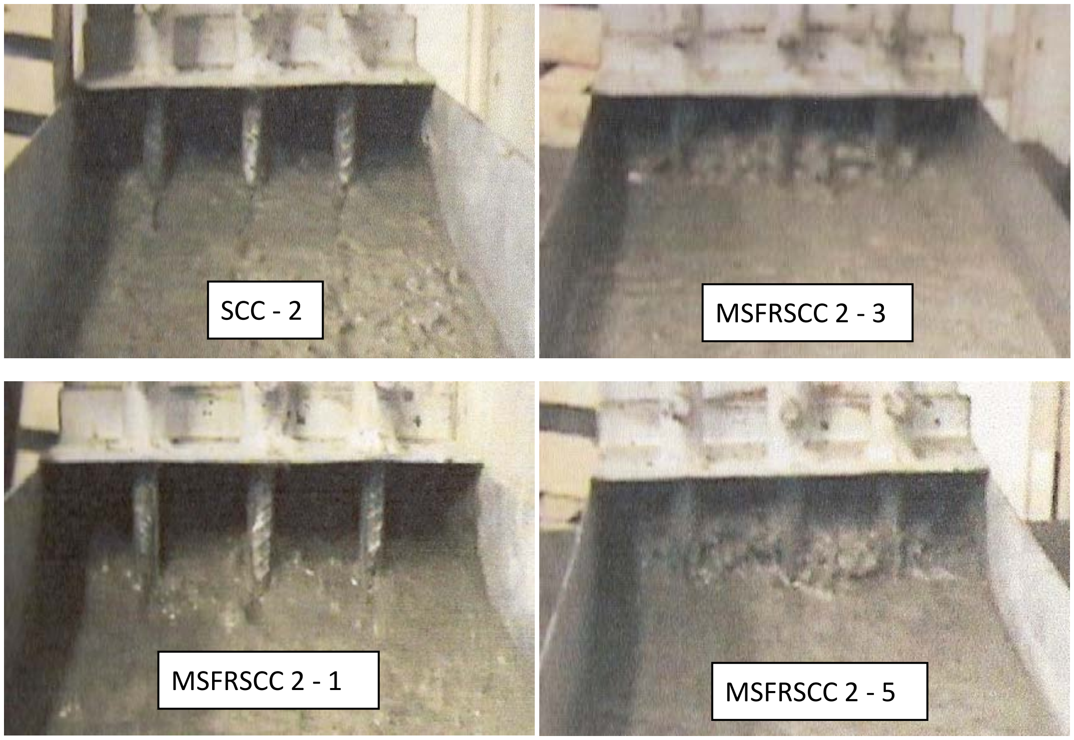


Figure 5. L-Box Test (Series 2)

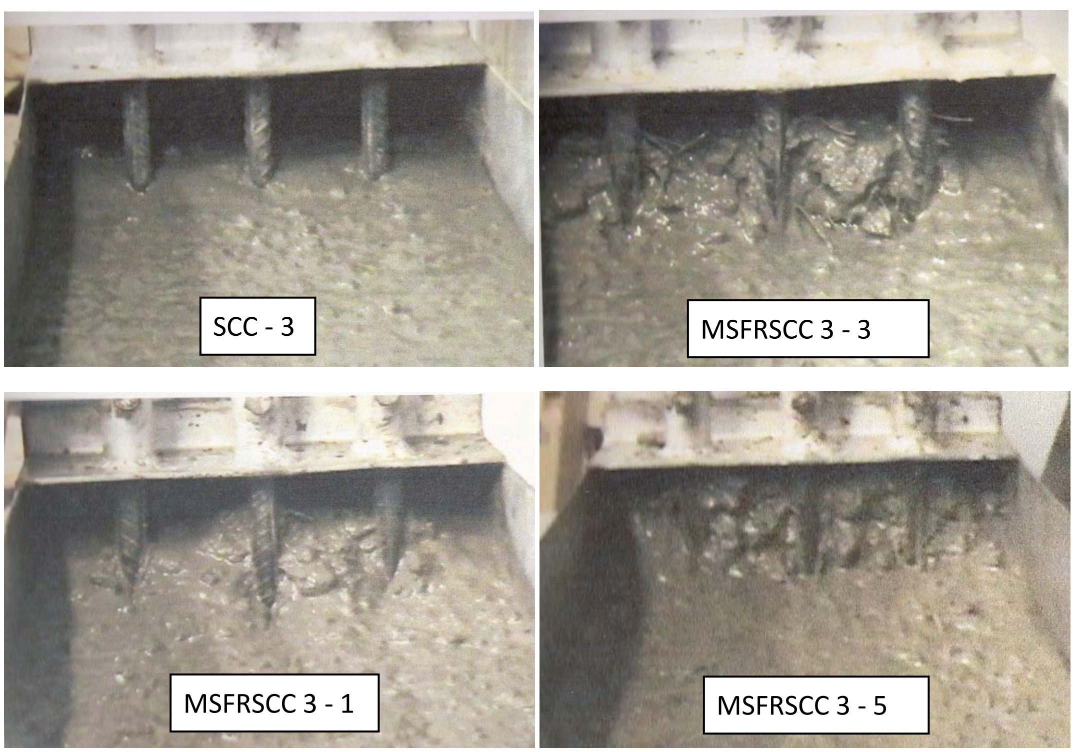


Figure 6. L-Box Test (Series 3)

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 mm²/(in²)	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 ($490mm^2$) and mixture SCC1($318mm^2$), 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($166L/m^3$) vs NC (V_p=$139L/m^3$) 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