Fresh Properties and Mechanical Properties of Steel Fibre Self-Compacting Concrete (SFSCC)

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Abstract. This paper investigates the fresh properties and mechanical properties of steel fibre self-compacting concrete (SFSCC). Self-Compacting Concrete (SCC) has several advantages over normal concrete. SCC does not require any efforts of vibrations as it becomes compacted under its own weight. The application of SCC can be greatly improved with steel fibres, randomly added into the mixtures as to enhance the performance of concrete matrix. Addition of steel fibre has shown an improvement on the mechanical properties of concrete such as the tensile and flexural performance. The aim of this study is to determine the mechanical performance of SFSCC with different percentage of steel fibres and also to observe the fresh properties of SCC with and without steel fibres compare to the normal vibrated concrete (NC). In order to compare the performance of SFSCC, the properties of NC and SCC were also studied. The volume percentage of steel fibre is varies at every increment of 0.25% from 0 to 1.25% The results reveal that the addition of steel fibres in concrete matrix shows better mechanical performance compared with NC and SCC with percentage increment more than 50% for tensile, flexural and toughness testing. However, this study also concludes that steel fibre has no significant improvement to the compressive strength where the increament is very little. Based on the overall results obtained from this study, the performance of steel fibre self-compacting concrete shows a significant improvement with the capabilities in absorbing relatively large capacity of energy while delaying the propagation of crack, thus, preventing sudden failure in the concrete matrix as happened in most of conventional concrete.

Introduction

Self-compacting concrete (SCC) is first introduced in Japan and the applications were first implemented in the early 1990s [1]. Combination of more significant impacts by using this type of concrete has led to further increased in utilization of SCC in the worldwide construction industry. Technology of SCC typically produced with the use of relatively high binder content which the requires the use of special admixture especially superplasticizer, so that it could enhance the flowability and stability characteristics of the fresh concrete [2]. In some cases, the use of special chemical admixtures is also required, which might increase the cost. However, this could be simply compensated with its valuable benefits due to less cement content needed as the cement could be replaced by mineral admixture such as fly ash. SCC leads to a well self-compacted concrete without external vibration and thus, producing high performance and quality of finished concrete products [3]. SCC turns to be quite economically where the casting time become shorter and also lower labour costs required due to direct placement of concrete. Therefore, there is no doubt SCC with its utmost advantages is an attractive and innovative construction material.

The benefits of SCC in terms of workability and quality of its end products are really worth in construction technology. On the contrary, in the hardened state, it acts very brittle without rebar as the conventional concrete does, where a total failure might occur due to a total loss of loading capacity as the crack initiated [3]. Thus, the new generation of SCC with the used of fibre such as steel fibre has come to the major development in self-compacting concrete technology to produce high strength self-compacting concrete to overcome the brittleness of SCC. The addition of steel fibres in self-compacting concrete forms a composite concrete called as steel fibre self-compacting concrete (SFSCC). Fibres are well known in bridging cracks and retard its propagation [4]. The addition of steel fibres extensively improves the tensile strength of SCC and also the ductility of concrete matrix [5].

Previous research in SFSCC shows that it could combines the benefits in the fresh state for easy concrete placement and shows a better performance in the hardened state compared with conventional concrete due to fibres addition. The application of using steel fiber in concrete is not new, but still, further attentions on SFSCC need to be given since the total potential of this material is still not totally examined. This is mainly caused by a lack of particular guidelines of SFSCC. The present guidelines for conventional concrete is not appropriate in designing SFSCC which has a noticeable nonlinear relationships because fibres start its function once cracking occurs in the concrete matrix [6].

The significant of this study is to investigate the workability and hardened properties of SFSCC so that it can help to improve the knowledge on self-compacting concrete industry when reinforced with randomly distributed steel fibres. The understanding knowledge regarding SFSCC could be used as an initiative to improve the weaknesses of conventional concrete or normal concrete (NC) technology.

Experimental

Materials and mix design

The type of cement used in this study was Ordinary Portland Cement (OPC) and the maximum size of aggregate used was 10 mm. Special superplasticizer was used named as Glenium ACE 389 RM. The end hooked steel fibres used in this study with aspect ratio (l/d) of 60 and length of 35mm. Class F fly ash produced by coal-burning electric utilities obtained from Tanjung Bin Power Plant was used. All the materials were used in developing the mix design which is based on EFNARC guidelines and modification of the previous research

Specimens

A total of 63 cubes (100x100x100mm), 21 cylinders (Ø=150mm, h=300mm), 21 prisms (100 x 100 x 500 mm) and 21 prisms (100 x 100 x 350 mm) were casted for 7 different mixtures labelled as NC, SCC, SFSCC-0.25%, SFSCC-0.50%, SFSCC-0.75%, SFSCC-1.0% and SFSCC-1.25%.

Fresh properties testing

This test consists of two different testing which was done in order to assess the flowability characteristics of the mixtures. Slump testing was conducted for NC while the slump flow testing was conducted for all SCC and SFSCC. All testing were carried out after the mixing process and before the concrete poured into the moulds.

Hardened properties testing

The test compares the properties between NC, SCC and SFSCC. The cube compressive test is carried out based on BS EN 12390-3:2009 tested at the age of 7 days, 14 days and 28 days. The second test is splitting tensile strength of cylindrical concrete specimens. The test was carried out in accordance to BS EN 12390-6:2009 tested after 28 days curing process. Another test was flexural test which is in accordance with BS EN 12390-5:2009 which also tested at the age of 28 days.

Flexural toughness testing

The flexural toughness performance of SFSCC is evaluated by using parameters derived from the load-deflection curve obtained by testing a simply supported beam under third-point loading. The bending test setup used in this study was based on ASTM C1609/C1609M-12 [7]. Specimens were made of prism shape with a dimension of 100x100x350 mm and the dimension arrangement is clearly detailed as in Figure 1. All specimens loaded and supported by the flexural test apparatus, as shown in Figure 2. A pair of LVDTs was mounted on a jig based on the ASTM C1609/C1609M-12 requirement to ensure accurate determination of the net deflection at the mid-span. The test were carried out in the 50 kN capacity electro-mechanical testing machine.

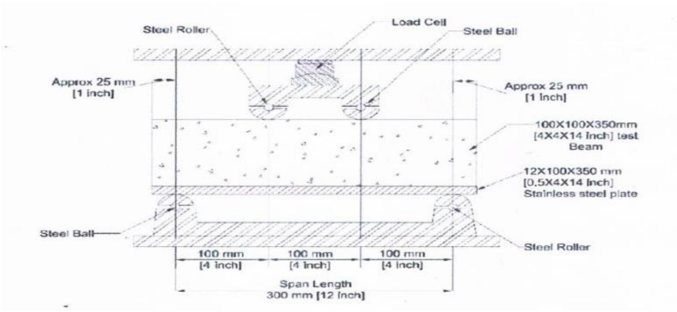

Figure 1: Dimension arrangement of flexural toughness test

Figure 2: Experimental Setup

Results and Discussions

Fresh properties

Figure 3 (a), (b) and (c) show the results obtained for the slump test and slump flow test. As shown in Table 1, the results for SCC and all SFSCC with fibres up to 1.25% indicate that the mixes produced are having self-compactability properties as the results are within the acceptable range of SCC criteria as given by EFNARC which is from 550 mm to 850 mm. In addition, the shape of flows also in a circular manner as can be seen in Figure 3, showing no segregation. However, the slump flow of the mixtures negatively affected by the inclusion of fibres which increasing the resistance of concrete to flow. The effects of fibres inclusion can be seen based on the slump flow diameter results which decreased from 810 mm to 680 mm. From the slump test observation for NC, the mode of slump obtained is true slump and the value is 50 mm which also satisfies the designed slump ranging from 30 mm to 60 mm.

Table 3: Results of fresh properties concrete

Mixture	NC	SCC	SFSCC-0.25	SFSCC-0.50	SFSCC-0.75	SFSCC-1.0	SFSCC-1.25
Slump/ Slump Flow (mm)	50	810	795	750	720	710	680

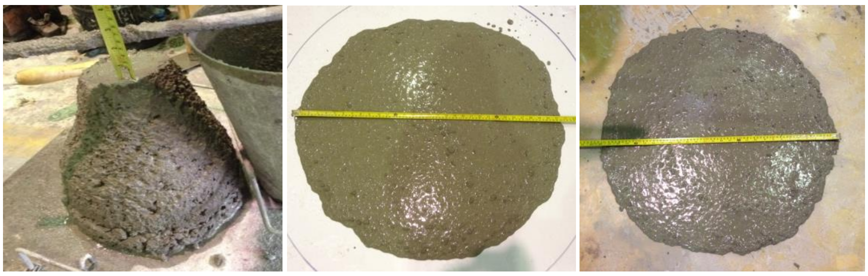

Figure 3 (a): Slump test for NC

Figure 3 (b): Slump flow test for SCC

Figure 3 (c): Slump flow test for SFSCC-1.0%

Compressive strength, tensile splitting strength and flexural strength

The results of compression test are presented in Figure 4. The average compressive strength at 7, 14 and 28 days for NC is the lowest compared to SCC and SFSCC as shown in Figure 4. At every age of testing, SFSCC-1.0% shows the highest compressive strength which shows 11.49% increment as compared to SCC and 15.56% compared to NC. The enhancement in compressive strength can be seen at every fibre volume fractions but it shows little decrement when the fibres added up to 1.25%. Therefore, SFSCC-1.0% is selected as an optimum steel fibre content which has higher average compressive strength of 47.66 MPa at 28 days.

Figure 5 reveals the results of flexural and tensile strength test. Both testing results show the same pattern increment of strength with corresponding fibre volume fraction. The gain in strength continues to occur from 0% up to 1.0% fibre volume fractions then it shows slightly decrease when fibres added is 1.25%. The average splitting tensile strength for NC is 4.29 MPa. SFSCC-1.0% with the highest splitting tensile strength shows 55.24% increment when 1.0% fibres added into the mixtures. The increment clearly indicates that steel fibres have a positive impact in increasing the tensile properties of concrete as fibres act to delay the opening of cracks [8]. The introduction of randomly distributed steel fibre in SCC significantly increased the flexural strength of SFSCC-1.0% fibres. The flexural strength for NC is 5.89 MPa, which is the lowest flexural strength that might due to the compaction problem in conventional concrete. Increment of flexural strength is from 14.26% to 59.25% compared to NC and this increment is totally affected by the fibres volume fractions.

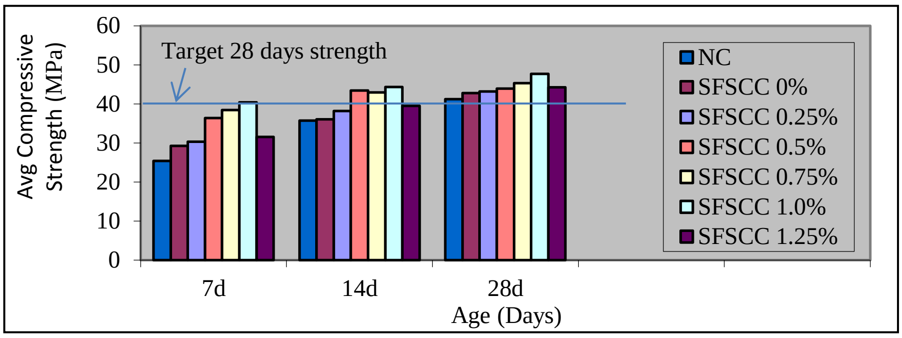

Figure 4: Compressive strength

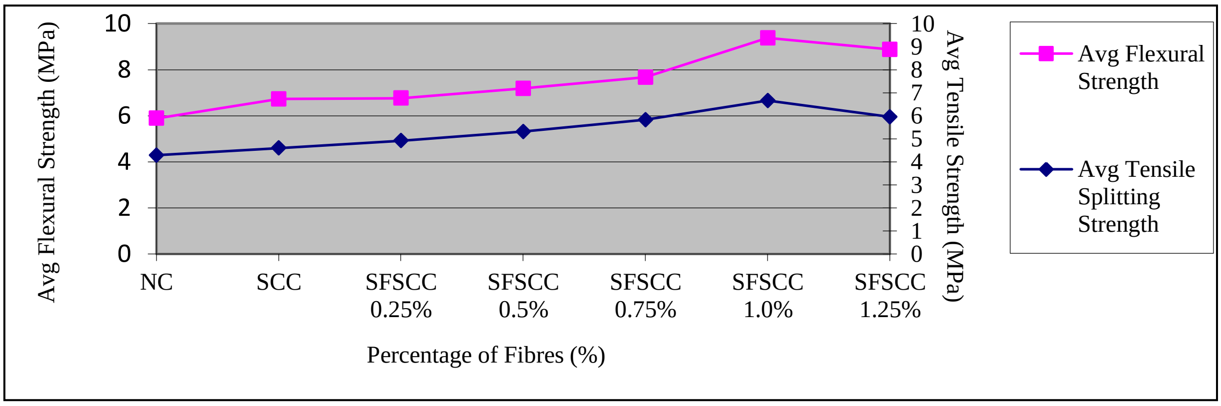

Figure 5: Relationship between flexural and tensile strength with fibre volume fraction

Flexural toughness

Toughness is the energy absorption capacity of test specimen due to the total area under the load-deflection curve up to a net deflection of L/150 of the span length. Based on the results from Table 2 and Figure 6, NC and SCC specimens which well-known having brittle characteristic, the recorded P_1 is equal to P_p and thus, f_1 and f_p is also the same. These two specimens also shows zero toughness indices after the first crack and it clearly reveals that concrete without fibres have a very low ductility characteristics to sustain more loads after the first crack occur, which then lead to a sudden concrete failure as been discussed earlier [3]. Meanwhile, all specimens which incorporated with an amount of steel fibre showed a different P_1 and P_P values where the load remain increased up to the peak load after first crack. Compared to NC and SCC, all SFSCC specimens showed fibre bridging action, where they do not break into two parts due to the action of steel fibres within the concrete matrix, thus allowing some energy absorption action by the residual strength in concrete.

Steel fibre is expected to act like a reinforcing bar which tends to show some plastic behavior. Therefore, the inclusion of steel fibre could create some amount of plastic behavior in the concrete matrix. The plastic behavior becomes the most vital factors in providing high residual strength in concrete which is very useful to resist cracks propagation and avoiding sudden failure. From Figure 6, the increasing amount of steel fibre in SCC could affect the performance of toughness characteristic. Besides, the study also found that SFSCC-1.0% has better toughness, T^D_{150} and T^D_{600}, which is higher than other fibrous concrete.

Based on the results obtained, steel fibre greatly improved the structural integrity of the concrete especially in absorbing relatively large amounts of energy before the ultimate failure, better resistance to propagation of crack, huge post-crack residual strength and ability to withstand large deformations compared to NC and SCC specimens.

Table 2: Flexural toughness results according to ASTM C1609/1609M-12

Parameter	**NC**	**SCC**	**SFSCC-0.25%**	**SFSCC-0.50%**	**SFSCC-0.75%**	**SFSCC-1.0%**	**SFSCC-1.25%**	**Unit**
1st Peak Load, P_1	12	12.2	12.6	15.2	16.9	18.5	17.4	kN
1st Peak Strength, F_1	3.6	3.66	3.78	4.56	5.07	5.55		N/mm²
Deflection at 1st Peak Load, δ_1	0.03	0.03	0.03	0.04	0.04	0.07	0.03	mm
Peak Load, Pp	12	12.2	12.9	16	19.7	26.9	21.9	kN
Peak Strength, *fp*	3.6	3.66	3.87	4.8	5.91	8.07		N/mm²
Deflection at Peak Load, *δp*	0.03	0.03	0.43	0.57	0.1	0.64	0.88	mm
Residual Load at Deflection of L/600, $P_{L/600}$	0	0	12.7	15.8	17	26	18.5	kN
Residual Strength at Deflection of L/600, $f_{L/600}$	0	0	3.81	4.74	5.1	7.8	5.55	N/mm²
Residual Load at Deflection of L/150, $P_{L/150}$	0	0	6.5	12.5	12.6	16	14	kN
Residual Strength at Deflection of L/150, $f_{L/150}$	0	0	1.95	3.75	3.78	4.8	4.2	N/mm²
Toughness at 0 to L/600, T^D_{600}	0.18	0.183	6.35	7.5	9.03	10	9.25	Joules
Toughness at 0 to L/150, T^D_{150}	0.18	0.183	20.5	28.6	31	42.9	36.69	Joules

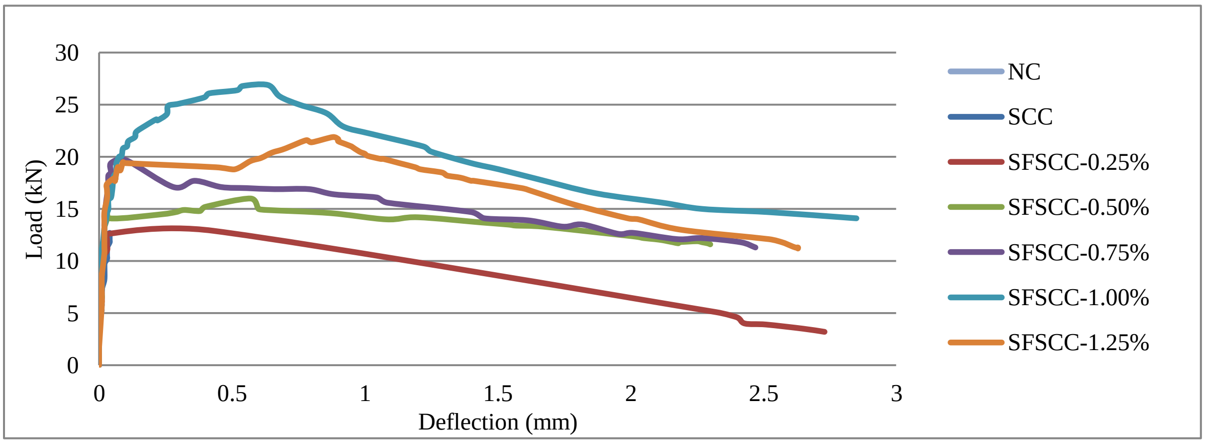

Figure 6: Load- deflection curves for toughness test

Conclusion

Overall conclusion that can be drawn from this study, the fresh properties of SCC is inversely affected where the slump flow diameter decrease with the increase in steel fiber content. However, all mixes fulfilled the SCC requirement as stated in European Guidelines and could be classified as SCC. At the same time, SCC and SFSCC mixes were easily poured into the mould and yet the strength performance was found better than normal vibrated concrete. Compare to the plain concrete, all SFSCC demonstrated a significant improvement in splitting tensile strength and flexural strength but the effect on compressive strength was very little. Based on all testing that have been conducted, the performance of SFSCC specimens were found to increase extensively for the specimens with percentage fibres of 1.0%. As a result, it can be concluded that the optimum volume fraction of fibre for a better strength development and workability was found to be 1.0%. Most of the specimens have shown that addition of steel fibres in SCC demonstrates higher residual strength and toughness parameter compare to NC and SCC. On top of that, the amount of different percentage of steel fiber in SCC clearly differentiates the levels of toughness performance. Higher amount of fiber leads to a better toughness performance and yet even with a small amount of fibres could overcome the problem of NC and SCC which generally produced very brittle characteristics.

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