THE EFFECT OF STEEL FIBERS ON THE RHYOLOGICAL AND MECHANICAL PROPERTIES OF SELF COMPACTING CONCRETE

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Abstract

Self-compacting concrete (SCC) is a highly flowable, non-segregating concrete that has the ability to flow in every spot of the complex formwork and consolidate within that without any external compaction. Steel fiber reinforced self-compacting concrete (SFR-SCC) is a new mixed material that merge the advantages of the SCC with those of steel fibers in improving concrete mechanical properties. This paper is part of a study to analyse the effect of steel fibers on the rheological [J-ring test] and mechanical properties [compressive strength and four point bending test] of SCC. Five concrete mixtures were evaluated. The primary experimental variables are the type and aspect ratio of steel fibers. Test results have shown that the inclusion of fibers improves the compressive strength of SCC but it has a negative effect on the rheological properties of the SCC by reducing the slump flow and increasing the flow time, but better workability was obtained as aspect ratio of the steel fibers decreased. It was also found that the fiber geometry is a key factor affecting the mechanical performance in particular the toughness of the SFR-SCCmaterial.

Keywords: SFR-SCC, J-ring, aspect ratio, rheological properties, hardened properties

Introduction

Reinforced concrete was and still is one of the most extensively consumed construction materials due to the continuous growth of urban areas that are spreading all around the world. SCC is approximately a unique formation of high-performance concrete that is able to attain remarkable deformability and homogeneity in its fresh state, filling all space around the reinforcement, passing between dense steel reinforcement bars while consolidating under its own weight without any need of vibration (Daczko & Vachon, 2006). During the last decade, SCC was highly enhanced because of the efforts of concrete technologists (Khayat, 2002; Kwan et al. 2010).

Concrete is known for being capable of attaining very high compressive strength; however its main weakness lies in its low tensile strength and low ductility due to its britlleness behavior. That's why steel fibers are being developed to enhance the mechanical properties of concrete. These fibers are discontinuous discrete entities and are distributed and oriented randomly (nominally uniformly) throughout the concrete matrix. SFR-SCC can be used by itself, or in conjunction with conventional reinforcing bars, depending on the application (Banthia, 2001).

The use of steel fibers in SCC has been investigated by many researchers for use as a composite material. The majority of those studies found that the rhyological and mechanical properties of the SCC varies when steel fibers are added to the matrix (Ferrara et al, 2012; Filiatrault et al. 1995; Hameed et al 2009; Deeb, 2013). This variation is based upon several factors: a) properties and types of the steel fibers, b) aspect ratio L/D, c) orientation of the fibers, etc. The above studies found that the addition of fibers to the SCC mixtures affects negatively its workability and the relationship between the steel fibers aspect ratio and its flowability is inversely proportional; i.e. when the aspect ratio increases, SCC workability decreases. Regarding steel fibers effect on the mechanical properties of SCC, previous work have shown that fibers had only minor effects on the ultimate compressive strength of concrete, slightly increasing or decreasing its magnitude, depending on the characteristics of the fibers themselves (ACI 544.1R-96, 1996, ACI 544.3R-2, 1998). However, their primary role in the SCC mixtues was to delay and limit the flexural cracking, as previous research indicated that steel fiber reinfroced beams absorbe more energy and provide better ductility (Daniel et al., 2002).

The use of SFR-SCC is continuing to increase, but this development is being hindered by a general lack of theoretical knowledge and methods for its design, particularly under flexural loading (Jones et al., 2008). Thus, the mechanical properties of SFR-SCC must be studied empirically by means of standardized laboratory tests (Deeb, 2013). The main objective of this experimental research was to inspect the interaction between SFR-SCC composites and SCC by marking the most sensitive variables in the SFR-SCC properties. This study compared the performance of steel fibers reinforcement systems used for strengthening self-compacting concrete structures.

Experimental Study

Materials

The cement used in this study is white Portland Cement identified as AALBORG WHITE® cement used in the preparation of concrete and mortar. The cement complies with all requirements according to EN 197-1, 2011 for Portland Cement CEM I 52, 5 R - SR5. Drinking-quality water was used in all concrete mixtures. To improve and maintain the workability of fresh concrete, a high range water reducing admixture (superplasticizer) commercially known as "Fosroc Auracast 200" that complies with EN 934 - 2, 2012 was used.

The volume of fibers used is constant (V_f = 0.5%), although four different types of fibers were used. The variation depends on the aspect ratio and shape of the fibers. The brand used is Dramix ® 3D and 5D fibers. Dramix® are certified for structural use according to BS EN 14889-1, 2006. The properties of the steel fibers used are summarized in table 1. Figure 1 describes the nomenclature present on the Dramix ® Company packages for the 80/60 fibers.

Table 1: Fibers Properties and Shapes

Fiber type	**45/50 BL**	**65/60 BG**	**65/60 BG**	**80/60 BG**
Tensile strength (N/mm^2)	1.115	1.160	2.300	1.225
Young's Modulus (N/mm^2)	± 210.000	± 210.000	± 210.000	± 210.000
Fiber Family	3D	3D	5D	3D
Length L (mm)	50	60	60	60
Diameter D (mm)	1.05	0.90	0.90	0.75
Aspect ratio (l/d)	45	65	65	80
Minimum Dosage (Kg/m^3)	20	15	15	10
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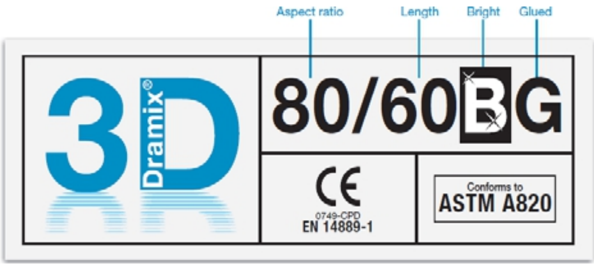

Fig. 3: Badge of Steel Fibers Packages

Mix Designs

Five concrete mixes were evaluated in this study. Of the five concrete mix designs, four contain different types of steel fibers. The fifth mix is a plain SCC acting the role of a control sample. For each mix, three replicate specimens were cast for each test conducted. These mixes are labeled and presented in table 2. The total number of specimens tested is thirty. The key mixture design information is presented in table 3.

Table 2: SCC Mixes Nomenclature

Mix 1	Plain SCC
Mix 2	SFR-SCC 45/50 3D
Mix 3	SFR-SCC 80/60 3D
Mix 4	SFR-SCC 65/60 3D
Mix 5	SFR-SCC 65/60 5D

Table 3. Mix Design Information

Materials	Amount (Kg/m^3)	Mix dosage (Kg)
Gravel	761.62	15.08
Sand	738.38	14.62
Added water	191.36	3.786
White cement	735.35	14.56
Superplasticizer	7.424	0.147
Fiber content	40	0.784

Sample Preparation

After measuring the material based on their proportions, they were placed in the concrete mixer in the following sequence. First, the gravel and sand were added and dry mixed for three minutes. Second, water and the superplasticizer were mixed together and then added to the drum and mixed for about 30 seconds. Cement was then added followed by another three minutes of mixing until the mix became homegenous. Finally, the steel fibers were added to the mix for a period of one minute and mixed for another 2 minutes.

SCC in its fresh state should satisfy simultaneously the filling ability and passing ability. The J-ring test according to BS EN 12350, 2010 was carried out on all mixes to simulate simple field conditions. The J-ring test provides the most fundamental information regarding the flowability of SCC and SFR-SCC because it also includes the slump flow test in it. A slump flow diameter of 600 mm was adopted as a minimum requirement for SCC; otherwise the test had to be repeated. Visual inspection was used to observe if segregation occured.

Following mixing, the concrete was directly poured into the molds. For the compressive strength test, standard plastic cubic molds 100×100×100 mm were used according to BS EN 12390-3, 2009. For the flexural test, standard beam specimen with internal dimensions 100×100×500 mm were used as shown in Figure 2.

Fig. 2: Casting of SCC Cubes and Beams

After casting the specimens, they were sealed using polyethylene sheets until they were demolded after 24 h. Once demolded, they were placed in a lime-saturated bath for the required number of curing days which was 28 days according to BS EN 12390, 2009.

Test Results

Fresh properties of SCC and FR-SCC Mixes

As mentioned previously, the fresh properties of SCC and SFR-SCC mixes were evaluated using the J-ring test. No significant problems were observed in flowability, segregation resistance, filling ability, and passing ability of the SFR-SCCs mixes (Figure 3). The test results are presented in Table 4. According to BS EN 12350-12, 2010, the parameters mentioned in table 4 are defined as follow: SF_J is the J-ring flow spread expressed to the nearest 10 mm and T500 is the J-ring flow time which is the time between elevating the cone from the base plate and the time SFR-SCC reaches a diameter of 500 mm.

Fig. 3: J-ring test - SFR-SCC (mix 5)

Table 4: J-ring Test Results

Mix number	Fiber type	SF_J (mm)	T_{500} (s)
1	-	775	4.1
2	45/50 3D	760	6.7
3	80/60 3D	720	9.7
4	65/60 3D	755	8.1
5	65/60 5D	740	9.2

As shown in table 4, the addition of steel fibers into the SCC mixes significantly affects its workability. This can be easily seen by making a few comparisons among SCC mixes. First, by comparing mixes 1 and 3, one can notice the difference in the flow spread and the flow time. For example, the flow spread for mix 1 [plain SCC mix] is 775 mm and it decreases with the addition of steel fibers to 720 mm for mix 3 [SFR-SCC]. Furthermore, the flow time is 4.1 for mix 1 and it increases to 9.7 sec for mix 3. This indicates that the addition of steel fibers decreases SCC workability and its passing ability as the possibility of blocking increases with the addition of steel fibers. Results as well indicate that workability decreases as the aspect ratio of steel fibers increases; i.e. for mix 2, the flow spread and the flow time are 760 mm and 6.7 s respectively whereas they are 720 mm and 9.7 s for mix 3. This point indicates that the presence of long fibers is more challenging to handle during concrete pouring.

To illustrate the effect of the type of fibers used on SCC workability, a comparison is made between mix 4 [65/60 3D] and mix 5 [65/60 5D] who have the same aspect ratio but different number of hooks. Results indicate that the effect of multiple hooks [5D steel fibers] on SCC workability is similar to the effect of increasing the aspect ratio of fibers. For example, the flow time for mix 4 [3D] is 8.1 s. On the other hand, it is 9.2 sec for mix 5 [5D]. The same effect can be seen on the flow spread as it decreases from 755 mm to 740 mm when using 5D steel fibers. This demonstrates the negative effect [from a workability perspective] of steel fibers with multiple hooks on SCC flowability. The above results are very consistent with what was mentioned in the literature.

Compressive Strength Tests

The results of 28 days compressive strength of 100×100×100 mm cubes are presented in table 5. A few observations can be made. First, the strength of all SCC mixes is above 65 MPa indicating that those mixes can be considered as high strength concrete. Second, it was noticed that the compressive strength of SCC mixes improves with the addition of steel fibers. According to ACI, the compressive strength is slightly affected by the presence of fibers and a 15% increase in strength was observed with mixes having 1.5% by volume of fibers. However, in this study a much higher increase was achieved with much lower amount of fibers [0.5% of fibers]. This improvement ranges from 11% for SFR-SCC 45/50 3D mix to 26% for SFR-SCC 65/60 3D mix. This amelioration can be to the fact that the addition of steel fibers fibers increases strainability in compression failure and hence the compressive strength increases [Hannant, 1978]. Lastly, the effect of multiple hooks steel fibers on SCC compressive strength doesn't appear to be significant [13% increase]. This is expected as its contribution is anticipated to be on the flexural strength.

Table 5: Compressive Strength Test Results

Concrete type	Average (3 samples) results of 28 days compressive strength (MPa)	% Increase
SCC	69	0
SFR-SCC 45/50 3D	76.75	11
SFR-SCC 65/60 3D	87.43	26
SFR-SCC 65/60 5D	78.33	13
SFR-SCC 80/60 3D	83.76	21

Flexural Strength Tests

Flexural strength is often needed as part of the design to check compliance with established specifications or to provide information necessary for the design of an engineering structure.

In this study, the flexural strength test was performed after 28 days of curing on SCC and SFR-SCC beam test specimens of size 100×100×500 mm with a span of 450 mm. The beams were subjected to a four-point loading in flexure at a constant deformation rate control of 1 mm/min in accordance with BS 14488, 2006 standards as shown in Figure 4. Two symmetrically placed LVDTs placed on opposite sides of the specimens were used to get the mid-span deflections of the beams, and the net mid-span deflection was considered as the average between the two outputs of the LVDTs. In order to measure the pure beam deflection, a yoke was attached to the specimen to discharge additional supports. Steel rods were used as roller supports at ⅓ points with spacing of 450 mm. To avoid readings outside the linear range of the external LVDT, the tests on fibrous specimens were stopped at approximately 4.1 mm of deflection. Furthermore, the test was stopped after a load drop of 90%. These two adjustments were made for safety in order to prevent any over load that can break the system. The load and strain data were recorded through a data acquissition system. Ultimately, this system converts the voltage readings into actual stresses and strains.

Fig. 4: Flexural Strength Test Setup for Beam Specimens

Behavior of SCC Mixes

To illustrate the behavioral variations of SCC mixes, the stress deformation response is plotted and presented in Figure 5. It should be noted that each plot is an average of three as each test was repeated three times to check the repeatability of the results.

Most of the plots display similar characteristics patterns. Three main stages occurs: (1) an elastic part of the ascending branch as the displacements increase linearly with the applied loads up to the first crack, (2) that part of ascending branch during which multiple cracks occur and (3) a descending branch well known as the post cracking stage dominated by the pull out of the fibers. The last step occurs when segments of the beams yield and start deforming plastically.

As shown from the plot, mix 1 [plain SCC] displays a brittle failure as the specimen reaches a stress of 10.24 Mpa and directly fails without any post-cracking resistance due to the absence of steel fibers. This is obvious, as the presence of steel fibers in a dispersed way in the SCC mix, limits the propagation of the cracks as the bonding effect of the steel fibers in the mix leads to a change in the failure mode from brittle to a more ductile mode. It also enhances the post-cracking load and toughness (energy absorption capacity).

On the other hand, all SFR-SCC mixes deform plastically. With sufficient plastic deformation, a hairline crack develops near the midspan of the segments where the stresses are the highest. Previous research (Banthia, 2001; Poh et al., 2009) indicated that when initial crack developed, the fibers began to tense up as the concrete experienced non-linear strain hardening. As shown, once the peak load is reached, the stress is supported by the fibers, which act as crack arresters, bridging the crack formation. The matrix is held together by the fibers as a long softening branch continues.

It can as well be seen from the figure that the (SFR-SCC 65/60 5D) specimen is the only one that exhibit a hardened behavior after the first crack, ultimately reaching a maximum compressive stress, followed by a softening branch. while all other SCC mixes have a softening behavior.This hardened behavior is the result of the multiple hooks in the 5D family steel fibers that made an extra bonding and bridging between the fibers and the concrete.

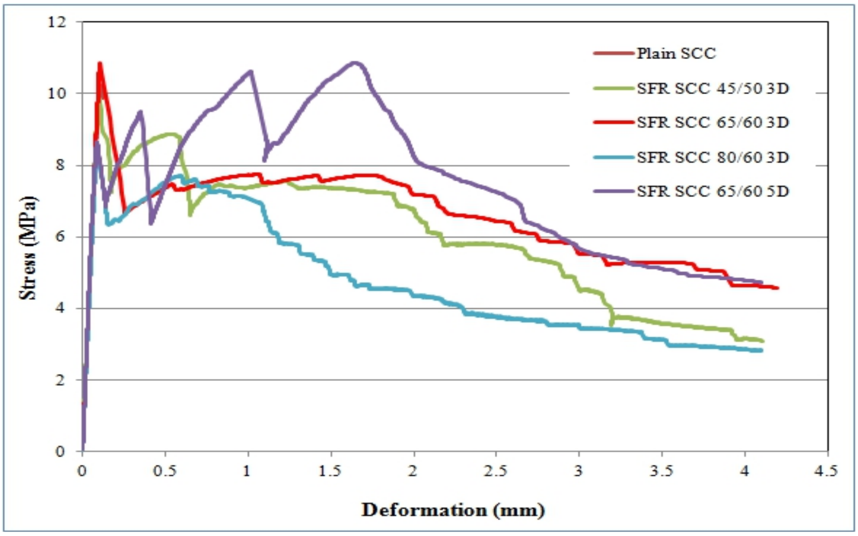

Fig. 5: Stress Deformation Curves For all Mixes.

One of the objectives of this work is to study the effect of steel fibers [aspect ratio] on the mechanical properties of SCC specifically its flexural performance. It was expected from the literature that upon increasing the steel fibers aspect ratio, the flexural performance of SCC mixes should goes up as well. This was found to be partially correct. By comparing SFR-SCC

45/50 3D with SFR-SCC 65/60 3D, it is noticed that the stress rate decreases is much higher as the aspect ratio of steel fibers decreases. This is due to the fact that shorter fibers hold the stresses for a shorter period of time as you need less energy to pull out the fibers out of concrete. On the other hand, it is found that SFR-SCC 80/60 3D exhibits a lower flexural performance than SFR-SCC 65/60 3D. This result comes as a surprise because it is anticipated that longer fibers should hold the stress for longer period of time as they are expected to produce more residual strength and more toughness. This may be possibly due to the fact that high aspect ratio can lead to a balling effect during mixing, resulting in loss of flexural resistance. Therefore a threshold limit on the steel fibers aspect ratio should be placed.

Flexural Toughness of SCC Mixes

The addition of steel fibers in SCC mixes makes it distinguishable from plain SCC by its ability to absorb a large amount of energy and to withstand large deformations prior to failure. This preceding feature is referred to as toughness. In this work, flexural toughness is measured by taking the area under the load-deflection curve in flexure up to deflection of 4.1 mm. The area was calculated using AutoCAD software computer program. The results are presented in figure 6 using column bar chart.

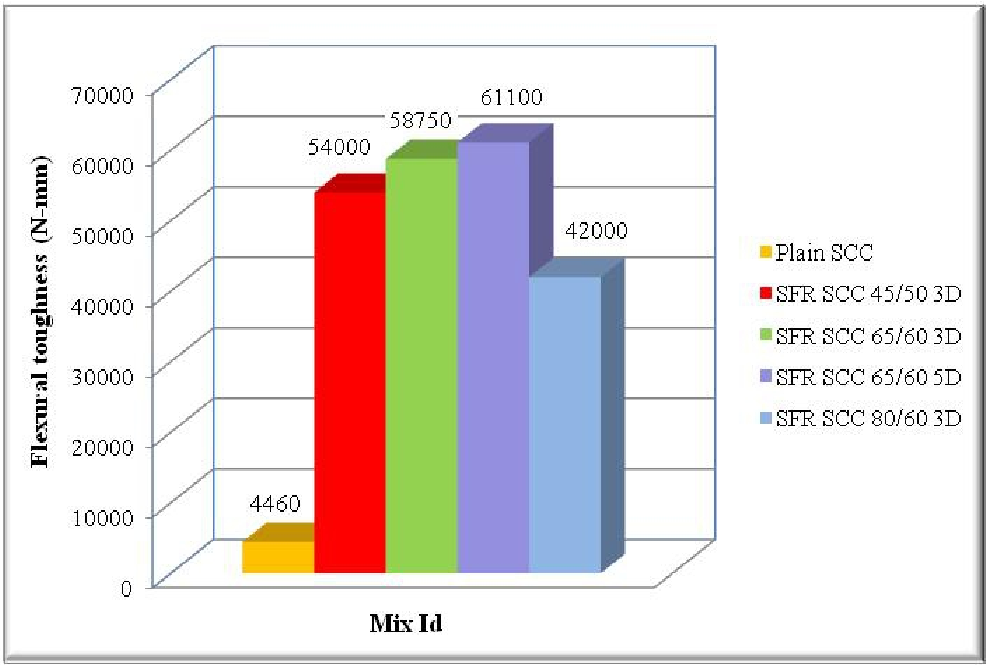

Fig. 6: Flexural Toughness of all SCC Mixes

It can be seen from figure 6 that plain SCC mix exhibits a very low flexural toughness of 4460 N-mm as plain SCC beam broke immediately into two pieces after the appearance of the first single crack in the middle of the beam. The introduction of steel fibers into SCC mixes significantly increases the beams toughness more than ten-fold as it enhances the post-failure strengths of the concrete after the formation of first crack. The bond between steel hook end fibers and concrete enables slower crack propagation and hence more energy is being absorbed by the specimen; this eventually allows the beams to deflect more before the commencement of first visible crack.

As shown from the bar chart, the effect of steel fibers aspect ratio on the SCC flexural toughness is very dependent. Toughness increases as aspect ratio goes up. For example, the flexural toughness is 54000 N.mm for SFR SSC 45/50 3D whereas it is 58750 N.mm for SFR SSC 65/60 3D. This is due to the fact that longer fibers have the capability of absorbing more energy and are efficient in bridging macro-cracks resulting in an additional straining in the steel fibers. This mechanism will result in a larger area under the load deformation curve, eventually yielding a higher toughness value. On the other side, the flexural toughness decreases significantly as aspect ratio increases from 65 to 80; i.e. for SFR-SSC 65/60 3D, it is 58750 N.mm while it is 42000 for SFR SSC 80/60 3D. This is equivalent to a 38% decrease. This result appears shocking as it was expected that higher steel fibers aspect ratio yields higher flexural toughness as longer fibers are capable of bridging wider cracks and therefore delaying beams failure. A possible explanation for this phenomenon is that very long steel fibers are very difficult to handle during mixing leading to a balling effect and therefore fibers won't be uniformly distributed throughout the beams contributing to a loss of flexural resistance. Another possible reason is that longer steel fibers with smaller diameter [i.e. high aspect ratio] don't have the same energy absorption potential as those who have larger diameter.

The type of steel fibers have a big effect on the flexural toughness of SCC beams as SFR SSC 65/60 5D beam holds the highest toughness value 61100 N.mm. This may be attributed to the excellent mechanical anchorage of multiple hooked 5D steel fibers leading to a hardening behaviour in the post cracking range.

The multiple hooking in the 5D family didn't only have a positive effect on the beam flexural toughness, but also on the cracking system. All SFR-SCC specimens using 3D family steel fibers displays a softening behavior in the load-deformation curves with a single cracking formation in the specimen surrounded by ramifications as shown in figure 7.

Fig. 7: Failure Mode and Crack Pattern of SCC Beams
a) 3D family steel fibers (SCC 45/50 3D), b) 5D family steel fibers (SCC 65/60 5D)

On the other hand, SFR-SCC 65/60 5D beam exhibits a hardening behaviour with multiple cracks in the middle third of the beam. It can be clearly seen from figure 7 that the cracks at failure for the SFR-SCC 5D beam specimen are greater in numbers and more distributed over the span of the beam specimen in comparison to the SFR-SCC 3D beams. This is due to the mode of action of multiple hooked end fibers [5D] which increase the number of cracks and reduce the spacing between cracks at failure. In this SFR-SCC 65/60 5D specimen, the steel fibers around these micro cracks will try to hold them and stop their propagation in the specimen matrix. Consequently, micro-cracks that are developing inside the beam specimen have to take a meandering path, rising the need for more energy for future propagation, which results in an increase in the ultimate load as seen in the load-deformation curves (figure 5).

Conclusion

In this study, different types of steel fibers were used to produce fiber reinforced self-compacting concrete. The effect of steel fibers aspect ratio and geometry on fresh properties such as J-ring test, and on hardened properties such as compressive strength and four point bending tests were examined. It should be noted that the behavior of SCC structural members might be affected by other variables not intended for investigation in this study. However, the conclusions made herein would be an important step toward the development of design guidelines for SFR-SCC members.

a) Regarding fresh properties, the J-ring test is used in this study to observe workability. Flow diameters above 600 mm are achieved in all cases without bleeding or segregation. It is observed that SCC workability [represented by the flow spread and flow time] increases as the aspect ratio of steel fibers decreases.

b) The addition of steel fibers in the SCC mixtures improves the compressive strength. This increase ranges from 11% to 26% depending on the aspect ratio and type of steel fibers.

c) From the flexural test, it is found that the addition of steel fibers to SCC mixes displays a deflection-softening response for all 3D types and a deflection-hardening response for the 5D type, both accompanied by single and multiple cracks respectively in the middle third of the specimens.

d) Test results indicate that higher aspect ratio provides better flexural properties as longer steel fibers tend to bridge more cracks and absorb more energy. However, SFR- SCC 80/60 3D specimen yields the lowest flexural toughness. This may be attributed to the balling effect during mixing. Therefore, on can deduct that an upper limit [based in this study, it is 65] should be placed on the aspect ratio of steel fibers used in SCC mixes.

e) By comparing flexural properties of SCC mixes, it was found that SFR-SCC 65/60 5D specimen has the highest flexural toughness. This indicates that 5D steel fibers provides better bond characteristics than 3D type steel fibers and has as well the highest energy absorption capacity.

f) A strict mixing procedure is followed in this study, in terms of time of mixing, addition of components, and sequence of material addition. In order to achieve high quality SCC and SFR-SCC mixes, it is essential to strictly follow the recommended mixing procedure. This procedure with the given mix proportions has led to an SCC mix that was able to flow and fill the molds without any need of vibration.

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