Self-Compacting Concrete Reinforced with Steel Fibers from Scrap Tires: Rheological and Mechanical Properties

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Abstract: The aim of this study is to evaluate the rheological behavior and the mechanical performance of SCC with different contents and lengths of recycled steel fiber (RSF) recovered from scrap tires. The rheological properties investigated in this study include: slump flow, J-ring, L-box, and V-funnel tests. The mechanical properties include: compressive and flexural strength. The parameters of the study are fiber content and length. In total, thirteen self-compacting concrete (SCC) mixtures were prepared. Three fibers contents 30, 60 and 90 kg/m^3 were investigated and for each fiber contents W_f, four mixes were prepared with four different fiber lengths (L_f) (10, 15, 25, 35 mm). A control mix (plain SCC) was also prepared for comparison reasons. The results showed that the addition of RSF decreased the slump flow, slowed down the flow rate and increased the V-funnel time but maintained the requirement of SCC up to 60 kg/m^3 fiber content. Shorter fibers had less effect on the rheological behavior of SCC than long fibers. Both RSF content and length affected the compressive strength and the flexural strength of SCC. Long RSF reduced compressive strength but increased the flexural strength.

Keywords: Recycled Steel Fiber, SCC, Rheological Properties, Compressive Strength, Flexural Strength

1. Introduction

Both developed and developing countries are suffering from the enormous number of tires accumulated every year. Billions of tires are discarded every year worldwide (Thomas & Gupta, 2016a). The disposal of such huge number of waste tires has a large impact on the environment. Also, waste tires can cause serious issues to the human health and increase fire hazards in the case of burning or illegal dumping (Younis, 2016; Thomas & Gupta, 2016b). The utilization of such huge waste of tires in the production of self-compacting concrete (SCC) is a decent and sustainable solution to mitigate serious environmental issues (Younis, 2016). Self-compacting concrete (SCC) is a type of concrete, which has unique properties that enable it to be placed and compacted during casting without any external aid saving time needed for construction (EFNARC, 2005). The use of recycled steel fiber (RSF) recovered from scrap tires as reinforcement in SCC can be a valuable solution for the aforementioned issues associated with the disposal of waste tires. This will also enhance the sustainability of SCC and make this type of concrete eco-friendly. The characteristics of SCC in the fresh state are vital since SCC should have the ability to consolidate, pass the reinforcing rebars and fill all form's parts and corners with no segregation (EFNARC, 2005). The addition of manufactured steel fibers to SCC mixtures affects its properties in fresh and hardened states (El-Dieb & Taha, 2012). Previous studies (El-Dieb & Taha, 2012; Gencel, 2011; Madandoust, 2015) have reported that the use of manufactured steel fibers in SCC may have an adverse effect on the rheological properties of SCC. Manufactured steel fibers can reduce the flow ability, increase the viscosity (decrease the passing ability), increase the risk of segregation and decrease the density of the fresh SCC. However, studies on the effect of use of RSF in SCC mixtures on the fresh properties are rare. The use of discontinuous manufactured steel fibers in different length and content by randomly distributing them in a concrete member may be useful to improve the tensile, flexural, shear, impact strength and reducing shrinkage. Due to the ability of these steel fibers to arrest and slow down the crack growth, these fibers can limit the cracks at early stage of loading history (micro cracks) (El-Dieb & Taha, 2012; Gencel, 2011). The effect using RSF on the mechanical properties of normal concrete has been reported by several studies (Younis, 2016; Younis & Pilakoutas, 2013; Tlemat, 2004; Pilakoutas, Neocleous, & Tlemat, 2004). It has been reported that RSF can show performance similar to that of manufactures steel fibers (Younis, 2016; Tlemat, 2004; Pilakoutas et al., 2004). Therefore, it can be used as alternative to the expensive manufactured steel fibres. Nonetheless, studies that tackle the influence of RSF on the mechanical performance of SCC are rare. Hence, this article is part of a research aims at assessing the properties of SCC with different content and length of RSF in both fresh and hardened conditions. This article describes the experimental program, presents the experimental results and analyses the effect of different content and length of RSF on the rheological and mechanical properties of SCC.

2. Experimental Work

2.1 Materials

Portland Cement (type I) produced by AL-MAS cement factory (42.5 R – B.S) 12/96 in Kurdistan-Iraq was used in this study. The specific gravity and specific surface area of cement were 3.12 and 314 m^2/kg, respectively. The adopted cement conforms to the Iraqi specification No.5/1984 [12] The silica fume used in this study was in the form of a gray powder having a specific gravity of 2.2. Its commercial name is Sika Fume-HR. It was used in all mixes as a partial replacement of cement with 10% by weight.

Natural rounded river aggregate was used as coarse aggregate with a maximum size of 14 mm. and specific gravity of 2.65. Natural river sand was used as fine aggregate with a maximum size of 4.75 mm. The specific gravity and fineness modulus are 2.67 and 2.8, respectively. High water reduction admixture (HWRA) as super plasticizer (SP) was used to provide high workability that essentially required for SCC. Sika viscocrete super E4-S was used in this study, the RSF was collected from a factory of recycling scrap tires located near Erbil city. The factory is recovering rubber from the scrap tires while the steel wires were discarded as waste as shown in Figure 1. In this study, those wires were collected and prepared to be reused as concrete reinforcement. These steel wires were cleaned from remaining rubber and burned carbon existing on the surface of these wires to provide a good adhesion with concrete, as seen in Figure 2. After cleaning, the steel wires were cut into four different lengths (10, 15, 25 and 35 mm) using plate cutting machine. The scrap steel wires were separated manually into fibers to form recycled steel fibres (RSF) before adding them to the concrete mixture (see Figure 2). The RSF had a diameter of 0.25 mm and a tensile strength of around 1000 MPa.

(a) (b)

Figure 1: Recycled steel wires a-before cleaning, b- after cleaning

Figure 2**:** Sample of the **r**ecycled steel fibers used in current study (for fibers with length =35mm)

2.2 Mix Proportions and Preparation of Specimens

There is no standard SCC mix design method; therefore, trial and error approach should be followed until the appropriate proportions of materials that verify SCC requirements are reached. In this study, thirteen SCC mixtures were prepared with the same total binder content and water to cement ratio as presented in Table 1 which shows the code and mix proportions of all mixes. As can be seen, the parameters of the study are fiber content and length: three fibers contents 30, 60 and 90 kg/m^3 were investigated and for each fiber contents, four mixes were prepared with four different fiber lengths (L_f) (10, 15, 25, 35 mm). A control mix (plain SCC) was also prepared for comparison reasons. In the study, all mixes have been prepared by following European guidelines of SCC EFNARC (2005). A 0.04 m^3 mechanical rotary mixer was employed in the production of concrete mixtures. Three (100 mm) cubes and three prisms 100×100×500 mm, were cast for each mix. After casting, the specimens were then covered by plastic sheets and allowed to cure for 24 hours before being demoulded. Then, the specimens were kept in water tanks for 27 days for further curing.

Table 1: Code of mixes and mix proportions in kg/m^3

mix name	W_f kg/m^3	L_f mm	Cement kg/m^3	SF kg/m^3	Water litre/ m^3	Sand kg/m^3	Gravel kg/m^3	SP litre/ m^3
M0	--	--	405	45	170	850	810	11.25
M1	30	10	405	45	170	850	810	11.25
M2		15	405	45	170	850	810	11.25
M3		25	405	45	170	850	810	11.25
M4		35	405	45	170	850	810	11.25
M5	60	10	405	45	170	850	810	11.25
M6		15	405	45	170	850	810	11.25
M7		25	405	45	170	850	810	11.25
M8		35	405	45	170	850	810	11.25
M9	90	10	405	45	170	850	810	11.25
M10		15	405	45	170	850	810	11.25
M11		25	405	45	170	850	810	11.25
M12		35	405	45	170	850	810	11.25

2.3 Test Methods

Rheological Properties

Slump flow, T_{50} flow time, J-ring, L-box, BJ, TJ, and V-funnel were conducted to assess the fresh properties of the SCC mixes. These tests were undertaken following the specifications and guidelines of European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC) for SCC. The sequence of performing the fresh concrete tests was the same with all mixes. The fresh properties were conducted immediately after the completion of concrete mixing.

Mechanical Properties

The compressive strength was obtained at age of 28 days using the (100 mm cubes) and BS EN 12390-3 (2009). The flexural strength was obtained at 28 days using (100×100 ×500) mm prisms. All prisms were tested in two-point loading over a span of 300 mm following the recommendations of the BS EN 12390-5 (2009).

3. Results and Discussions

3.1 Rheological Properties

To evaluate the effect of the use of RSF on the performance of SCC mixtures, the rheological behavior of all mixes was quantified by assessing: 1- flow, viscosity and filling ability of concrete by slump flow and V-funnel tests; 2- the passing ability of concrete by j-ring and L-box tests (see Figure 3). The results of all fresh concrete properties and the limits of EFNARC are presented in Table 2. In general, it can be seen that the rheological properties of SCC showed a gradual degradation with the addition of RSF. It was shown that both RSF content (W_f) and length (L_f) affected the rheological of SCC.

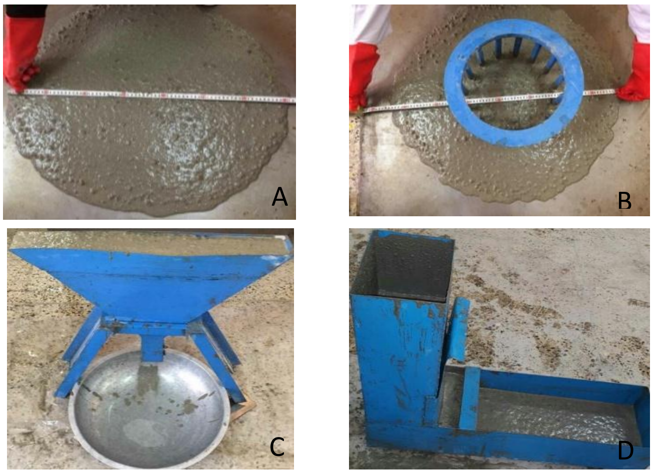

Figure 3: Rheological properties tests: a- slump flow, b- j-ring , c-V-funnel, d- L-box

Table 2: Result of rheological properties of all mixes

Mix code.	W_f, kg/m^3	L_f, mm	Slump Flow		J-Ring		V-Funnel, sec	L-box %
			Flow, mm	T_{500}, sec	Flow, mm	B_J		
M0	-	-	788	2.25	760	0.65	8	0.95
M1	30	10	755	2.3	740	0.975	8.3	0.9
M2		15	745	2.47	720	1.35	8.35	0.85
M3		25	725	2.7	700	1.45	8.46	0.833
M4		35	720	3	695	2.125	8.68	0.82
M5	60	10	720	2.35	715	1.22	9.4	0.87
M6		15	700	2.38	710	1.5	10.5	0.82
M7		25	665	3.38	655	1.625	11.45	0.78
M8		35	645	4.6	615	2.15	11.6	0.76
M9	90	10	670	2.8	650	1.7	12	0.82
M10		15	660	3.4	630	1.95	13.5	0.814
M11		25	575	5	540	4.75	15.6	0.77
M12		35	560	6.3	495	8.25	17	0.75
Limits of EFNARC			650-800, mm	2-6, sec	650-800,mm	0-20	8-12, sec	0.8-1%

Slump flow and J-ring tests

For the slump flow test results, as can be seen in Table 2 and Figure 4, the flow characteristics decreased proportionally with increasing RSF content. The reduction in flow properties was clearly observed when long fibers are used rather than short ones.

The control mix M0 which is plain SCC (without RSF) showed a 788 mm slump flow and 2.25sec.

flow time (T_{500}). For mixes having 30 kg/m^3 fibers content, a marginal effect on slump flow and fluidity was observed compared to the control mix M0. Where, the slump flow of M1, M2, M3 and M4 reduced by only 4.2 %, 5.5 %, 8.0% and 8.6%, for fiber lengths of 10, 15, 25 and 35 mm, respectively. The reduction in slump flow clearly increased when fiber content increased to 60 kg/m^3. Table 2 shows that the reduction in slump flow of M5, M6, M7 and M8 compared to M0 was 8.6%, 11.1%, 15.6 %, and 18.1%, respectively. Additionally, at higher fibers content 90 kg/m^3, the reduction in slump flow significantly increased, particularly with long fibers. In comparison to M0, the slump flow of mixes M9, M10, M11 and M12 declined by 15.0%, 16.2%, 27% and 28.9%, respectively.

All mixes of the fiber contents of 30 and 60 kg/m^3 fulfill the EFNARC requirements of slump flow as can be seen in Figure 4. This means that these mixes still maintain the characteristics of SCC. However, for mixes with 90 kg/m^3 content, the slump flow of the mixes with long fibers (25mm and 35mm) does not meet the requirements of EFNARC.

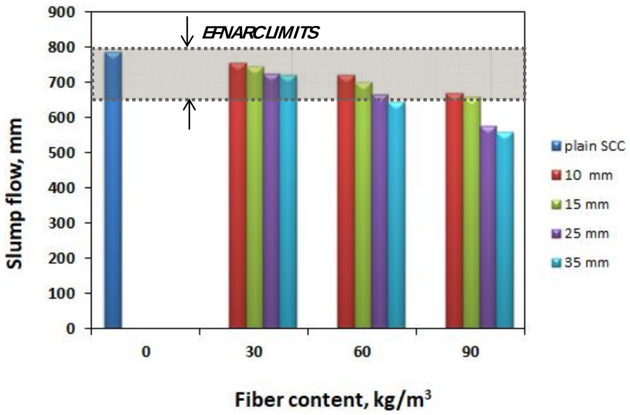

Figure 4: Effect of RSF content on slump flow

This reduction in slump flow due to the addition of RSF could be attributed to the resistance to flow that develops because of the presence of RSF; hence increasing the internal friction between aggregate particles and fibers (El-Dieb & Taha, 2012; Gencel, 2011). The increasing in the internal friction proportionally increased with fiber content (Wf). The high stiffness (modulus of elastic) of steel fibers could be one of the sources for a likely increase in inter-particle friction under the free flow (El-Dieb & Taha, 2012; Khayat & Roussel, 2000) with a possible absorbing of the moving energy (Centonze, Leone, & Aiello, 2012). In terms of RSF length, regardless of the fiber content, the tangle of long fibers caused reduction in slump flow more than short fibers.

As far as the results of flow time, j-ring (flow and Bj) are concerned, similar behavior to that of the slump flow was observed for the mixes containing RSF. The increase in the fiber content and length adversely affected the results of flow time and j-ring tests. The reduction in flow time and j-ring flow is an indication of the high viscosity of the mixes with RSF. Despite the negative effect of the RSF on the results of flow time and j-ring tests, all mixes with RSF (apart from M11 and M12) conform with the limits of EFNARC as can be seen in Table 2.

V-funnel and L-box tests

The results of V-funnel test, as can be seen in Table 2, show that the mixes incorporating of RSF exhibited an increase in V-funnel time compared to the plain SCC. The V-funnel time gradually increased with RSF content and length. The addition of RSF with 30 kg/m3 showed little effect on passing ability of concrete through the V-funnel. At this RSF content, time recorded in V-funnel test in comparison to M0 decreased by 3.75%, 4.4%, 5.75% and 8.5% for M1, M2, M3 and M4, respectively. The time needed by RSF mixes to pass through the V-funnel increased with RSF content at 60 kg/m^3 by 17.5%, 31.25%, 43.12% and 45% for M5, M6, M7 and M8 compared to the control mix M0; Figure 5. As the fibers content increased to 90 kg/m^3, V-funnel test results exceeded the upper limit of EFNARC guidelines. Much higher increase 50%, 68.7%, 95% and 112.5% in the V-funnel time was recorded for mixes M9, M10, M11 and M12, respectively, compared to the control mix. This could be due to the same reasons mentioned previously related to the increased internal friction between aggregate particles and RSF leading to high viscosity and increased flow time through V-funnel (Khayat & Roussel, 2000). Additionally, the long fibers prevent the aggregate particle from the free movement causing delay in flow (Khayat & Roussel, 2000).

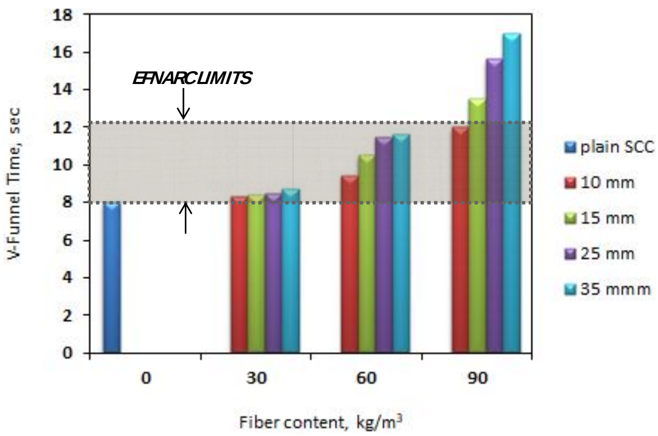

Figure 5: Effect of RSF content on V-funnel time (sec)

L-box test was performed to assess passing ability of all SCC mixes, and the results of which are shown in Table 2. The results showed that the incorporation of RSF negatively affected the passing ability of mixes with RSF. It is clear that this reduction in blocking ratio depends on both the fiber content W_f and fiber length L_f. The higher the RSF content the higher the reduction in the passing ability of the mixes. Also, the passing ability decreased when the length of the fibers increased. However, all mixes with RSF (apart from M11 and M12) meet the requirements of EFNARC as can be seen in Figure 6. The reduction in passing ability can be attributed to the presence of fibers which work as obstacles and de-accelerate the movement. The influence of adding RSF is significantly appearing with high contents (90 kg/m^3) and with long fibers. Long fibers could lead to a reduction in the internal energy needed for the mix to move freely.

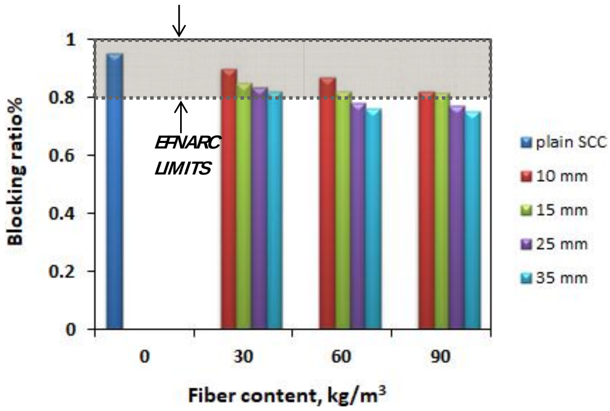

Figure 6: Effect of RSF content on blocking ratio (L-box test)

From the results of the rheological properties, it seems that the RSF can be used up to 60 kg/m^3 content with no effect on the properties of being SCC as all requirements of EFNARC can be satisfied. Higher contents such as 90 kg/m^3 can be used but the length of the RSF should not exceed 15 mm.

3.2 Mechanical Properties

The results of the mechanical properties including compressive strength and flexural strength for all mixes are presented in Table 3. The results are the average of three specimens.

Table 3: Result of compressive and flexural strength of all mixes

Mix code	W_f, kg/m^3	L_f, mm	Compressive strength, MPa	Flexural strength, MPa
M0	0	-	55	6.2
M1	30	10	62	6.88
M2		15	61	7.24
M3		25	59	7.86
M4		35	56	7.9
M5	60	10	58	7.88
M6		15	56	8.05
M7		25	52	8.15
M8		35	50	8.33
M9	90	10	54	7.3
M10		15	53	7.34
M11		25	50	7.98
M12		35	48	8.1

Compressive strength

The inclusion of RSF doesn't show significant effect on compressive strength of SCC mixtures. From test results presented in Table 3, mixes show either a slight increase or decrease in compressive strength comparing to the control mix (plain SCC).

The results show that the two parameters (fiber content and length) examined in this study affected the compressive strength of SCC mixes containing RSF. The effect of these parameters is shown in Figure 7. It can be seen that for low fiber content (30 kg/m^3) the compressive strength increases (for all RSF lengths) up to 12.7% compared to the control mix; whereas for high fiber content (90 kg/m^3), the strength decreases (for all RSF lengths) by up to 12.7% compared to the control mix. However, for moderate fiber content (60 kg/m^3) the compressive strength slightly increased for short fibers (10 and 15mm) and slightly declined for long fibers (25 and 35mm). Same results were concluded by researchers (Madandoust, 2015; Khayat & Roussel, 2000) but for manufactured steel fibers. For all fiber contents, the compressive strength increased with the decrease of the length of the fibers which means shorter fibers exhibited better performance in terms of comressive strength.

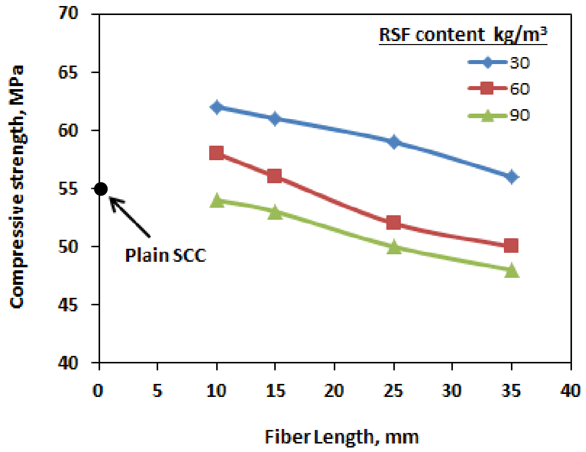

Figure 7: Effect of RSF length and content on the compressive strength of SCC

The increase in compressive strength for low content and short fibers could be due to the ability of short fibers in delaying the propagation of micro cracks and slowing down the development of micro cracks to macro cracks and; thus delaying the failure of concrete (Younis, 2016; Younis & Pilakoutas, 2013). Also, the incorporation of RSF could transfer the compression failure from collapse/ brittle to ductile failure (Younis & Pilakoutas, 2013) which also lead to higher strength before failure. This result was in a compatibility with the previous results (Khayat & Roussel, 2000).

The reduction in compressive strength for high contents and long fiber might be due to a reduction in rheological of RSFSCC mixes as mentioned in the previous section. Furthermore, adding RSF could increase the porosity of concrete due to the increase in the entrapped air voids which considered as concrete defect (Younis, 2016). During mixing and casting, fibers may entrap large air voids especially with high content of fibers (Younis, 2016). Moreover, the reduction in strength can be attributed to the existence of long fibers ineffective in arresting micro cracks (Centonze, Leone, & Aiello, 2012). Additionally, the existence of long RSF could increase the entrap air voids due to balling and tangle of fibers. This would result in accelerating the propagation of cracks and failure.

Flexural Strength

Table 3 also shows the results of the flexural of all SCC mixes. The performance of SCC mixes with RSF under compression loading is not the same as under bending loading. Regardless of the fiber content, all SCC mixes with RSF show higher flexural strength than that of the plain SCC. Additionally, for the same fiber content, the higher the fiber length the higher the flexural strength as can be seen in Figure 8. For example, the flexural strength increased by 11.0%, 16.8%, 26.8% and 27.4% for mixes M1, M2, M3 and M4 compared to M0, respectively. It was expected that mixes with 90 kg/m^3 RSF content would show the best flexural performance; however, these mixes exhibited less flexural strength enhancement compared with the 30 kg/m^3 fiber content. This could be due to the same effect related to the development of air voids at high contents of RSF which is mentioned earlier. The best flexural performance is shown by mixes with 60 kg/m^3 fiber content. At this fiber content, enhancements in the flexural strength of up to 34% were observed.

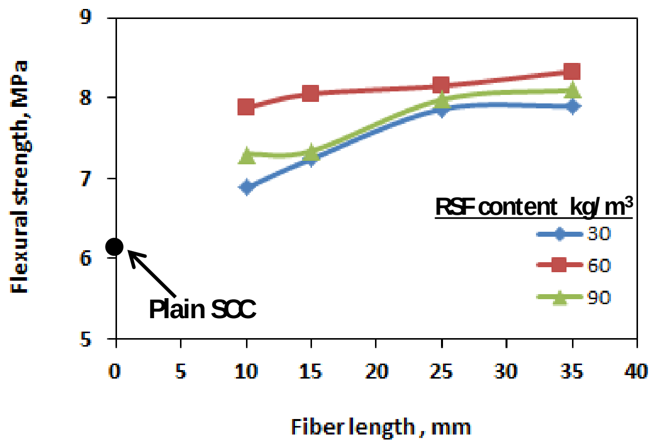

Figure 8: Effect of RSF length and content on the flexural strength of SCC

The enhancement in flexural strength due to RSF incorporation can be mainly attributed to the role of fibers in bridging the microcracks and arresting the sides of the macrocracks in concrete body and hence delaying the occurrence of concrete failure (Centonze, Leone, & Aiello, 2012; Younis, 2016). Also, this behavior could be partly due to the pull-out resistance of fibers (Centonze, Leone, & Aiello, 2012) which increases with the increase of fiber length. This can result in a significant increase in fracture resistance and thus increasing the ductility of SCC mixes (Centonze, Leone, & Aiello, 2012).

4. Conclusion

The discussion of the results can lead to the following conclusions:

- The use of RSF reduced the slump flow and J-ring flow and decelerated the flow rate (T_{500}) of SCC mainly due to the increase in inter-particle friction under the free flow. However, all mixes with RSF (apart from mixes with high content 90 kg/m^3 and long fibers 25 and 35 mm) maintain the EFNARC requirement of slump flow and flow rate.
- Mixes with RSF exhibited higher viscosity and lower passing ability than that of plain SCC as the V-funnel time increased and the blocking ratio decreased with the increase of RSF content and length. Nonetheless, all mixes with RSF (apart from mixes with high content and long fibers) comply with EFNARC requirements.
- For low fiber content (30 kg/m^3) the compressive strength increased (for all RSF lengths) up to 12.7% compared to the control mix; whereas for high fiber content (90 kg/m^3), the strength decreased (for all RSF lengths) by up to 12.7% compared to the control mix. However, for moderate fiber content (60 kg/m^3) the compressive strength slightly increased for short fibers (10 and 15mm) and slightly declined for long fibers (25 and 35mm).
- All SCC mixes with RSF showed higher flexural strength than that of the plain SCC by up to 34%. For the same fiber content, the higher the fiber length the higher the flexural strength.
- The utilization of RSF in SCC can lead to an innovative, sustainable and cost-effective self-compacting fiber reinforced concrete.

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