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Fresh and Hardened Properties of Steel Fiber-Reinforced Self-Consolidating Concrete

Dr. Maan S. Hassan
Building and Construction Engineering Dept., University of Technology / Baghdad.
Email: maan_s_h@yahoo.co.uk
Dr. Iqpal N. Gorgis
Building and Construction Engineering Dept., University of Technology / Baghdad.
Aymn H. Ali
Building and Construction Engineering Dept., University of Technology / Baghdad.

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ABSTRACT

The main aim of this research is to study the effect of using hooked end steel fiber on the fresh and hardened properties of self-consolidating concrete. The experimental work includes two stages. First stage involved conducting several trial mixes and then choosing the one that conform to the international standards in terms of fresh properties. Second stage concerned on the compressive, flexural tensile and splitting tensile strengths evaluation of the selected mixes, at 28 and 90 days. Four concrete mixes were obtained and evaluated. They were similar in mix proportions and differ only in volume fractions of steel fibers incorporated: 0%, 0.5%, 1%, and 1.5%.

Results showed that adding hooked steel fibers adversely affect SCC workability and thus more dosage of SP should be added to stay within the standard limits. Similar to conventional HPC, the presence of steel fibers with SCC provide slight increase in compressive strength at 28 days, (up to 11%), while significant enhancement in tensile properties were observed (up to 68% and 80% for splitting and flexural strength respectively). Flexural strength (i.e. modulus of rapture) was generally still higher than splitting testing results in a decreasing order. This order is still applicable in SCC even with the presence of steel fibers.

Keywords: Self-Consolidating Concrete (SCC); fresh properties; compressive strength; splitting tensile; Modulus of Rupture; steel fibers.

خواص الخرسانة ذاتية الرص الطرية والمتصلبة والمعززة بالألياف الفولاذية

الخلاصة

ان الهدف الرئيسي من هذا البحث هو دراسة تأثير استعمال الالياف الفولاذية المعقوفة النهايات على الخواص الطرية والمتصلبة للخرسانة الذاتية الرص . اشتمل البرنامج العملي على مرحلتين: الاولى اجراء عدد من الخلطات التجريبية للوصول الى الخلطة المثلى والتي تطابق المواصفات العالمية المعتمدة للخرسانة ذاتية الرص، الثانية تضمنت تقييم بعض الخواص الميكانيكية (الانضغاط والانثناء والانفلاق) وبعمر 28 و 90 يوم.

تم اضافة اربعة نسب من الالياف الفولاذية للحصول على اربع خلطات مع الاحتفاظ بنفس المكونات وقابلية التشغيل للخلطة التجريبية وتغيير نسب المادة المضافة فقط. وقد كانت النسب الحجمية للألياف الفولاذية المستعملة 0%، 0.5%، 1%، و 1.5%.

بينت النتائج ان وجود الالياف الفولاذية ذات النهايات المعقوفة يؤثر سلبا على قيم قابلية التشغيلية ولذلك يتطلب اضافة نسبة اكبر من الملدن المتفوق للمحافظة على القابلية التشغيلية للخلطة الخرسانية ضمن الحدود المقبولة. ان اضافة الالياف الى الخرسانة ذاتية الرص يؤثر بطريقة مشابهه لدوره في الخرسانة عالية الاداء فهو يؤدي الى تحسين طفيف في مقاومة الانضغاط .حيث كان معدل الزيادة في مقاومة الانضغاط للخلطات التي تحوي نسبة الياف 1% وبعمر 28 يوم حوالي 11% وفي مقاومة الانفلاق حوالي 68%. وكان تأثير الالياف ملحوظا في مقاومة الانثناء وحققت بشكل عام نتائج اعلى من مقاومة الانفلاق وكانت الزيادة حوالي 80%.

INTRODUCTION

Self-Consolidation Concrete (SCC) defined as a concrete that is able to flow in the interior of the formwork, filling it in a natural manner and passing through the reinforcing bars and other obstacles, flowing and consolidating under the action of its own weight [1]. SCC was originally developed with the intention of simplifying casting operations in Civil Engineering constructions of large dimensions, where high percentage of reinforcement or complex geometries difficult concrete flow. Soon it became clear, though, that the great productivity increase associated to SCC technology also habilitates it as a good solution for housing construction, precast industry and other applications [2].

The fresh SCC requirements are mainly resumed to the filling ability, the passing capacity and the resistance to segregation. These properties are evaluated at the mix design stage, based on a series of tests in fresh samples with distinct apparatus **(EFNARC 2002)**[3]. Self-compacting ability in concrete depends on the performance level reached by the fresh mix in these tests.

The introduction of steel fibers in concrete is another issue of interest on the concrete technology. Steel fibers proved to have the potential to increase the post-cracking energy absorption capacity of cement based materials, enhancing the ductile character of concrete structures behavior, mainly of those with high redundant supports [4].

Plain concrete is a brittle material with low tensile strength and poor fracture toughness; it imposes numerous design constraints and often leads to long term durability problems. Therefore, discrete fibers with adequate mechanical properties can be added in fiber reinforced concrete (FRC) to improve toughness; increase resistance to impact; reduce spalling of the reinforcement cover; and improve abrasion resistance and flexural and shear strength[5].

In plain SCC and similar brittle materials, structural cracks (micro-cracks) that develop even before loading, particularly due to drying shrinkage, cause volume change. The width of these initial cracks seldom exceeds a few micros, but their other two dimensions may be of higher magnitude. When loaded, the micro cracks propagate and open up, and owing to the effect of stress concentration, additional cracks form in places of minor defects. The structural cracks proceed slowly or by tiny jumps owing to the various obstacles that retard them. The development of such micro cracks is the main cause of inelastic deformations in concrete [6].

The objective of this study is to evaluate the effects of hooked end steel fiber on the fresh and hardened properties of SCC. Moreover, locally source raw materials will be investigated for possible utilization to produce SCC concrete that conform international standards [3&7] as presented in Table (1).

Research Significance

Different types of steel fibers are commonly included in concrete to enhance the flexural behavior and in particular post cracking zone. However, limited understanding regarding the factors influences the combined effect of SCC composite and steel fibers due to possible conflict of these two factors on the resultant fresh and hardened properties of such materials. More insight on this combined effect and the influence of fiber content on the resulted workability, compressive, and flexural behavior my help to increase its use and practical applications, and engineers that utilize SCC in different structural applications and projects.

Experimental work

Material and concrete composition

In order to achieve the scopes of this study, four SCC concrete mixes were produced. Fine aggregate (Zone 2) and coarse aggregate, with max size of 14mm conform to Iraqi specification No.45/1984[8] were used. Limestone powder of 100 kg/m^3 with a surface area of 3100 cm^2/gm **(**Blain method) and silica fume of 50 kg/m^3 were implemented to increase the volume of mortar and then enhance workability. Cement content was 400 kg/m^3, chemical and physical properties of both cement and silica fume are given in Table (2-4).

Hooked ends steel fibers which are commercially known as ‘Sika Fibers’ were also used throughout the experimental program. Table (6) indicates the properties of steel fiber used.

Table (1) Test methods for workability properties of SCC [3&7]

No.	Test	Range
1	Slump flow	650-800 mm
2	T50 cm slump flow	2-5 sec
3	J-Ring flow	580–780 mm
4	V-funnel	6- 12 sec
5	Increase in V-funnel at T_5 min	+3 sec, max
6	L-box (H_2/H_1)*	0.8- 1.0
*H_2/H_1 the height of concrete at the end of horizontal section to that remaining in the vertical section of L-box.		

Table(2): Chemical composition and main compounds of cement* and silica fume.**

Oxide composition	Abbreviatio n	Cement %-by weight	Limits of IQS. No. 5/1984	Silica fume	ASTM C1240-05[9]
Lime	CaO	61.85	-	0.85	<1%
Silica	SiO_2	21.77	-	91.54	Min. 85%
Alumina	Al_2O_3	4.65	-	0.72	<1%
Iron oxide	Fe_2O_3	3.35	-	0.47	< 2.5%
Sulphate	SO_3	2.55	$\leq$ 2.8%	0.01	
Magnesia	MgO	3.06	$\leq$ 5%	0.16	< 0.2%
Loss on Ignition	L.O.I.	2.16	$\leq$ 4%	4.36	Max. 6%
Lime saturation factor	L.S.F.	0.87	0.66-1.02	…	
Insoluble residue	I.R.	0.88	$\leq$ 1.5	…	
Main compounds (Bouge eq.)		% by weight of cement			
Tricalcium silicate (C_3S)		43.88			
Diacalcium silicate (C_2S)		29.43			
Tricalcium aluminate (C_3A)		6.51			
Tetracalcium aluminoferrite (C_4AF)		10.18			

**Chemical and physical analysis for silica fume were conducted by National Center for Construction Laboratories and Researches

Mix Design

For the production of SCC, the mix design should be performed so that the predefined properties of the fresh concrete are reached. The basic components of the mix composition of SCC are the same as those used in conventional concrete. However, to obtain the requested properties of fresh concrete in SCC, a higher proportion of fine materials and the incorporation of chemical admixtures are necessary**[11]**. The mix constituents shall be identified so that segregation and bleeding are prevented while workability enhanced. Initially, JAPNESE**[12]** design procedure is followed for primary identification of mix proportions, which help to reduce number of trial mix cycles required to recognize precise material fractions. A serious of trial mixes were then carried out and final four concrete mixes were obtained in compliance with standard acceptable limits as indicated in Table (1). Resultant compressive strengths were above 50 MPa and workability values were above 650 mm and up to 790 mm, for all mixes. The details of the final concrete mixes are given in Table (8).

Table (3) Physical properties of ordinary Portland cement*

Properties	Test results	IOS 5:1984 limits
Fineness (Blain) m^2/kg	310	>230
Setting time (Vicat's apparatus) Initial setting time, hrs: min. Final setting time, hrs: min.	 1.58 3.28	 ≥ 45 min. ≤10 hours
Mortar Compressive strength (MPa) at: 3 days 7 days	 19.4 29.75	 > 15 > 23
Soundness: autoclave %	0.19	< 0.8

*Chemical and physical analysis for cement was carried out in the Central Organization for Standardization and Quality Control.

Table (4) Physical properties of silica fume

Property	Result	ASTM C1240-03
Strength activity index	106%	≥ 105
Specific gravity, kg/m^3	2.2	_
Physical form	powder	_
Color	grey	_
Size	0.15	~0.15 micron
Density	0.5	0.5±0.1kg/liter(dry bulk)
Moisture	0%	< 2%
Specific surface, m^2/g	16	≥ 15

Table (5): Properties of the used steel fibers*.

Description	Hooked end
Length	30 mm
Diameter	0.5 mm
Aspect ratio (***L/D***)	60
Relative Density	7800 kg/m^3
Ultimate Tensile Strength	1180 MPa

*According to manufacturer

Mixing, curing and fresh properties test methods

The concrete was mixed using a drum mixer of 50 L capacity. In this study, the procedure of mixing follows the laboratory mixing procedure outlined by Emborg[13], and modified by Al-Jabri[14]as follows: 1) Adding the fine aggregate to the mixer with 1/3water, and mixing for 1minute; 2) Adding the powder (cement+ limestone (Table 6) +silica fume) with another 1/3mixing water, and mixing for 1 minute; 3) After that, the coarse aggregate is added with the last 1/3mixing water and 1/3 of superplasticizer (Table 7), and mixing for 1.5 minutes; 4) Then, the remaining 2/3 of the superplasticizer is added and mixed for 1.5 minutes. The mixture is then discharged, cast and tested. The total time of mixing is 5 minutes.

Table (6): Chemical Composition and physical properties of Limestone dust.

Chemical Properties	
Oxides	Content %
CaO	60.01
Fe_2O_3	0.2
Al_2O_3	0.61
SiO_2	1.22
MgO	0.32
SO_3	0.1
L.O.I	36.5
Physical Properties	
Color	White
Fineness (Blain)	3100

Table (7): Technical description of Glenium 51

Basis	modified polycarboxylic ether
Appearance	Light brown /viscous liquid
Specific gravity	1.1 at 20°C
PH	6.6
Viscosity	128 ± 30 cps @ 20 °C
Storage	Should be stored in original containers and at above 5°C
Transport	Not classified as dangerous
Labeling	Not hazard label required

Table (8) Mix proportions for fiber reinforced SCC

Mixes	**Cement kg/m^3**	**Silica fume kg/m**	**LSP kg/m^3 Table 6**	**Total powder Kg/m^3**	**w/c 0.4**	**Sand kg/m^3**	**Crushed Gravel kg / m^3**	**S.P. L/m^3 Table7**	**Steel Fiber kg/m3**
SCC0%	400	50	100	550	160	805	805	15	0
FR-SCC 0.5%	400	50	100	550	160	805	805	16.5	42
FR-SCC 1%	400	50	100	550	160	805	805	17.5	84
FR-SCC 1.5%	400	50	100	550	160	805	805	19	126

The workability tests of the fresh concrete were measured, for the four mixes were made on fresh concrete immediately after mixing including. Measured fresh properties include: slump flow, J- ring, V-funnel and L-box tests. The tests were carried out to determine the w/cm ratio that capable to keep all these fiber reinforced SCC within the standard limits [3&7]. Workability tests for all concretes were determined in compliance with ASTM C1611-09[15]and ASTM C1621-09[16]. Table (9) shows workability measurement values for all concrete mixes, including slump,T_{500}, J-Ring, V-funnel, and L-box

Table (9) Effect of steel fiber on fresh properties of SCC

Mix	**Slump flow**		**J-ring (mm)**	**L – box H1/H2**	**V-funnel (sec)**
	D (mm)	T500 (sec)			
Ref SCC 0%	775	3.5	755	0.96	6.2
SF-SCC 0.5%	738	3.8	716	0.91	7.5
SF-SCC 1%	698	4.2	681	0.86	9.3
SF-SCC 1.5%	669	4.5	657	0.82	11

Casting and Curing of SCC

The steel molds (100×100×100 mm cubes) for compression tests and (d=100, h=200 mm) cylinders for splitting test, and (100× 100× 400 mm prisms) for flexural test were well cleaned. The internal faces were thoroughly oiled to avoid adhesion with the concrete after hardening. SCC mixes do not require compacting, so the mixes were poured into the tight steel molds (cubes, cylinders and prisms) until these molds were fully filled without any compaction. The moulds were covered with polyethylene sheet for about 24 hours to prevent loss of moisture from the surface and to avoid plastic shrinkage cracking. Then the specimens were demoulded for curing. Specimens were kept after demoulding in plastic bags sealed and saturated until the age of test.

Experimental Tests

Compressive Strength

The compressive strength was determined according to **B.S 1881:part 116, 1989**[17] .The average compressive strength of three cube specimens was recorded. This test was conducted at 7, 28 and 90 days of age.

Splitting Tensile Strength

Test was done according to **ASTM C496 –07**[18] and the average splitting tensile strength of three specimens was recorded. This test was conducted at ages 28, and 90 days.

Modulus of Rupture

Third point loading test according to **ASTM C78-02**[19] was carried out on simply supported prisms. The specimens were tested at 28, and 90 days, and the rate of loading was about 0.015 MPa/sec. The average strength of three specimens was recorded. The fracture occurs within the central third for all specimens.

Results and Discussions

During the conductive of the trial mixes of this experiment, a reduction in workability were observed associated with adding more steel fibers, subsequently, more water and/or higher dosage of high range water reducing agent were added to keep the slump, J-ring, L-box, and V-funnel test values, as a workability measurement indicator, as much as possible within the acceptable standard limits. Accordingly, it is suggest that, from practical point of view, steel fibers have definite adverse effect on workability properties of fresh SCC. Consequently, higher chemical admixture dosages should be added. This finding is in agreement with other research work [20&21].

Table (10) and Figures (1) to (6) show the results of compressive strength, splitting tensile strength, and Modulus of Rupture for all SCC concrete mixes, with and without steel fibers. An increase was observed for all strengths, which is referred to the continuous hydration process leading to densify and producing more hydrated calcium silicate in concrete matrix.

Compressive Strength

The average results of compressive strength test at 7, 28, and 90 days gained from cubes were tabulated in Table (10) and Figure (1). As observed from results, there were slightly developments in the compressive strength (up to 11 %) for SCC reinforced with fibers when compared with non fibrous SCC specimens. Observed behavior is in agreement with other researchers [14, 22 and 23].

Table (10) Effect of Steel Fiber on the Hardened properties of SCC

Mixes	**Compressive strength(Mpa)**			**Splitting tensile strength (Mpa)**		**Modulus of Rupture(Mpa)**	
	7 days	28 days	90 days	28 days	90 days	28 days	90 days
Ref SCC 0%	40.3	55	68.2	3.5	4.1	5.6	6.5
SF-SCC 0.5%	41.6	57.3	72.6	4.5	5.1	7.2	8.5
SF-SCC 1%	43.2	59.5	74.1	5.4	5.9	9.2	10.1
SF-SCC 1.5%	45.5	61.2	76.3	6.3	6.9	10.2	11.9

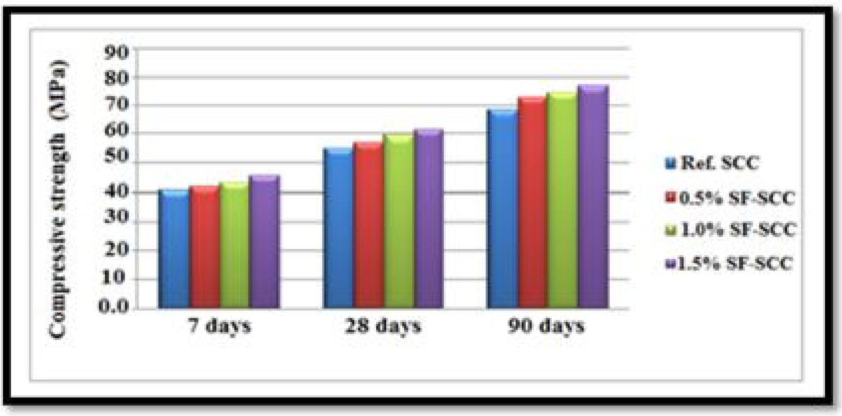


Figure (1): Relationship between compressive strength of SF-SCC with Time.

The percent of increase in the compressive strength were 4.1%, 8.9% and 11.27 % of reference concrete reinforced with volume percent of 0.5%, 1%, and 1.5% of hooked end steel fibers at 28days respectively. While, the percent of the increase in the compressive strength were 6.5%, 8.6% and 11.8% of reference concretes at 90 days. Figure 2 reveals that when V_f increased from 0, 0.5, 1, to 1.5%, similar slight rate of increase in compressive strength for all ages.

Splitting Tensile Strength

The average results of tensile strength test at 28 and 90 days gained from cylinders were listed in Table (10) and indicated in Figures 3 and 4.Unlike compressive strength, splitting tensile strength test results clearly showed the benefit of using fibers to reinforced concrete matrix. The trends illustrated a definite increase in tensile capacity attributable to higher fiber content.

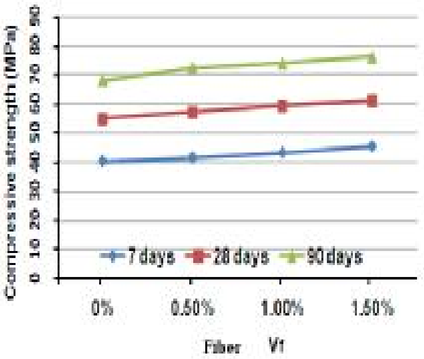
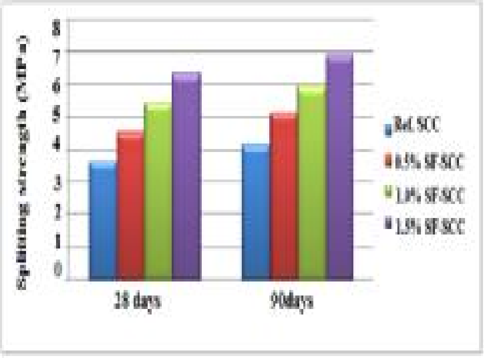


Figure (2): Effect of steel fiber content on compressive strength of SCC.



Figure(3): Relationship between Splitting strength of SF-SCC with Time.

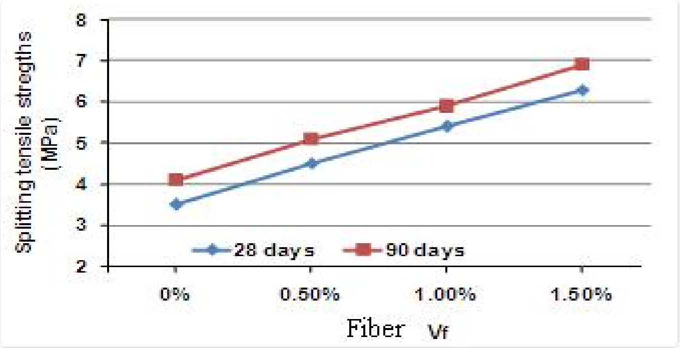


Figure (4): Effect of steel fiber content on splitting tensile strengths of SCC.

The tested specimens for plain concrete failed suddenly and split into two separate parts, while the cylinders with fibers was cracked at failure without separation. All fibrous mixes demonstrated higher splitting tensile strength relative to plain mix. The percent of increase in splitting tensile strength was found to be increased with the increase in V_f %. With an increase in fiber content, the fibers become more densely spaced, and they may hinder growth of micro cracks within the brittle matrix leading to increase splitting tensile strength of the fiber reinforced SCC.

The percentage of increases in tensile strength was 28.5%, 54.3% and 80% at 28 days and 24%, 43.9% and 68.3% at 90 days, of reference SCC (i.e. without fibers), with V_f 0.5%, 1% and 1.5% of steel fibers. The SF-SCC mix demonstrated, comparatively, higher splitting tensile strength relative to reference mix**.** Moreover, comparable to compressive behavior, figure 4 also shows similar rate of increase in tensile strength associated with the increase of v_f regardless the age of test 28 or 90, indicating that the same v_f of steel fiber role no matter the age of test.

Modulus of Rupture

The flexural strength results for the different mixes were presented in Table (10) and indicated in Figure 5**.** It is worthwhile to note that the fibrous SCC mixes stand out higher in the flexural strength when compared to the non-fibrous SCC mixes. SCC mixes reinforced with steel fibers showed significant improvement in flexural strength at all ages relative to the reference mixes without fibers. This is mainly due to the increase in crack resistance of the composite and to the ability of fibers to resist forces post-cracking stages, leading to prevent or at least delay matrix failures. The percent of increase in flexural strength was found to be increase with the increase in steel fiber content as indicated in Figure 6.

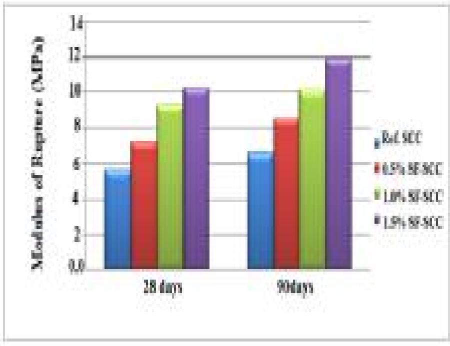


Figure (5): Relationship between Modulus of Rupture Strength of SF-SCC with Time.

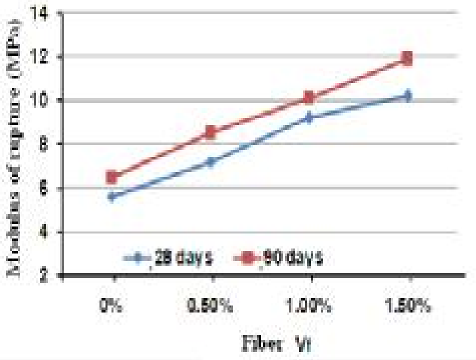


Figure (6): Effect of steel fiber content on the flexural tensile strengths of SCC.

The percent of increase in flexural strength were 28.6%, 64.2%, and 82.1% at 28 days; and 30.7, 55.4 and 83.1% at 90 days; of reference SCC reinforced with 0.5%, 1% and 1.5% V_f respectively.

Other studies [24&25] investigate the role of adding steel fibers to high-performance concrete and in comparable to what has been revealed in this research work it can be concluded that there are no significant differences in compressive and tensile behaviors between SCC and conventional high-strength concretes.

CONCLUSIONS

Based on the experimental work results in this investigation, the following conclusions can be drawn:

1. Steel fiber has definite adverse effect on all workability properties of fresh SCC. Consequently, higher water demand, or chemical admixture dosages should be added to keep the targeted workability values constant.
2. All SCC mixes that incorporated hooked end steel fiber have slightly higher compressive strength, (up to 11%), than reference SCC without steel fiber at all curing age.
3. All SCC fiber mixes demonstrated higher splitting (up to 80% and 68% at 28 days and 90 days respectively), and flexural tensile strengths (up to 82% and 82% at 28 days and 90 days respectively), relative to plain mixes. The strengths increased as the fiber content increased.
4. Among the used tensile strength testing methods, as expected, the results of modulus of rapture was generally higher than splitting testing results in a decreasing order. This order still applicable even with the presence of steel fibers (i.e. the presence of steel fibers does not change this fact).

This study demonstrates the beneficial combined effect of steel fiber and SCC on the fresh and key hardened properties of SCC. The limited understanding regarding the factors influence such combined effect may lead to reduce field and practical utilities of FR-SCC, and hence provide more insight would be useful for the engineers that utilize SCC in different structural applications and projects.

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