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The Effects of Using Steel Fibers on Self-Compacting Concrete Properties: A Review

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K E Y W O R D S

Steel fiber, Self-compacting concrete, steel fiber reinforced self- compacting concrete.

A B S T R A C T

In this literature review, steel fibers reinforced self-compacting concrete properties in fresh and hardened states and factors affecting them were reviewed. In spite of the high workability of self- compacting concrete, using steel fibers depending on their length, aspect ratio, shapes and volume fraction can cause detrimental effects on it. Using steel fibers improves hardened properties especially flexural and post-peak performance, and this improvement depends on how fibers can distribute and orientate in the fresh state. The better hardened properties can be obtained when fibres aligned and orientated in the direction parallel to tensile stress.

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1. Introduction

Self-Compacting Concrete (SCC) is the concrete that is able to compact, flow and fill the formwork with its congested reinforcement by its own weight only, without changing its homogeneity [1]. Ozawa et al., [2] have defined SCC as a concrete with high flow-able that should provide; flow-ability, passing ability and segregation resistance. The main advantages of using SCC are; no need to vibration, so noise level, manpower and construction time can be reduced, easy to fill and place with better finishing of concrete surfaces and enhance of durability because of the dense matrix of SCC, high consolidation ability and better bond with reinforcement [3]. Steel fiber reinforced concrete (SFRC) is the concrete reinforced with discontinuous steel fibers [4]. The steel fibers (SFs) have a wide range of types, aspect ratios and properties. (SFRC) can be used for multi applications in building and construction works, such as ground supported slabs, pavements of an airport, linings of mine and tunnel, hydraulic and underwater concrete structures [5]. The advantages of using (SFRC) include supplying of reinforcement with multidirectional, high impact resistance, post-fire durability, and increase in productivity, reducing the damages at corner and edges because of the forces of spalling [6]. The use of steel fiber in concrete can improve the strength and toughness of concrete by bridging of cracks, transmitting of stress across cracks and preventing of cracks propagations [7]. In the last decade, steel fiber reinforced self-compacting concrete (SFRSCC) has been used in several structural applications such as precast pre-stressed concrete members, slab on grade and sheet piles, etc. Using of fibers in SCC which it can be consolidated without needing for vibration, reduce the risk of fibers segregation and downward settlement during of compaction lead to distribute of fibers uniformly within concrete member [8]. The synergic between the (SCC) and (SFRC) can develop the economic efficiency of the construction process by reducing construction time, work force, energy consumption and enhancing the working environment with reducing noise and health risks [9].

2. SFRSCC Properties

I. SFRSCC properties in fresh state

The performance of SFRSCC depends on the properties of both concrete and fibers. The main fibers properties that are more interesting are fiber volume fraction Vf, fibers shape, fibers aspect ratio (fiber length lf /fiber diameter df), fibers distribution and orientation [3]. Fibers volume fraction and length selections based on the maximum size of aggregate used. Johnston [10] stated that the number of steel fibers that can be spread within a unit volume increases with reducing of maximum aggregate size as shown in Figure 1.

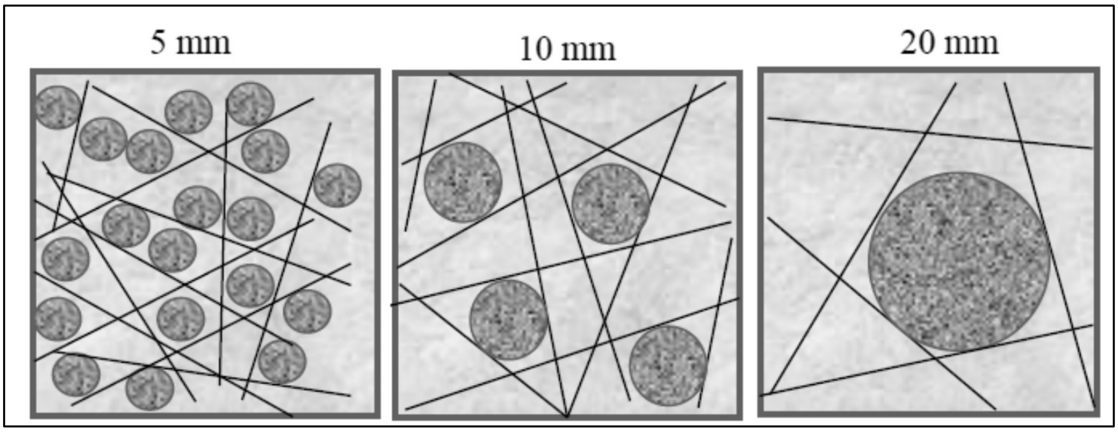

Figure 1: Max aggregate size when fibers length is 40mm [10].

The effects of fibers on the fresh properties of SFRSCC depend on fiber factor Vf l f /d f [11]. The higher the fiber content Vf and aspect ratio lf /df, with increasing coarse aggregate content and decreasing paste content the worse the fresh properties of the SFRSCC can be obtained , i.e. the lower the slump flow [12]. Therefore to avoid the risk of blocking a minimum of 600 mm slump flow must be obtained before the addition of fibers to the concrete mixture, especially when fibers are used incorporation with traditional reinforcement bars [13]. Grünewald and Walraven [14] attributed the increase of internal friction when SFs were used to increasing of granular skeleton internal porosity and decreasing of paste thickness surround each aggregate particle. The paste in SCC acts as a vehicle to transport of aggregate, therefore, the paste thickness must be increased excessively and the ratio of coarse to fine aggregate in the mix is reduced to reduce voids volume created by aggregate, and to ensure that all aggregate particles are fully surrounded and lubricated by a layer of paste as shown in Figure 2 [15]. The criteria of excess paste thickness had been also adopted to explain the performance of SFRSCC in the fresh state. The excess of paste thickness is necessary to fill the voids and lubricate the SFs and particles of coarser aggregate as shown in Figure 3 [16].

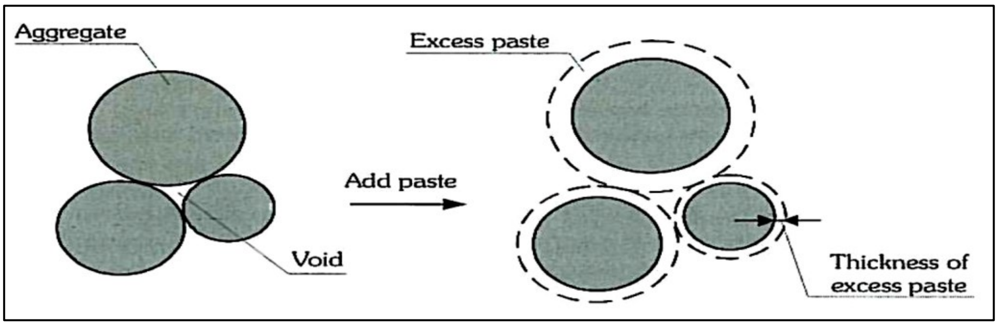

Figure 2: Excess paste layer around aggregates [15]

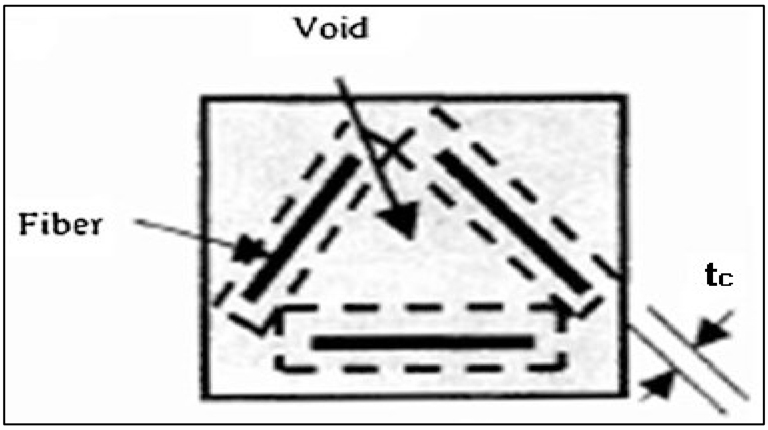

Figure 3: Concept of excess mortar thickness t_c [16]

S. Grünewald [7] attributed the negative effect of SF on SCC fresh properties to four main reasons:

1- The shape of SF when compared with aggregate is more elongated, so the surface area of SF with the same volume is larger.

2- Increasing of granular skeleton porosity by stiff fibers, which are push particles that are larger than the length of SF.

3- The surface properties of SF, which are different than cement and aggregate.

4- The friction between deformed shapes of SF (hooked end or wavy shaped) and aggregate is higher than that between straight steel fibers and aggregate.

S. Grünewald and J. C. Walraven [14] examined the maximum SF Content which can be added without affecting the SCC fresh properties. SF with an aspect ratio (lf/df) of (30/0.4, 61/0.7 and 41/0.6) were used the SF contents were increased by 20 kg/m^3. A slump flow of 600 mm at least with homogeneous distribution was adopted to investigate the maximum SF content. Figure 4 exhibited that the SF content was surpassed fibers with large surface area reduced the flow-ability of SFRSCC. Figure 4A shows that the fibers are distributed homogeneously but the contour of concrete flow is not rounded. This flow pattern associated with slump flow with a flow diameter of less than 600 mm. Figure 4B shows that SCC with larger aggregate and/ or longer fibers flows with clear clustering along flow path and the diameter of flow is affected marginally. Figure 4C shows that the intermediate (lf/df) (41/0.6) exhibited an intermixing flow pattern of Figure 4A and 4B. Figure 4C shows also that the flow is obstructed with clustering of fibers and or aggregate in the center of flow. Notable that at fiber contents lower than the maximum fiber content , The flow patterns below were not observed, When maximum fibers content is exceeded the paste adjustment (superplasticizer or water), the separation between fibers and matrix will happen. Obtaining of high slump flow when high fiber content is used that indicates a stability lacking.

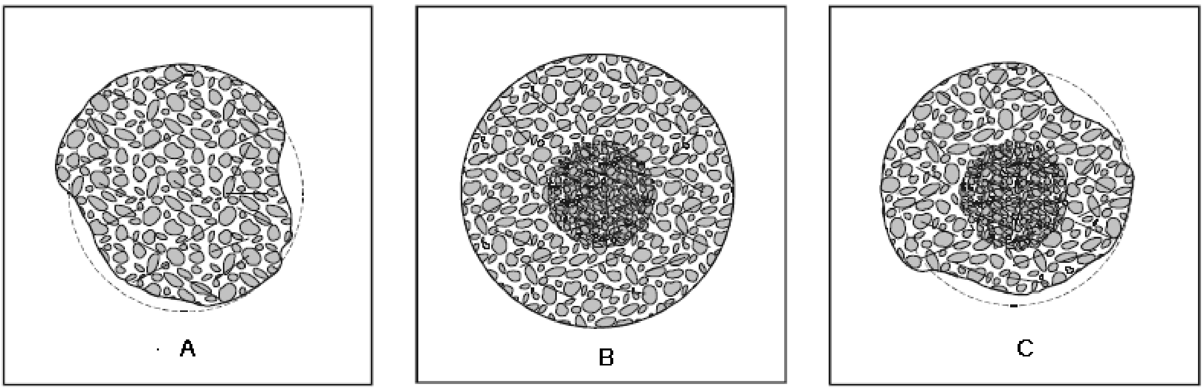

Figure 4: Spread area (A) for fibers having a large surface area (30/0.4); (B) for long fibers (61/0.7) and (C) for fibers with low to intermediate aspect ratio (41/0.6) [14]

P. Groth [17] proposed by using J ring test and hooked end SFs a relationship between clear spacing required between bars to avoid blocking of SFRSCC (c) and SF length L_f depending on SFs maximum content (m_f) and aspect ratio (L_f / d_f) .The proposed guideline is shown in Table 1.

TABLE I: Recommendation on the normalised bar spacing to avoid blocking of SFRSCC [17]

c/L_f	L_f/ d_f	Max. m_f (kg/m^3)
≥3	80 65	30 60
≥2	65 45	30 60
≥1.5	45	30

H. Ghanem and Y. Obeid [18] investigated the effect of using SF on the rheological properties of SFRSCC. Mixes with different SF length, aspect ratio and shape (hooked end and double hooked end) were used. The SF content of 0.5% was constant for all mixes. The results showed that using SF decreased the flow-ability and the passing ability of all mixes, and the possibility of blocking in J ring test increased with increasing of aspect ratio. The results also showed that the shape of SF had significant effects on SFRSCC fresh properties, and the effect of double hooked end SF was similar to the effect of using higher aspect ratio.

Yardimici, et., al [19] investigated the effect of aggregate grading and SF properties on flow-ability and passing ability of fresh SFRSCC mixes. Two types of hooked end SF (length of 30 mm with aspect ratio l/d of 55 and length of 60 mm with l/d of 80) with different SF content of (20 kg/m^3, 40 kg/m^3 and 60 kg/m^3) were used. All mixes had a similar paste volume but with different fine to coarse aggregate ratio. The results show that using SF led to a negative effect SFRSCC rheological properties especially with high aspect ratio at high SF content. The results SFRSCC mixes that using of high fine to coarse aggregate ratio enhanced rheological properties and compensated the losing in flow-ability and passing ability when higher aspect ratio at high SF content was used.

El-Dieb and Taha [20] suggested new single acceptance criteria for SFRSCC by combination of V funnel and filling box tests results. Three reference mixes with different cement content, paste volume and w/c ratio, and three types of straight SF with different aspect ratio were used. For each reference mix, four volume fraction of SF for each aspect ratio were used. The authors attributed their suggestion to use a single acceptance criteria to the difficulty of achieving all acceptance criteria of all tests together, and the depending on slump flow test to evaluate flow-ability of SFRSCC might not exhibit results consistently, especially with restricted flow. Depending on the results of V funnel and filling box tests, the authors suggested the following single acceptance criteria of SFRSCC flow-ability:-

$$f_{SCC} = \frac{1}{2}\left[\left(\frac{T}{T_{SCC}}\right)^2 + \left(\frac{100-\gamma}{100-\gamma_{SCC}}\right)^2\right] \quad (1)$$

Where T is the V-funnel test flow time and T_{SCC} is the acceptable flow time (12 seconds) according to acceptance criteria of ENFRAC [21]. While is γ the filling box test filling capacity ratio and γ_{SCC} is the acceptable filling capacity ratio (90%) according to acceptance criteria of ENFRAC [21]. SFRSCC mixes with a $f_{SCC} \leq 1$ can be considered as SFRSCC, while mixes with a $f_{SCC} > 1$ cannot be considered as SFRSCC

II. SFRSCC properties in hardened state

The main advantages of using fibers in concrete are improvement of flexural strength, in addition, improve toughness, post-peak performance and fracture energy under the impact. The improvement in flexural strength is greater than that in compressive strength because of the modifying of elastic distribution of strain and stress over the depth of member due to the ductile behaviour of SFRCC. The modified stress distribution which is elastic in compression zone and plastic in the tension zone leads to shifting the neutral axis to the direction of the compression zone [22].

A. The mechanism of SFs action

The mechanism of fibres action in concrete depends on the resistance of the fibers to pull out from the cement matrix when the equivalent -matrix interfacial bond is breakdown [23]. As a result of gradual pull out nature of fibers, fibers yield post-crack ductility to the cement matrix that would fail and behave as a brittle manner. Enhancement of ductility when SFs are used depends on type and volume fraction of fibers [24]. To increase SF pull out resistance, end anchorage must be increased by using deformed surface, wavy or hooked end SF instead of using straight fibers with the equivalent length and diameter. I.e. the amount of these types of SF used to improve ductility and strength is less than the amount of equivalent straight uniform SFs [25].

B. The orientation and distribution of SFs

To obtain a better contribution of SFs in strength and crack width control, it is very necessary to make the orientation and distribution of SFs with respect to the plain of cracks, because more effectiveness of SFs can be obtained with the alignment of them in the direction of the principal stresses [26]. As shown in Figure 5 ,when the alignment of SFs in concrete at a right angle to the formed crack, SFs are capable to bridge the cracks as soon as they formed , while SFs effectiveness becomes less in parallel location to the crack propagation direction [5].

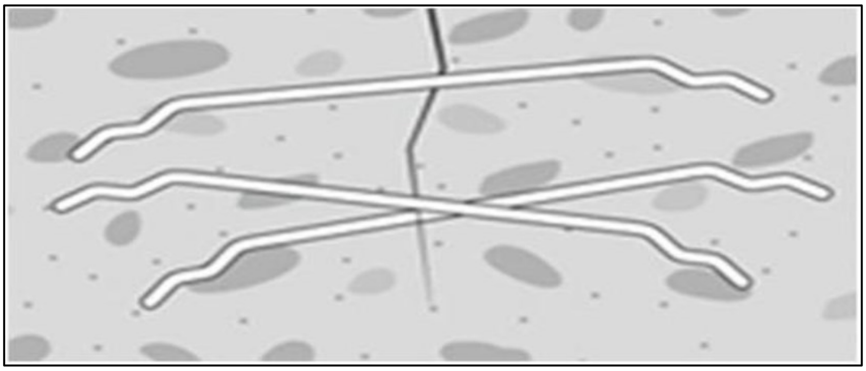

Figure 5: Fibers alignment in concrete matrix [5].

The orientation of fibers in SFRSCC is due to two reasons; firstly shear stresses of flowing concrete led to parabolic flow-velocity cross profiles, this acting transversely to the axis of a SF immersed in the flowing concrete, and inducing a torque making the fibers to align parallel to the direction of flow as shown in Figure 6.[27]. The second reason for orientation of fibers is ‘‘wall effect’’, where it is not possible at a distance lower than half the length of the SF to find fibers perpendicular to a wall of mould [28].

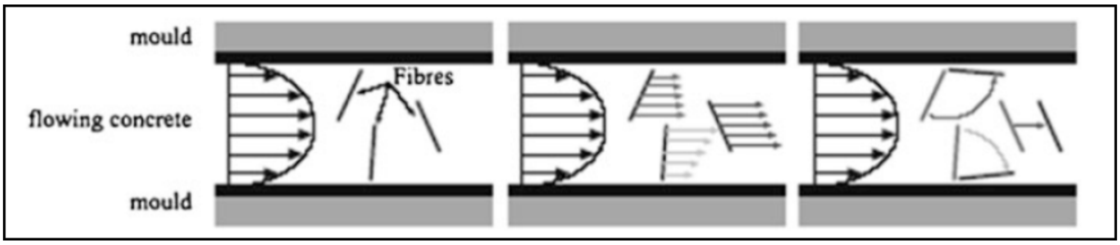

Figure 6: Mechanisms of fibers orientation in a shear-flow [27]

Ghanem and Obeid [18] investigated the effect of SFs on compressive and flexural strength depending on the mixes details mentioned previously. The results showed that using of SFs improved compressive strength, and the increasing varied between 11% to 26% depending on the aspect ratio and the length of SFs. While the shape of SFs (double hooked end) had a marginal effect 13% increase. For flexural strength, the results showed that better flexural strength and flexural toughness can be obtained by using SFs with higher aspect ratio because by using the longest SFs more cracks were bridged and more energy can absorb. However, for the same SF length, the mix contained the highest aspect ratio exhibited the lowest flexural strength due to the balling effect of the thinnest fibers during mixing. The results showed also that mix contained doubled hooked end SFs exhibited higher flexural properties than mixes contained single hooked end SFs at the same aspect ratio due to the better bonding with cement matrix.

Yardimici et., al [19] investigated the effect of aggregate grading and SF properties on some hardened properties of SFRSCC depending on mixes details mentioned previously. The results showed that the compressive strength decreased by increasing of SFs content due to its negative effects on the workability of fresh concrete. The reduction in compressive strength seems to be clearer by using longer SFs with higher aspect ratio, but using of high fine to coarse aggregate ratio decreased the reduction in compressive strength due to improving of workability. For flexural strength the results illustrated that using of SFs with high content and aspect ratio led to increasing flexural strength due to improving the post-peak performance of SFRSCC, and as general trend using of high fine to coarse aggregate ratio is very important when SF content and aspect ratio are high to compensate the detrimental effects of them on workability. The researchers studied also the effects of the numbers per cm^2 and the orientation of SFs on flexural strength and found a strong correlation between it and the numbers of SFs per cm^2 at failure surface. The flexural strength increased directly with increasing the number of SFs per cm^2 at the failure surface. The orientation of SFs with respect to the main tensile stress direction had significant effect on flexural strength. Generally, better orientation can be obtained with better fresh properties of SFRSCC.

P. Stähli et., al [29] investigated the effect of changing flow properties of fresh SFRSCC on the distribution and orientation of SFs by using straight with a length of 30 mm and containing 3% of SFs for all mixes. Three mixes (M1, M2, and M3) with slump flow of (450, 590 and 640) mm respectively were examined. U shape specimen was used to obtain a flow with three different directions as shown in Figure 7 below. The fresh concrete flows down firstly across branch (A) then flows horizontally across branch (B), finally rises vertically across branch (C).

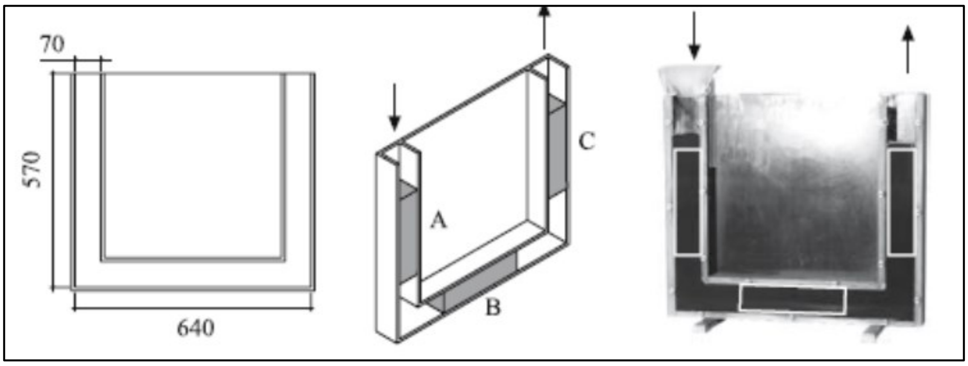

Figure 7: U-shaped mould with locations where three (70 × 70 × 280) mm3 prisms are cut-out after hardening [29].

After demoulding, the hardened concrete was cut out to a prism for each branch with dimensions of (70 ×70 × 280) mm. To analyse the orientation of the fiber inside a specimen, the specimen was cut into slices and the fibers were counted or it can be computerized tomography by using CT scan. To compare the specimens, across and longitudinal sections were analysed as shown in Figure 8. The CT scan images showed that fibers aligned with the direction of flow and the alignment increased with increasing of flow velocity, i.e. mixes with high slump flow showed the best fibers alignment. The CT scan showed also that the fibers are not aligned over the whole area, because the flow velocity in the centre is faster than near the walls. For flexural strength, the results showed that mixes had the highest flow-ability exhibited the highest flexure strength results, because these mixes showed the best fibers alignment. For prism (C) the results showed that the increase in slump flow caused a marginal increase in flexural strength because of fibers segregation where the concrete materials were not able to carry the fibers all the way of the prism (C). The highest flexural strength result was noticed for prism (B) due to the best fibers alignment. Figure 9 shows the results of flexural strength.

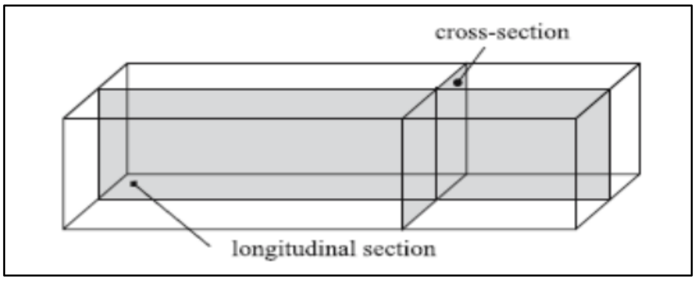

Figure 8: Nomenclature for the different cross-sections [29]

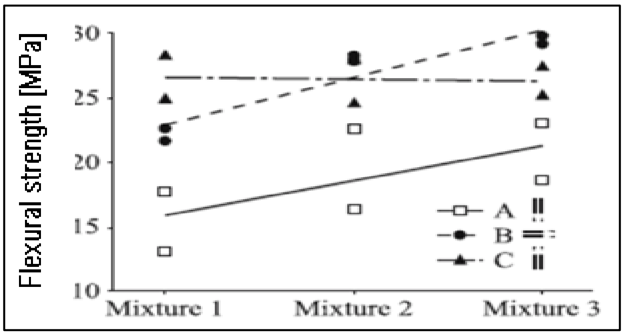

Figure 9: the results of flexural strength [29]

Torrijos et., al.[30] investigated the effects of casting procedure, orientation and distribution of SFs on SFRSCC flexural strength. Two SFRSCC mixes were used with fiber content of 35 kg/m^3 each. SFRSCC1 contained hooked fibers with length of 50 mm and diameter of 1 mm and SFRSCC2 contained hooked fibers but with length of 30 mm and diameter of 0.38 mm. for each mix twelve beams with a dimension of (150 ×150 × 600) mm^3 were cast. Four beams were cast conventionally by pouring the concrete from the mould centre (C). Four beams were cast by pouring the concrete from any end of mould after the concrete had flown across a tube with a length of (5) m with a diameter of 150 mm and a slope of 20º (T). The last four moulds were cast as column by pouring the concrete from the top (V). Figure 10 shows the casting methods. The flexural test was carried for each beam, to evaluate fibers orientation the halves of beams used in the flexural test were cut in multi directions. For SFRSCC1, the results of flexural strength showed that (T) beams showed the highest flexural strength. Beams (C) showed the intermediate value and the lowest flexural strength was noticed with (V) beams. For SFRSCC2 which contained shorter fibers, casting procedure showed a lower effect on test results. Both (C) and (T) beams showed similar test results. As in SFRSCC1 (V) beams showed the lowest test results. The researcher concluded that the casting procedure had a significant effect on fibers distribution, fibers tend to orientate a long horizontal plane and the transversal plane contained highest fibers density and the better hardened properties can obtain with the better fibers orientation.

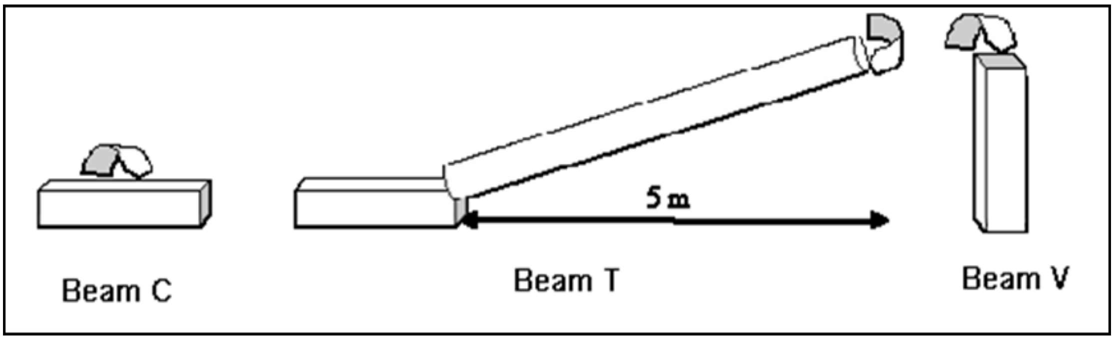

Figure 10: casting procedure of molds [30]

Ghailan and Al-Ghalib [31] devised a procedure to align the SFs in fresh SCC parallel to tensile stress by using external electromagnetic fields. To achieve a uniformly magnetic field, the current was passed through a cylindrical coil. The magnetic field lines are straight, so SFs will spin in the same direction of them as shown in Figure 11. The cylindrical coil warped over the plastic pipe with a diameter of 200 mm and length of 600 mm, these dimensions will permit a mould with dimensions of $(100 \times 100 \times 500)$ mm^3 to be inside it during the preparation of concrete prism. The coil fixed on the vibrating table as shown in Figure 12. Three series of mixes were used depending on micro SFs content (0.35%, 0.7% and 1.05%). For each series nine prisms were cast, three with random fibers, three for aligned fibers without vibration and the last three prisms for aligned fibers with vibration. For aligned with vibration prisms, the concrete was poured in the mould and vibrated for 30 seconds without electromagnetic induction, and then electromagnetic induction was applied simultaneously with vibration for an additional 30 seconds. Distribution and orientation of fibers were examined visually on prisms after carried out of flexural strength. For aligned with vibration prisms, the visual inspection showed that most fibers aligned horizontally with parallel orientation, while for random prisms the visual inspection showed less horizontal alignment. The negligible effect of magnetic fields was noticed for aligned without vibration prisms. For flexural strength test, the aligned with vibration prisms exhibited the highest flexural strength and at SFs content of 0.35%, the test result increased by 40% compare to randomly aligned prisms. While the increment reached 115% when SFs content was doubled.

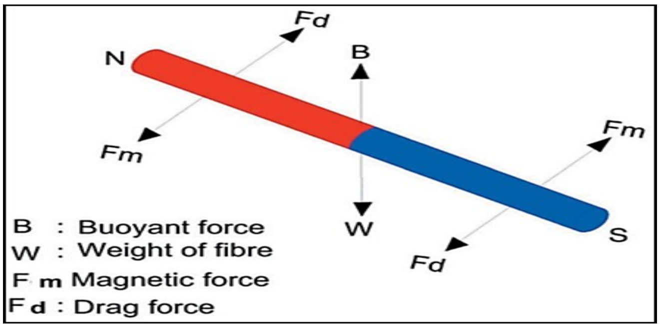

Figure 11: Forces on SFs in SCC [31].

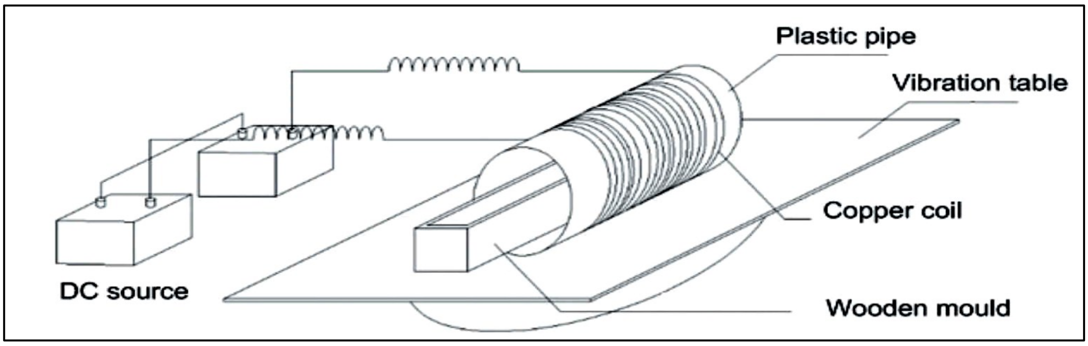

Figure 12: Experimental set-up [31].

3. CONCLUSIONS

1- Using of SFs in SCC led to a negative effect on the flow, filling and passing abilities of SFRSCC, and these negative effects increased with increasing SFs length, aspect ratio and volume fraction. The wavy, hooked end, double hooked end SFs were more pronounced in their detrimental effects on SFRSCC fresh properties than straight SFs.

2- The negative effects of SFs using in SCC can be overcome by increasing of paste volume and fine to coarse aggregate ratio and reducing of maximum aggregate size. While increasing of SFRSCC flow-ability by depending on a high dosage of superplasticizer alone can cause segregation and balling of SFs.

3- Using SFs in SCC improved hardened properties such as flexural strength, toughness and post-peak performance, while less effect was noticed in compressive strength.

4- A better hardened properties can be obtained with better fresh properties and more adequate mix design.

5- SFs tend to align in the direction of flow, and SFs alignment depends on flow velocity, viscosity and cast procedure of fresh SFRSCC in addition to the wall effect of moulds.

6- The distribution and orientation of SFs had a decisive effect on the improvement of SFRSCC's hardened properties. For a better improvement, SFs should be aligned and orientate in the direction parallel to the direction of tensile stress to prevent the propagation of cracks by bridging the plane of them.

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