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Properties of Fresh and Hardened High Strength Steel Fibres Reinforced Self-Compacted Concrete

Saad Ali Al-Ta'an[1] , Wail Nourildean Al-Rifaie[2] , Khalid Ahmed Al-Neimee[3]
Civil Engineering Department, Collage of Engineering, University of Mosul, Mosul, Iraq
E-Mail: Saadaltaan@yahoo.com
Civil Engineering Department, Collage of Engineering, Tikrit University, Salahaldeen, Iraq
E-Mail: wnrifaie@yahoo.com
Civil Engineering Department, Collage of Engineering, University of Mosul, Mosul, Iraq
E-Mail: Kalid.engg2013@gmail.com

Abstract

Fresh and hardened properties of high strength steel fibrous self-compacted concrete were studied in this investigation. One reference high strength self-compacted concrete mix is used, with five percent (by weight of cement) silica fume and eight percent of the cement replaced by limestone powder. Three steel fibres percentages by volume of concrete are used (0.4, 0.8, and 1.2). The used steel fibres were a shelled Harex type with irregular cross-section, equivalent diameter of 0.9278 mm, and 32 mm long. Super plasticizer was used to improve the workability and flow ability of the mixes. The test results showed that the presence of steel fibres decrease the flow ability, and increase the time of spreading, segregation, and passing ability of the fresh concrete. For the fibres percentages used, the fresh properties were within the recommended specifications for the self-compacted concrete. The test results showed an early strength development rate more than that for plain normal concrete due to the presence of the fine materials. As for normal concrete, the test results showed also that the increase in the splitting strength is more than the increase in the compressive strength due to the presence of the steel fibres. The brittle mode of failure of the plain unreinforced specimens changed to a ductile one due to the presence of the steel fibres.

Keywords: Compression, limestone powder, Self-compacted concrete, Silica fume, splitting, Steel fibres, Strength.

خواص الخرسانة الطرية والمتصلبة الليفية عالية المقاومة ذاتية الرص

الخلاصة

في هذا البحث تم دراسة خواص الخرسانة الطرية والمتصلبة الليفية عالية المقاومة وذاتية الرص. استعملت خلطة مرجعية واحدة للخرسانة عالية المقاومة، مع 5% من وزن الأسمنت رماد سيليكا وتم تعويض 8% من وزن الأسمنت بمسحوق الحجر الجيري. كما استعملت ثلاث نسب مئوية (0.4، 0.8 و 1.2) من حجم الخرسانة ألياف فولاذية من نوع الهاركس القشرية غير منتظمة الشكل بقطر مكافئ 0,9278 ملم وبطول 32ملم. استعمل أيضا ملدن فائق لتحسين قابلية التشغيل والجريان للخرسانة. أظهرت نتائج الفحوصات أن الألياف الفولاذية تقلل من قابلية الجريان للخرسانة الطرية وتزيد من وقت الانتشار، العزل والمرور. ولكن الخواص الطرية لجميع الخلطات الخرسانية المستعملة حققت المواصفات المطلوبة للخرسانة ذاتية الرص. كما أظهرت نتائج الفحص تطورا لمقاومة الانضغاط أكثر من الخرسانة العادية بسبب وجود المواد الناعمة. وكما في حالة الخرسانة العادية أظهرت النتائج أن الزيادة في مقاومة الانشطار أكثر منها في مقاومة الانضغاط بسبب وجود الألياف الفولاذية. نمط الفشل القصف للخرسانة العادية تحول إلى فشل مطيلي بسبب وجود الألياف الفولاذية أيضا.

الكلمات الدالة: الانضغاط، مسحوق الحجر الجيري، خرسانة ذاتية الرص،رماد السليكا، الانشطار، ألياف فولاذية، مقاومة.

Notations

B_j Difference between the heights of concrete at the periphery and at the centre of the J-ring.

d_f Fibre diameter (mm)

D_{avg} Average spread diameter (mm)

f_c' Cylinder strength MPa

f_{ct} Cylinder strength at time (t) MPa

f_{sp} Splitting strength (MPa)

l_f Fibre length (mm)

t Age (days)

T_o Time required for emptying the funnel (sec)

T_5 Time required for emptying the funnel for the second time (sec)

T_{500} Time required to reach the 500 mm diameter

V_f Fibres volume fraction

Introduction

Fibre reinforced concrete (FRC) is a concrete with a tensile strength, flexural strength, flexural toughness, cracking resistance, and strain capacity more than those of plain concrete. Moreover, it is characterized by multiple cracking, well-defined post cracking behavior, and a ductile mode of failure under all types of loading [1,2]. Self-compacting concrete (SCC) is a concrete with good flow, spreading, and passing abilities and a good resistance to segregation[3,4]. High strength fibre reinforced self-compacting concrete (HFRSCC), can be considered as a high performance hybrid of high strength fibre reinforced and self-compacting concrete, which retain the properties of both concretes.

It was shown by Miao et al. [5], that self-compacted steel fibre reinforced concrete can be produced with a good fluidity and without bleeding and segregation by using 52% and 70% of the weight of cement, slag and fly ash respectively. Three volume percentages (0.5, 1, and 1.5) of hooked steel fibres (aspect ratio =60) were used. The test results showed that, there was an improvement in the compressive strength up to 20% over the plain concrete, and the fibre / plain concrete strength ratio decreased with time. The flexural strength and toughness of the produced mixes increased with the fibres percentage.

An investigation was performed by Rao and Ravindra [6], to compare the properties of plain self-compacting concrete (SCC) with (SCC) with steel fibres having a diameter of 0.92 mm. One control (SCC) and ten (SCC) mixes with steel fibres were investigated. Thirty percent of the Cement was replaced by Class F fly ash, and two types of plasticizers were used. The variables were the aspect ratio (15, 25 and 35) and the volume percentage of the fibres (0.5, 1.0, and 1.5). The test results showed that all the mixes can be considered as SCC, although all the mixes satisfy the suggested lower and upper limits[3]. The fibres inclusion did not significantly affect the measured compressive, splitting, and flexural strength. However, the strength and ductility of the fibre reinforced (SCC) specimens increased substantially in the case of specimens with v_f =1% and aspect ratio of 25.

The effect of the fibre type on the rheological and fresh properties of self-compacting concrete was studied by Ozbay et al. [7]. One percent by volume of steel, polypropylene, and polyvinyl alcohol fibres were used, all the three types were of relatively similar sizes. Forty percent of the binder was replaced by fly ash. It was found that steel fibre reinforced SCC can be produced by increasing the amount of high range water reducer. While, polypropylene and polyvinyl fibre reinforced SCC cannot be produced even if the amount of the high range water reducer is increased.

Bohnemann and Brameshuber [8], developed high-strength self-consolidating concretes of a strength up to 115 MPa. A standardized Portland cement was used fly ash (dry bottom furnace) and a high effective super plasticizer based on polycarboxylate ether were applied. Sand with a maximum particle size of 2 mm and a basalt split within the range of 2 mm up to 16 mm were used. Additionally silica slurry with 50 M.-% solid content of amorphous silicon dioxide was added.

High-strength self-consolidating mortars (HSCM) were optimized on a laboratory scale regarding the flow behavior. The HSCC were prepared by adding the coarse aggregate. The results for the stress-strain behavior for compression, tension, shrinkage and creep were comparable to those of high-strength vibrated concretes. Overall, the investigations have shown that SCC can be designed as high-strength concretes by using silica fume.

The aim of this study is to assess the possibility of producing high strength (SCC) with low fines percentage reinforced with steel fibres of low aspect ratio and varying volume percentages. The study aimed also to find out the effect of the steel fibres on the fresh and hardened properties of the produced mixes.

Experimental Program

Materials

Many mixes were tried to obtain the target cylinder compressive strength (70 MPa). The final adopted mix proportions by weight were (0.92:0.08:0.05:1.18:1.46: 0.3:0.015) which represent (C:L:SF:S:G: W/C:SP), as shown in Table (1). Ordinary Portland cement conforming to BS 12[9], eight percent by weight of the cement was replaced by limestone powder passing sieve No. 200 (75 microns). The limestone powder used to act as filler, increase the flow ability, and decrease friction between the mix constituents. Silica fume is used as five percent of the weight of cement to increase the strength of the mix, the chemical and physical properties are shown in Tables (2) and (3)[10], Fine aggregate with a fineness modulus of 3.1 and coarse aggregate with maximum aggregate size of (10 mm) were used which are conforming to BS 812 [11]. The mix proportions were chosen to produce a nominal cylinder compressive strength of 70MPa. Structuro 504E was used as a super plasticizer whose physical properties are shown in Table (4). The dosage was adjusted as shown in Table (1) to satisfy the SCC specifications [4].

Harex steel fibres of shelled deformed cross section, with a length l_f of 32 mm, equivalent diameter of 0.9278 mm, and aspect ratio of (l_f / d_f =36.5), and three volume percentages (v_f = 0.4, 0.8, and 1.2) were used. To get optimum strength improvement, the fibres length should be more than the maximum aggregate size, which in this case 10 mm.

Table 1. Mix Proportions

Physical properties	Standard limits	SF
Specific surface,min,(m^2/g)	15	20
Accelerated pozzolanic strength activity index: with Portland cement at 7 days, min percent of control	105	146
Percent retained on 45µm (NO.325), max , %	10	7

Table 2. Chemical properties of the used silica fume*

Mix. No.	V_f %	Plasticizer By weight of cement %	Mix proportions by weight
M0.0-1.5	0	1.5	0.92 Cement 0.08 Limestone 0.05 silica fume 1.18 Sand 1.46 Gravel 0.3 Water
M0.4-1.8	0.4	1.8	
M0.8-2.0	0.8	2.0	
M1.2-2.5	1.2	2.5	

Table 3. Physical properties of the used silica fume with the ASTM 1240-03 limits[10]

Oxides	Content (%)	ASTM C1240-03 [10]
SiO_2	95.95	≥ 85
Al_2O_3	0.02	
Fe_2O_3	1.10	
CaO	1.21	
MgO	0.10	
SO_3	0.22	≤4
L.O.I	2.50	≤ 6

Table 4. Properties of the Structuro 504 E Hyper plasticizer*

Colour	Light brown
Density	1.05
Physical state	Liquid
Dose	(0.21-3.15) % of the cement weight
PH Value	6.5
Chloride content	Nil

***Provided by the manufacturer**

Methods of Testing the Fresh Concrete

The following tests were used to measure the properties of the fresh concrete; the slump flow test for the spreading and filling abilities, J-ring test for the passing ability, V-funnel test for the segregation resistance and the L-box for the passing ability. The description of these tests and the corresponding limitations is cited in References [3,4].

Specimens for Hardened concrete

The specimens used for measuring the properties of the hardened concrete were; thirty cylinders (150×300 mm) for the compressive and twelve cylinders for the splitting strength.

Results and Discussion

Properties of Fresh Concrete

Flow and filling abilities

Table (5), and Figure (1) show that the steel fibres increased the time T_{500} for the three fibre mixes. Table (5) and Figure (2) show also that the average spreading diameter D_{avg} for the three fibres reinforced SCC mixes did not show a general trend with the fibres volume and this may be attributed to the used relatively high dosage of the super plasticizer. However, both T_{500} and D_{avg} for the four SCC mixes are within the specified limitations [3,4], which means that the four mixes have a reliable flow and filling abilities. Figures (1) and (2) show the overall limits for T_{500} and D_{avg} .

Table 5. Spreading ability of the high strength self-compacted concrete mixes (Slump flow test)

Mix No.	T_{500}(sec)	Limits[4] T_{500}	$D_{max.}$ (mm)	$D_{perp.}$ (mm)	$D_{avg.}$ (mm)	Limits [4] $D_{avg.}$
M0.0-1.5	2.5	(2 - 5) sec	770	710	740	SF2 for normal applications 660-750 mm
M0.4-1.8	3.0		790	690	740	
M0.8-2.0	4.1		800	720	760	
M1.2-2.5	4.0		720	650	685	

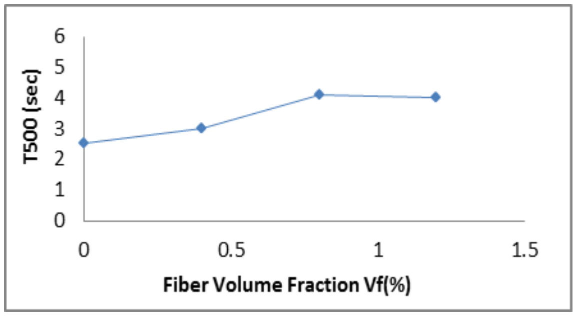

Fig. 2a. Influence of the fibres volume on the spreading time (Slump flow test)

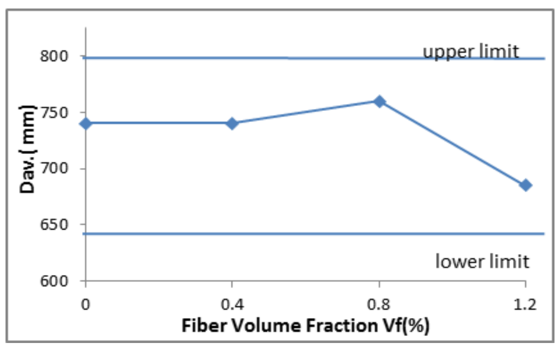

Fig. 2b. Influence of the fibres volume on the spreading diameter (Slump flow test)

Passing ability

Table (6), and Figures (3) to (5) show the test results for the passing ability of the four SCC mixes, the average diameter D_{avg}, the time required to reach the 500 mm diameter T_{500} and the difference B_j between the heights of concrete at the periphery and at the center of the J-ring. The test results show that the presence of the steel fibres decreased the average diameter D_{avg}, increased the time T_{500} required for concrete to reach the 500 mm diameter, and increased the difference B_j between the heights at the periphery and at the center of the J-ring. All the test results are within the specified limits [3,4].

Table 6. Resistance to passing of the high strength self-compacted concrete mixes (J-ring test)

Mix No.	$D_{max.}$ (mm)	$D_{perp.}$ (mm)	$D_{avg.}$ (mm)	T_{500}(sec)	B_j(mm)	Limits [4] B_j(mm)
M0.0-1.5	750	750	750	3.0	7.3	≤ 20 mm
M0.4-1.8	770	720	745	3.3	10.0	
M0.8-2.0	730	680	705	4.2	12.5	
M1.2-2.5	715	675	695	4.4	15.0	

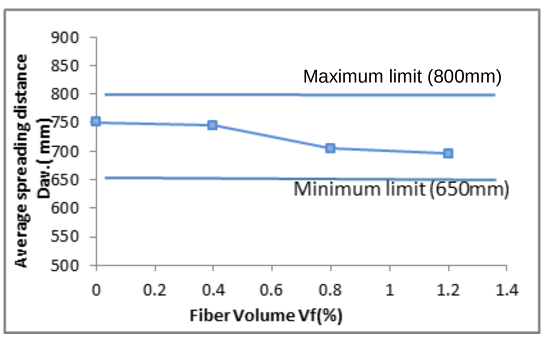

Fig. 3. Influence of fibres volume on the spreading distance in the J-ring test

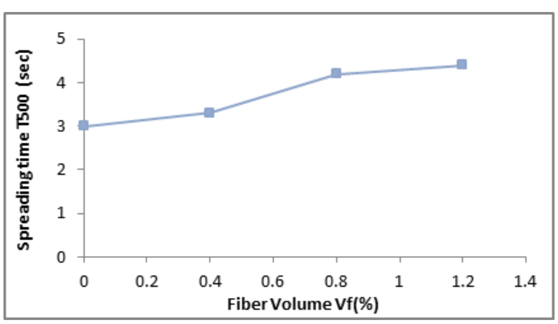

Fig. 4. Influence of fibres volume on the spreading time in the J-ring test

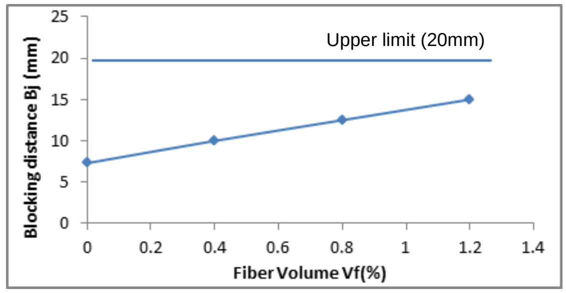

Fig. 5. Influence of fibres volume on the blocking distance Bj in the J-ring test

Filling and segregation resistance

Table (7) and Figures (6) and (7) show the results of the V-funnel test results, which are an index of the filling, segregation resistance, and viscosity of the SCC mixes. The test results show that all the *To* values are within the specified limits. The results show also, that the *T*5 values for all the mixes are more than *To*, and this may be attributed to the more hydration that may take place between the time intervals *To* and *T*5. Figure (8) shows the difference in times *T*5 −*To* for the four mixes, all the test results comply with the specification limits [3,4].

Table 7. Separation and segregation times of the high strength self-compacted concrete mixes (V-funnel test)

Mix No.	To (sec)	To Limit [4] (sec)	T5 (sec)	T5-To (sec)	T5-To Limit [4] (sec)
M0.0-1.5	9	6-12	11	2	0-3
M0.4-1.8	11.4		13.5	2.1	
M0.8-2.0	11.2		13.7	2.5	
M1.2-2.5	12.0		14.8	2.8	

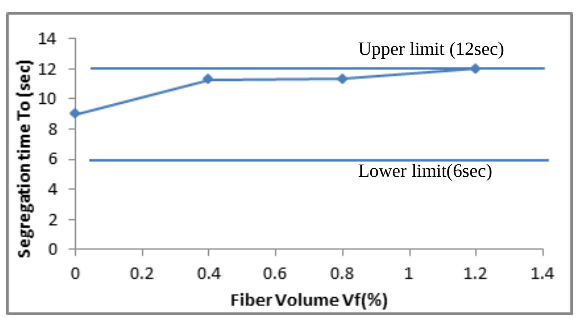

Fig. 6. Influence of fibres volume on the segregation time To in the V-funnel test

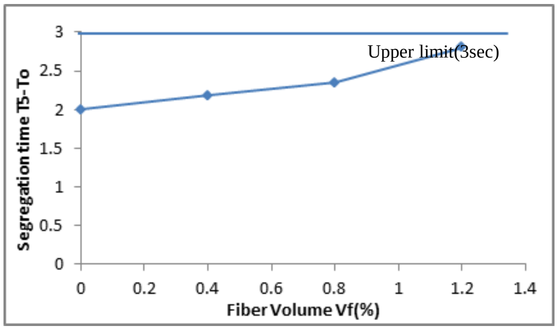

Fig. 7. Influence of fibres volume on the segregation time (T5-To) in the V-funnel test

Passing ability

Table (8) and Figure (8) show the results of the L-box test results, which are an index of the passing ability of the SCC mixes. The first three SCC mixes comply with the L-box requirements except the fourth one with fibres volume percentage of 1.2 which fall outside the specified range. However, no fibres balling or concrete blocking were noticed for this mix.

Table 8. Passing ability of the high strength self-compacted concrete mixes (L-box test)

Mix No.	H1 (mm)	H2 (mm)	P_A= (H2/H1)	Limits[4] P_A
M0.0-1.5	60	70	0.85	0.8 – 0.85
M0.4-1.8	70	85	0.82	
M0.8-2.0	75	90	0.83	
M1.2-2.5	60	80	0.75	

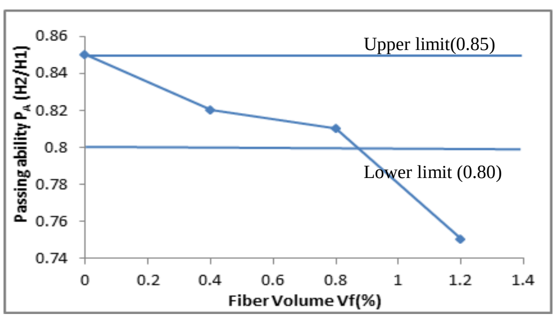

Fig. 8. Influence of fibres volume on the passing ability in the L-box test

Properties of Hardened Concrete

Strength development in compression

The strength development is investigated in this study, by casting eighteen cylinders (without steel fibres) and testing each three at different ages as shown in Table (9) and Figure (9). A regression analysis was performed and the following equation was obtained:

$$\frac{f_{ct}}{f'_{c28}} = \frac{t}{0.98t + 1.3} \quad \text{.................} \quad (1)$$

f_{ct} = the strength at the age (t) days and f'_{c28} = the strength at the age 28 days. The test results, as shown in Table (9) and Figure (9) revealed that SCC develops strength at the early ages faster than the normal concrete as shown by the following Equation recommended by the ACI Committee 209 [12]:

$$\frac{f_{ct}}{f'_{c28}} = \frac{t}{0.85t + 4} \quad \text{....................} \quad (2)$$

The faster strength development may be attributed to the greater percentage of fines that is present in the SCC, which in turn increase the rate of hydration, the other factor is the presence of the super plasticizer that separates the cement particles and distributes them more uniformly in the concrete mix.

Table 9. Ratios of the concrete strength to the strength at 28 days

Time (Days)	f_{ct} / f'_{c28} normal concrete	f_{ct} / f'_{c28} (SCC)	Difference = 100×(normal-SCC)/normal
3	0.46	0.71	54
7	0.70	0.86	23
10	0.80	0.90	13
14	0.88	0.93	6
21	0.96	0.96	0
28	1.0	1.0	0

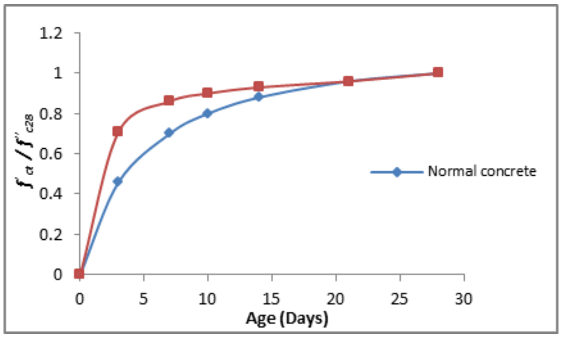

Fig. 9. Strength development for normal and high strength SCC

Compressive and splitting strength

Compression strength is one of the important properties of hardened concrete. Each figure in Table (10), and Figure (10) represent the average of three cylinders and shows the percentage increase in the compressive and splitting strength with the steel fibres volume. The Figure shows that the rate of increase in the splitting strength is three times the rate of increase in the compressive strength due to the steel fibres addition. This can be attributed to the different failure mechanisms. The increase in the splitting strength is higher than that reported for normal strength fibre SCC by AlTaan and AlNeimee [13], and this can be attributed to the higher bond strength between the matrix and the steel fibres in the high strength fibre reinforced SCC. The strength enhancement depends of course on the mix proportions, fines percentage, and the percentage and dimensions of the fibres.

Table 10. Compressive and splitting strength of the four high strength SCC mixes

Mix No.	f_c' **MPa**	**% increase in** f_c'	f_{sp} **MPa**	**% increase in** f_{sp}
M0.0-1.5	70.5	-----	5.9	-----
M0.4-1.8	74.8	6.1	6.9	16.9
M0.8-2.0	77.7	10.2	7.6	28.8
M1.2-2.5	82.1	16.5	8.9	50.8

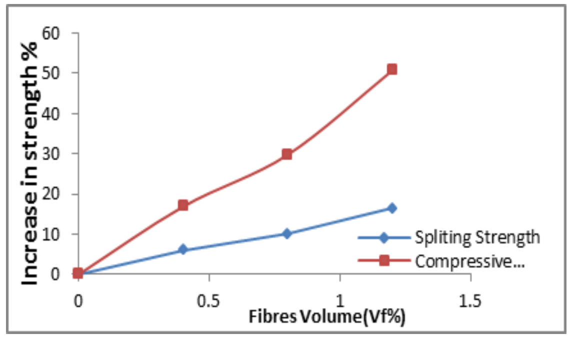

Fig. 10. Increase in compressive and tensile strength with the fibres volume

Mode of failure

Figures (11) and (12) show some of the tested cylinders in compression and splitting. These Figures show that the steel fibres have changed the brittle and sudden mode of failure of plain concrete to a gradual and ductile one, and retain the integrity of the failed specimens.

Fig. 11. Typical failed specimens, compression specimen

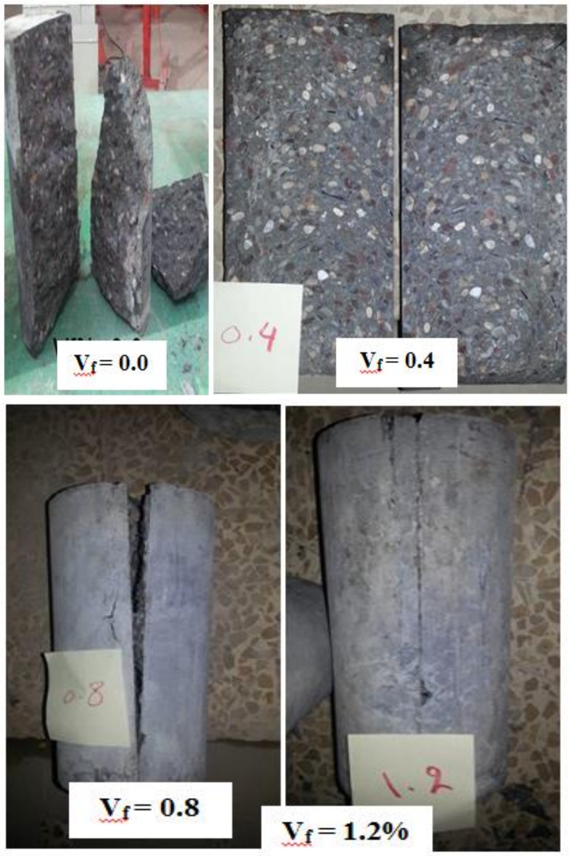

Fig. 12. Typical failed specimens, splitting specimens

Conclusions

Fibre reinforced self-compacted high strength concrete can be produced using low percentage of limestone powder and silica fume. However, the steel fibres have adverse effect on the spreading, passing, and segregation resistance, which can be compensated for by adjusting the super plasticizer dosage. The strength development in compression of the fibre reinforced high strength SCC at the early ages is more than the usual rate for normal concrete. The maximum increase in the compressive strength due to fibres addition was 16.5%, while the maximum increase in the splitting strength was up to 50.8%. The brittle mode of failure of the fibrous specimens was changed to a ductile one, and the compressive specimens retained their integrity at the ultimate stage.

More test results are required for this type of concrete so that they can be used as guidelines for future mix design and fresh and hardened properties.

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