Behavior of Steel Fiber Reinforced Self Compacting Concrete Slabs under One-way Bending

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ABSTRACT

This paper presents an experimental investigation on the flexural behavior of reinforced concrete slabs under one way bending. Sixteen simply supported slabs of dimensions 1000mm×450mm×50 or 70mm were manufactured and tested. Twelve slabs were constructed using self compacting concrete (SCC) and four using conventional concrete (CC). Four variables were adopted to investigate slabs behavior: type of concrete (CC or SCC), longitudinal steel ratio (ρ), slab thickness (t) and steel fiber ratio (V_f). Test results showed that slab thickness (t) was the most effective factor in increasing ultimate load (P_u) of SCC slabs (up to 111%) as compared to the longitudinal steel ratio (ρ) and steel fiber ratio (V_f) with ΔP_u up to 64% and 75%, respectively. Results also showed that using steel fiber in SCC up to 0.8% reduces its filling and passing abilities but it still satisfies the requirements of SCC specifications. In contrast, steel fiber increase compressive strength and modulus of rupture of SCC up to 10% and 60%, respectively.

Keywords: Self Compacting Concrete, One-way Slab, Steel Fiber.

سلوك بلاطات الخرسانة ذاتية الرص المسلحة بالياف الفولاذ تحت تأثير الانحناء احادي الاتجاه

الخلاصة

يقدم هذا البحث تحريا مختبريا عن سلوك الانحناء للبلاطات او السقوف الخرسانية المسلحة تحت تاثير الانحناء احادي الاتجاه. تم تصنيع و فحص ست عشرة بلاطة بسيطة الاسناد بابعاد 1000ملم *450ملم *50 او 70ملم. صنعت اثنتا عشرة بلاطة من الخرسانة ذاتية الرص (SCC) و اربع بلاطات من الخرسانة التقليدية (CC). تم اعتماد اربعة متغيرات لدراسة سلوك البلاطات و هي نوع الخرسانة (SCC او CC) و نسبة الفولاذ الطولي (ρ) و سمك البلاطة (t) و نسبة الياف الفولاذ (V_f). اظهرت نتائج الفحوص ان سمك البلاطة كان العامل الاكثر تاثيرا في زيادة الحمل الاقصى (P_u) لبلاطات الخرسانة ذاتية الرص (زيادة تصل الى 111%) بالمقارنة مع نسبة الفولاذ الطولي (ρ) و نسبة الياف الفولاذ (V_f) حيث كانت الزيادة تصل الى 64% و 75% على التوالي. كما اظهرت النتائج ان استخدام الياف الفولاذ في SCC بنسبة تصل 0.8% قلل قابليتي الملىء و العبور الا انه ما زال يحقق متطلبات مواصفات الخرسانة ذاتية الرص. بالمقابل فان الياف الفولاذ زادت مقاومة الانضغاط و معاير الكسر بنسب تصل الى 10% و 60% على التوالي.

INTRODUCTION

Self-Compacting Concrete (SCC) is a highly flowable, non-segregating concrete that can consolidate purely under its own weight, spread into place, completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity without the need for any additional compaction [1,2,3].

SCC, also known as self consolidating concrete, provides distinct advantages over conventional concrete (CC) due to liquid nature such as: minimal concrete voids, ease of flow around congested reinforcement, earlier removal of molds and faster use of elements and structures, elimination of vibrating equipment, faster construction and improving quality and durability [4,5,6,7,8].

Incorporating steel fiber can extend the above benefits of SCC by also providing crack bridging ability, higher toughness and long-term durability[9]. Also, using steel fiber in SCC is easier than using it in conventional vibrated concrete[10] which complicates the construction process and requires higher level of vibration to overcome the construction problems.

Barros et al. (2005)[11] stated that steel fiber reinforced self-compacting concrete (SFRSCC) presents a clear technical advantages in terms of costs/benefits ratio when compared to conventional concrete.

Al-ameeri (2013)[12] found that using steel fiber content in SCC more than 1% had best effect on hardened properties but the worst on fresh properties of SCC as compared to lower steel fiber contents. He suggested that 0.75-1% steel fiber content was sufficient to achieve optimum performance in fresh as well as hardened properties of SCC.

Many previous studies on SFRSCC were limited to small scale specimens such as cubes, prisms and cylinders, and few researches were conducted to investigate SFRSCC structural members.

The present work is aimed to investigate flexural behavior of SCC as well as conventional concrete (CC) slabs under one way bending with and without using steel fiber.

Experimental Program

Experimental program consists of manufacturing and testing sixteen simply supported reinforced concrete slabs under one-way bending. Twelve slabs were constructed using SCC and four using CC. Four variables were adopted to investigate slabs behavior: type of concrete (CC or SCC), longitudinal steel ratio (ρ), slab thickness and steel fiber ratio (V_f). All experimental works were conducted at structures laboratory of college of engineering /Al-Mustansiriya University.

Materials

Ordinary Portland cement (ASTM Type I), natural sand of 4.75mm maximum size and crushed gravel with maximum size of 10mm were used for production of both CC and SCC.

In addition, SCC mixtures contained limestone powder with particle size less than 0.125mm as filler, modified poly carboxylates based high range water reducing admixture (superplasticizer) (density = 1.09 kg/l at 20 °C) and short steel fibers with aspect ratio of 65 (length = 13mm and diameter = 0.2mm) and yield stress of 1130 MPa.

Deformed steel bars of nominal diameter of 6mm were used for main reinforcement in the tested slabs. Yield stress and ultimate strength of used steel bars are 435 MPa and 540 MPa, respectively.
Based on several trial mixes, one CC and three SCC mixes were used in tested slabs. Materials quantities of CC and SCC mixes are listed in Table (1)

Table (1) Mix proportions of CC and SCC

Concrete Type	CC	SCC		
Cement (kg/m^3)	400	400		
Sand (kg/m^3)	600	800		
Gravel (kg/m^3)	1200	770		
Limestone powder (kg/m^3)	-	170		
Water (kg/m^3)	200	190		
Superplasticizer (ltr/m^3)	-	8.1	9.2	10.8
Steel Fibers (kg/m^3)	-	0	31.4	62.8
V_f (%)	-	0	0.4	0.8

Mixing and Casting

CC was mixed in a common procedure where coarse and fine aggregate are mixed first for 2 minutes then cement is added and the dry components are mixed for about 3 minutes to obtain a homogeneous dry mix, then water is added during the mixing process which continued for another 3 minutes or until obtaining a homogeneous mixture. For SCC, the following mixing procedure was used by many researchers [13] and adopted in this work:

1. Fine aggregate with 1/3 of water quantity are first mixed for 1 minute.
2. Cement and limestone powder then added with another 1/3 of water quantity and mixed for 1 minute.
3. Coarse aggregate is added with the remaining water and 1/3 dosage of super plasticizer, and mixed for 1½ minutes then the mixer is left for 1/2 minute to rest.
4. Then, the remaining 2/3 of superplasticizer is added and mixed for 1½ minutes.
5. For fibrous mixes, steel fibers are added within 2 minutes during mixer rotation.
6. The concrete is then discharged for performing fresh properties tests and casting.

Slabs were cast in molds immediately after completing mixing without compaction where the concrete filled the molds easily and permeates between reinforcing bars without any segregation. Then, the specimens were covered with a nylon sheet to prevent evaporation of water. After 24 hours, the specimens were demolded and cured in a water bath for about one month. Three 100x200mm cylinders and three 100x100x500mm prisms were cast with each batch to determine compressive strength and flexural strength (modulus of rupture), respectively.

Tests of fresh SCC

The slump flow and L-box tests are performed on fresh concrete immediately after finishing of mixing process to investigate whether the concrete is SCC or not.

Slump flow test

The Slump flow test is the most widely used to evaluate concrete consistency and filling ability. This test can also indicate segregation resistance of SCC. The basic equipment used is the same as that used for the conventional slump test where truncated cone with internal 200 mm diameter at the base, 100 mm diameter at the top and a height of 300 mm and base plate at least 800 mm square marked with a circle marking the central location of the slump cone as shown in Figure (1). The test procedure can be summarized as follows[14]:

1- The slump cone is placed centrally on the table.
2- The slump cone is filled with about 6 liters (0.006 m^3) of concrete without compaction.
3- The slump cone is lifted vertically.
4- Simultaneously, the timing starts when lifting the slump cone starts and the time required for the concrete to reach 50 cm diameter is recorded (this is the $T_{50\ cm}$ time).
5- When the concrete has stopped flowing, the final diameter of the concrete is measured by measuring two perpendicular diameters.

According to EFNARC 2002[14], a slump flow diameter ranging from 650 mm to 800 mm is considered as the slump required for a concrete to be self compacting while according to the ACI 237R- 07[3], the slump flow diameter ranging from 450 mm to 760 mm is considered as the slump required for the concrete to be self compacting. For T_{50} the acceptance range is between 2 to 5 seconds according to the two committees.

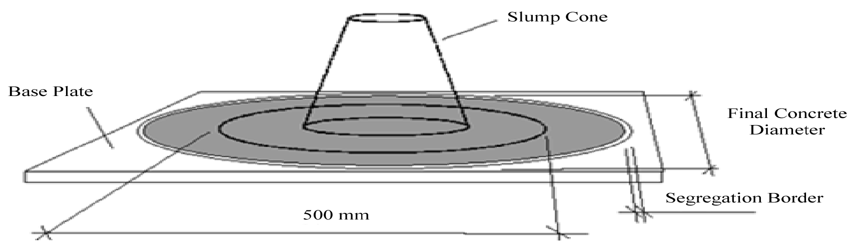


Figure (1) Measurements of the Slump Flow test for SCC[13]

L – box test

The L-box test assesses passing ability of SCC. In addition, segregation can easily be observed during the testing. The testing apparatus is shown in Figure (2). The test procedure can be summarized as follows[14]:

1. The vertical section of the apparatus is filled with 14 liters of concrete without rodding and left to stand for 1 minute.
2. The sliding gate is lifted and the concrete is allowed to flow out into the horizontal section.

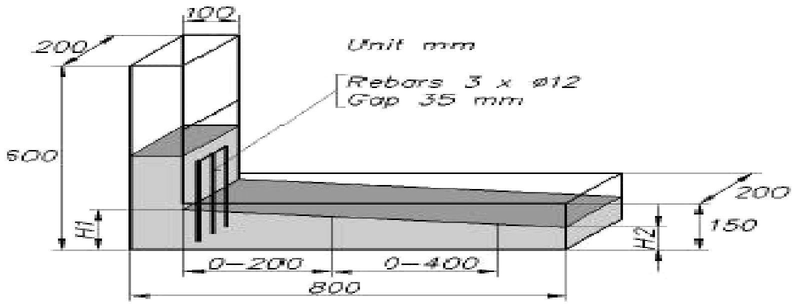


Figure (2) L-box test for SCC[14]

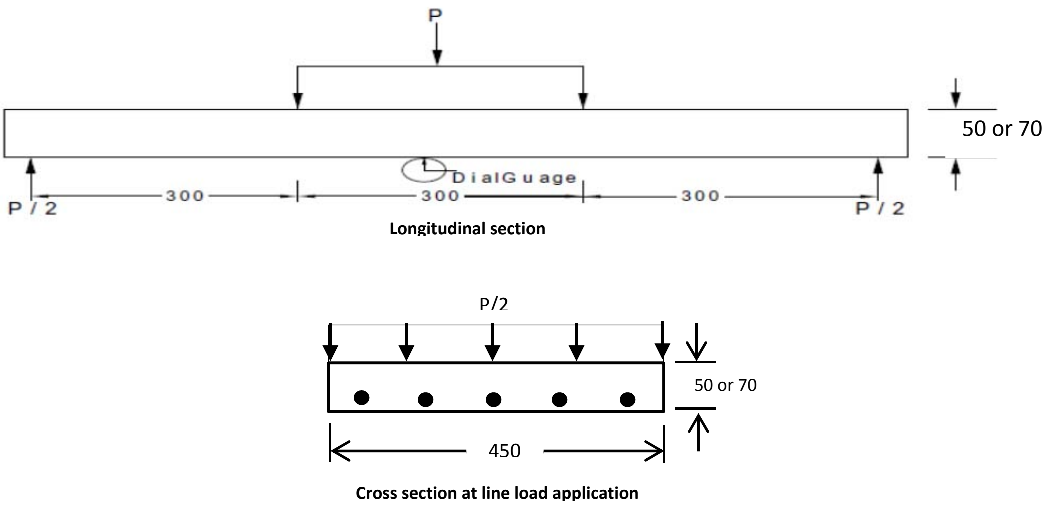
3. When the concrete stops flowing, the distances H_1 and H_2 are measured. Where H_1 is height of remaining concrete in vertical section while H_2 is the height of the concrete at the end of the horizontal section. The blocking ratio (H_2/H_1) is calculated which should ranges between 0.8 and 1.

Details and testing of slabs

Sixteen simply supported slabs of dimensions 1000mm×450mm×50 or 70mm were tested in one-way bending in this work. Four of these slabs are made with CC and twelve with SCC. A dial gauge was arranged to measure the central deflection of the slabs loaded by two line loads using two steel blocks of dimensions 450mm x 30mm x 30mm which applied at the third points of the slab by means of a hydraulic jack (Figure (3)).

The test procedure included crack monitoring and central deflection measurements for load increments of 5 kN.

Also, for each concrete mix, three 100x200 mm cylinders and three 100x100x500 mm prisms were tested to determine compressive strength ($f'c$)and modulus of rupture (f_r), respectively.



[All dimensions are in millimeters]

(A)

(B)

Figure (3) A- Loading arrangement and test set-up. B- Specimen under testing.

In addition to type of concrete (CC or SCC), three other variables were used in the investigated slabs: longitudinal steel ratio (ρ), slab thickness and steel fiber ratio (V_f) as listed in Table (2).

Slabs designation can be explained as follows: letter C or S refers to CC or SCC, respectively; number 1 refers to ρ= 0.33% or 0.5% for t=70 or 50 mm, respectively; number 2 refers to ρ= 0.66% or 1% for t=70 or 50 mm, respectively; numbers 0, 0.4 and 0.8 refer to V_f= 0, 0.4 and 0.8%, respectively and numbers 5 and 7 refer to slab thickness of 50 and 70 mm, respectively.

Table (2) Details of the tested slabs

Slab Designation	Concrete type	Longitudinal steel ratio (ρ) (%)	Steel fibers ratio (V_f) (%)	Slab thickness (mm)
C1-0-5	CC	0.5	0	50
C1-0-7	CC	0.33	0	70
C2-0-5	CC	1	0	50
C2-0-7	CC	0.66	0	70
S1-0-5	SCC	0.5	0	50
S1-0-7	SCC	0.33	0	70
S2-0-5	SCC	1	0	50
S2-0-7	SCC	0.66	0	70
S1-0.4-5	SCC	0.5	0.4	50
S1-0.4-7	SCC	0.33	0.4	70
S2-0.4-5	SCC	1	0.4	50
S2-0.4-7	SCC	0.66	0.4	70
S1-0.8-5	SCC	0.5	0.8	50
S1-0.8-7	SCC	0.33	0.8	70
S2-0.8-5	SCC	1	0.8	50
S2-0.8-7	SCC	0.66	0.8	70

Results and Discussion

Fresh SCC properties results

Table (3) illustrates the results of slump flow and L-box tests that conducted on SCC mixes and the corresponding standard limitations. As shown in this table, results of all mixes satisfy the requirements of EFNARC[14] and ACI-237R-07[3] specifications. However, increasing steel fiber ratio reduces SCC filling and passing abilities as can be indicated from the lower slump flow and blocking ratio results when V_f increases from 0 to 0.8%. This is because steel fibers hamper easy flow of concrete mix.

Hardened concrete properties results

Table (4) shows test results of compressive strength (f'_c) and modulus of rupture (f_r) for the four mixes. The effect of steel fibers on concrete compressive strength seems to be very small for SCC where increasing ratio is about 10% for V_f of 0.8%. Modulus of rupture is significantly affected by using steel fibers where increasing ratio is about 60% for V_f of 0.8%. Table (4) also shows that using ACI-code to calculate modulus of rupture gives values of about 90% of experimental results for nonfibrous CC and SCC and conservative values of about 60% for fibrous SCC.

Table (3) Tests results of fresh SCC properties

V_f (%)	Slump flow (mm)	T_{50} (sec)	L – box (H_2/H_1)
0	750	2.5	1
0.4	720	3	0.96
0.8	680	4	0.90
Limits of EFNARC[14]	650-800	2-5	0.8-1
Limits of ACI-237[3]	450-760	2-5	0.8-1

Table (4) Hardened concrete tests results

Mix type	V_f (%)	f'_c (MPa)	f_r (MPa)	$f_{r,ACI}$* (MPa)	$f_{r,ACI}/f_r$
CC	0	27	3.91	3.64	0.93
SCC	0	29.7	4.41	3.81	0.87
	0.4	31.1	6.32	3.90	0.62
	0.8	32.9	7.02	4.02	0.57

$*f_r = 0.7\sqrt{f'_c}$

Results of slab tests

Ultimate loads

Generally, tests results show that ultimate load (P_u) of the tested slabs increases when SCC used and with the increase of slab thickness (t), longitudinal steel ratio (ρ) and steel fiber ratio (V_f) as shown in Tables (5) to (8) and Figure (4).

Table (5) show that P_u values of SCC slabs are higher than those of CC slabs by 10-38% (except slab S1-0-5) with higher effect of 70 mm thickness. This may be attributed to the higher performance of SCC due to its higher homogeneity and less porosity.

Table (5) Effect of concrete type on ultimate loads of slabs

Slab	C1-0-5	S1-0-5	C1-0-7	S1-0-7	C2-0-5	S2-0-5	C2-0-7	S2-0-7
P_u (kN)	29	27.5	42	58	41	45	56.5	73.5
ΔPu (%)	-5.2		38.1		9.8		30.1	

Increasing slab thickness (t) from 50 to 70 mm increases P_u of nonfibrous CC and SCC slabs by about 38-45% and 63-111%, respectively as shown in Table (6). This reflects the efficiency of SCC sections in improving structural behavior of concrete members. For fibrous SCC slabs, Table (6) lists increasing ratios of about 43-85% and 43-46% for steel fiber ratio of 0.4 and 0.8, respectively, which are generally lower than corresponding ratios of nonfibrous SCC slabs due to that incorporating steel fiber enhances bending capacity of lower t slabs more than higher t ones at constant ρ then reduces the effect of increasing t.

It is also concluded from Table (6) that increasing t was more efficient in lower ρ slabs (0.33% or 0.5%) as compared to higher ρ ones (0.66% or 1%).

Table (6) Effect of slab thickness on ultimate loads of slabs

Slab	C1-0-5	C1-0-7	C2-0-5	C2-0-7	S1-0-5	S1-0-7	S2-0-5	S2-0-7
P_u (kN)	29	42	41	56.5	27.5	58	45	73.5
ΔPu (%)	44.8		37.8		110.9		63.3	
Slab	**S1-0.4-5**	**S1-0.4-7**	**S2-0.4-5**	**S2-0.4-7**	**S1-0.8-5**	**S1-0.8-7**	**S2-0.8-5**	**S2-0.8-7**
P_u (kN)	36.5	67.5	56.5	81	48	70	58.5	83.5
ΔPu (%)	84.9		43.4		45.8		42.7	

Table (7) show that increasing ρ from 0.5% to 1% and from 0.33% to 0.66% increases P_u by about 22-64% and 19-35% for 50 and 70 mm thickness slabs, respectively. This indicates the higher effect of increasing ρ on lower thickness slabs. Table (7) also indicates that increasing ρ was more effective in nonfibrous SCC slabs (ΔP_u =27-64%) than fibrous ones (ΔP_u =19-55%).

Table (7) Effect of longitudinal steel ratio on ultimate loads of slabs

Slab	C1-0-5	C2-0-5	C1-0-7	C2-0-7	S1-0-5	S2-0-5	S1-0-7	S2-0-7
P_u (kN)	29	41	42	56.5	27.5	45	58	73.5
ΔPu (%)	41.4		34.5		63.6		26.7	
Slab	**S1-0.4-5**	**S2-0.4-5**	**S1-0.4-7**	**S2-0.4-7**	**S1-0.8-5**	**S2-0.8-5**	**S1-0.8-7**	**S2-0.8-7**
P_u (kN)	36.5	56.5	67.5	81	48	58.5	70	83.5
ΔPu (%)	54.8		20.0		21.9		19.3	

Table (8) and Figure (4) show that increasing V_f from 0% to 0.4% and 0.8% increases P_u of all SCC slabs with more evident effect in slabs of lower t (50 mm) and ρ (0.5%) where ΔP_u was about 33% and 75% for V_f = 0.4% and 0.8%, respectively, while ΔP_u for other SCC slabs of higher t and/or ρ was about 10-30%. Similar trend was also recorded by *Barros et al. 2008*[15].

Table (8) Effect of steel fiber ratio on ultimate loads of slabs

Slab	S1-0-5	S1-0.4-5	S1-0.8-5	S1-0-7	S1-0.4-7	S1-0.8-7
P_u (kN)	27.5	36.5	48	58	67.5	70
ΔPu (%)	0.0	32.7	74.5	0.0	16.4	20.7
Slab	**S2-0-5**	**S2-0.4-5**	**S2-0.8-5**	**S2-0-7**	**S2-0.4-7**	**S2-0.8-7**
P_u (kN)	45	56.5	58.5	73.5	81	83.5
ΔPu (%)	0.0	25.6	30.0	0.0	10.2	13.6

The above results lead to the conclusion that (within the ranges used in this work) slab thickness (t) was the most effective factor in increasing ultimate load (P_u) of SCC slabs (up to 111%) as compared to the longitudinal steel ratio (ρ) and steel fiber ratio (V_f) with ΔP_u up to 64% and 75%, respectively.

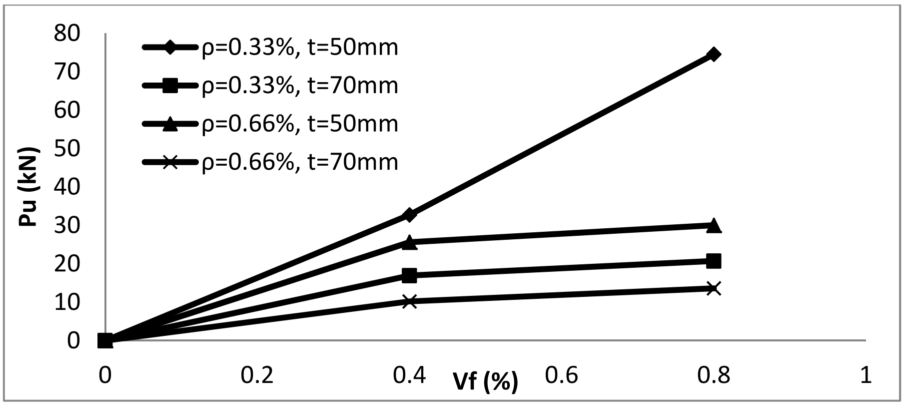


Figure (4) Effect of steel fiber ratio on ultimate loads of slabs

Load-deflection behavior

Figures (5) to (12) illustrate the load-deflection behavior of the tested slabs. Generally, at initial loading stage, slabs showed approximately linear elastic response until cracks were initiated at the bottom of the slab within the middle third where maximum bending occurred. After cracking, the gradient of the initial load–deflection curve reduced and continued to reduce gradually until the steel yielded. The post-yield behavior of the slab then resulted in a third region of greatly reduced gradient within which strain hardening occurred such that a slight increase in load resulted in a large increase in deflection until failure occurred.

It is shown in Figures (5) to (12) that increasing slab thickness (t), longitudinal steel ratio (ρ) (Figures (5) to (8)) and steel fiber ratio (V_f) (Figures (9) to (12)) stiffens load-deflection curves leading to smaller deflections at a certain load. Higher toughness and more ductile failure were also observed in load-deflection curves when t, ρ and V_f increase.

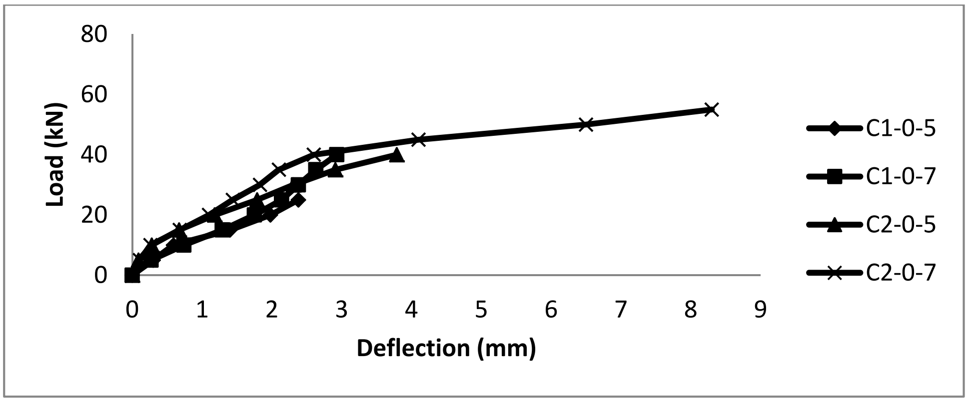


Figure (5) Load-deflection curves of CC slabs.

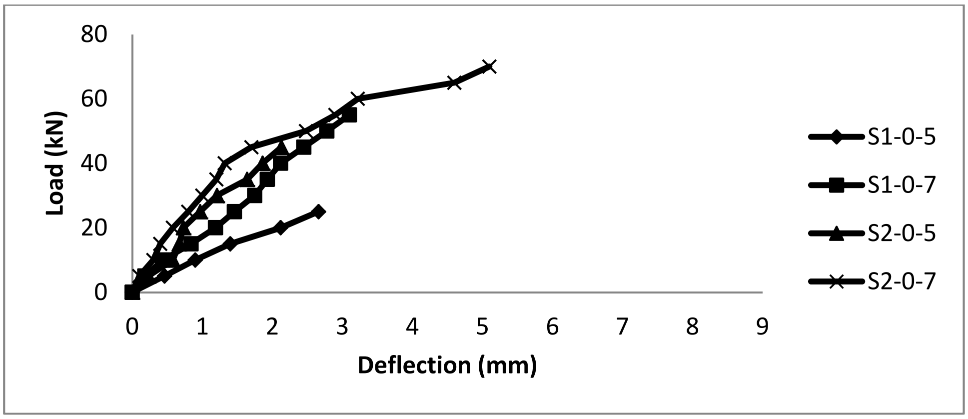


Figure (6) Load-deflection curves of SCC slabs with V_f=0%.

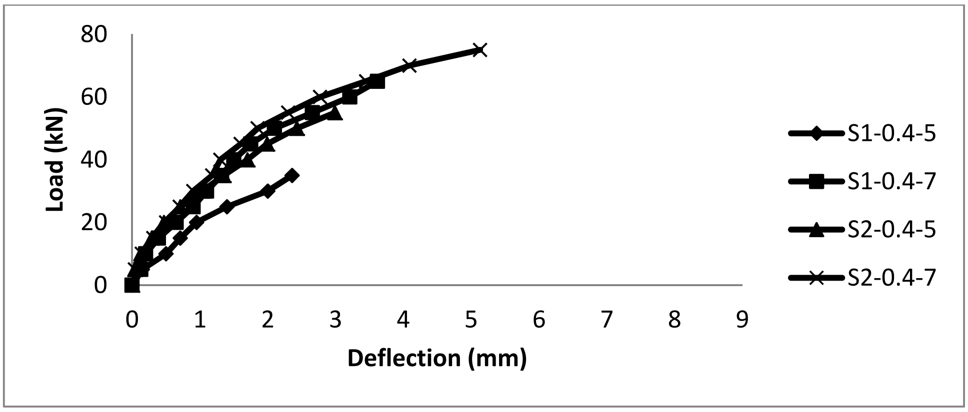


Figure (7) Load-deflection curves of SCC slabs with V_f=0.4%.

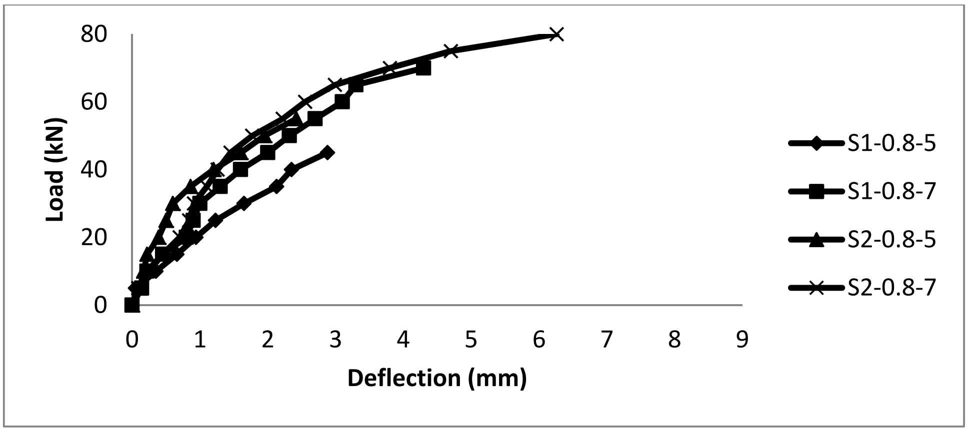


Figure (8) Load-deflection curves of SCC slabs with V_f=0.8%

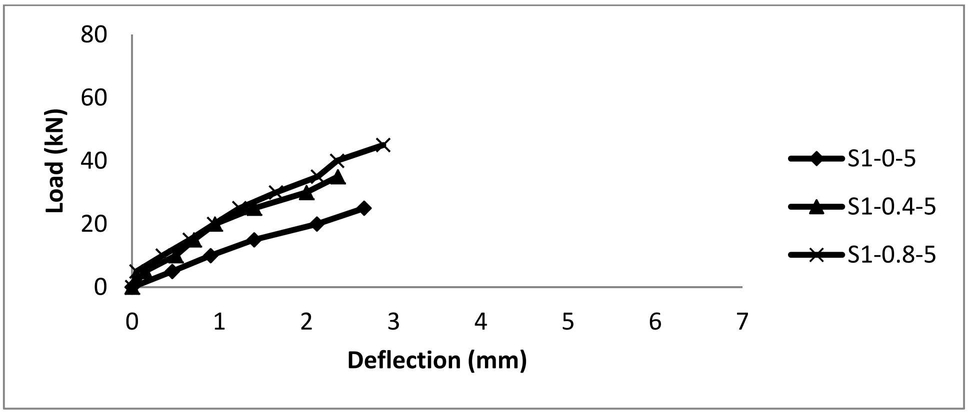


Figure (9) Load-deflection curves of SCC slabs with ρ=0.5% and t=50mm

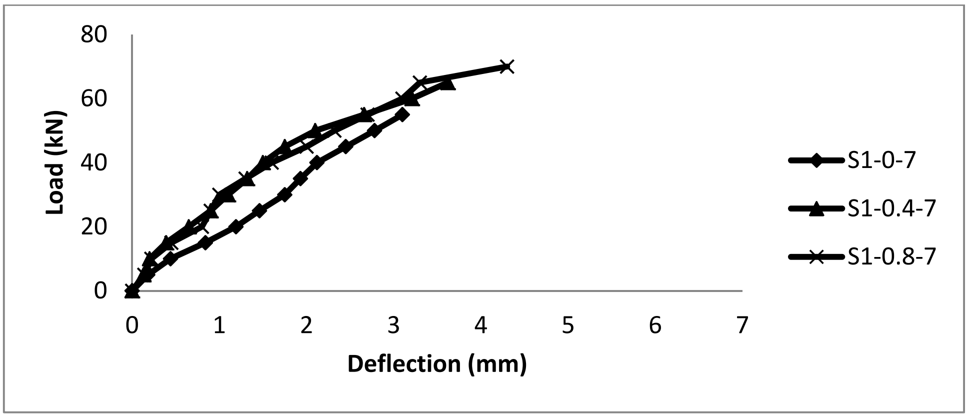


Figure (10) Load-deflection curves of SCC slabs with ρ=0.33% and t=70mm

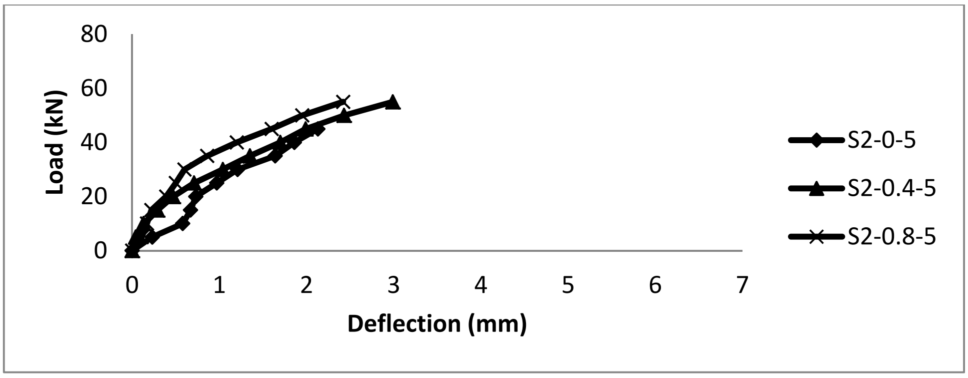


Figure (11) Load-deflection curves of SCC slabs with ρ=1% and t=50mm

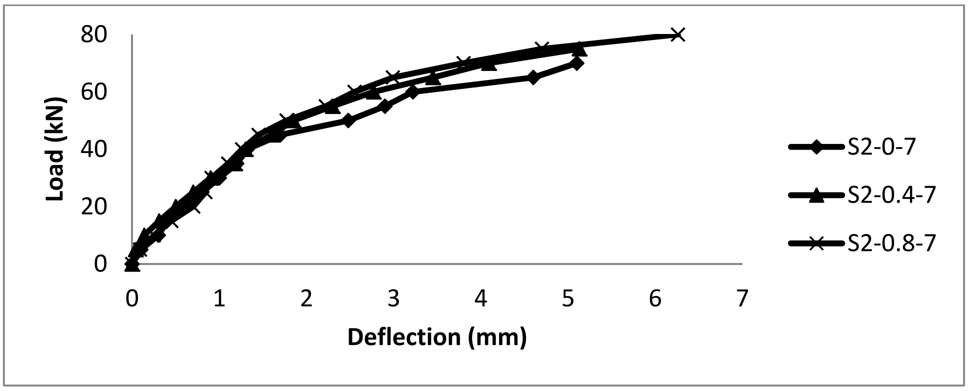
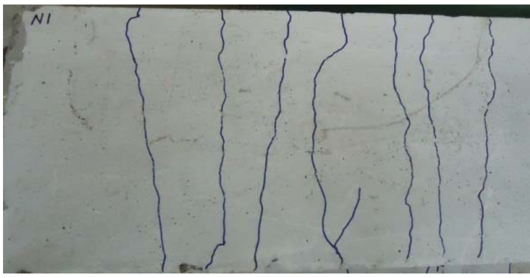


Figure (12) Load-deflection curves of SCC slabs with ρ=0.66% and t=70mm

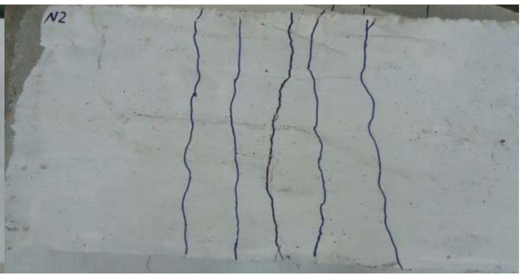
Crack patterns

Crack patterns of the tested slabs are shown in Figure (13). At early stages of loading, several flexural cracks were initiated when concrete tensile strength exceeded in the tension face at the constant maximum moment region (middle third of the slab). With further loading these cracks extended upwards and became wider while other cracks initiated at each of the adjacent shear spans. One of the middle third cracks (or more) propagated and widened faster than the others passing through the compression zone, then longitudinal steel yielded and consequently the slab failed.

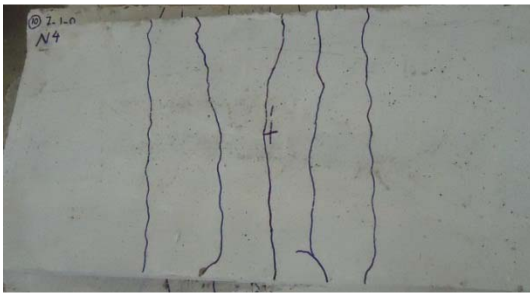
Increasing longitudinal steel ratio (ρ) increases number of cracks and reduced their widths and spacing as shown in Figure (13), while increasing slab thickness (t) or steel fiber ratio (V_f) had marginal effect on crack patterns of the tested slabs.



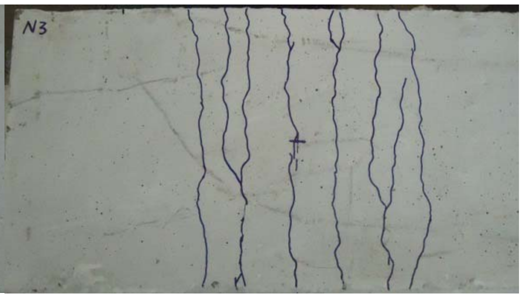
C1-0-5



C1-0-7

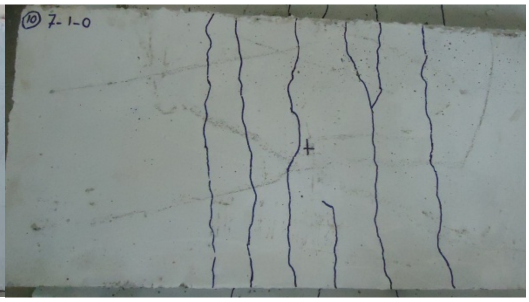


C2-0-5



C2-0-7

S1-0-5



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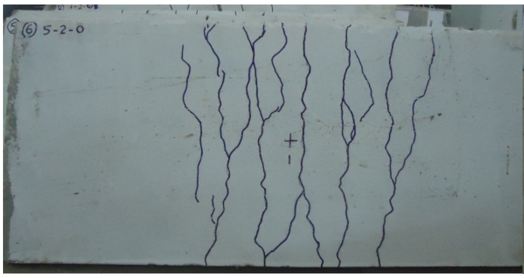

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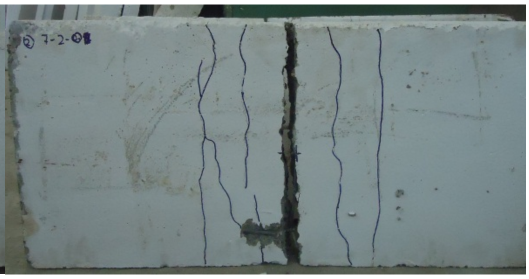

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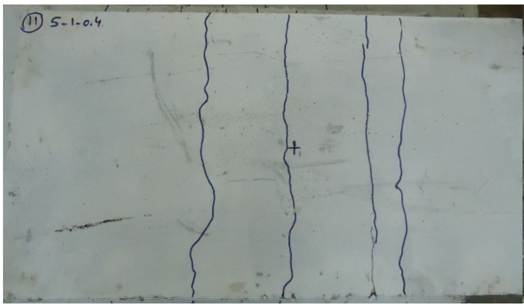

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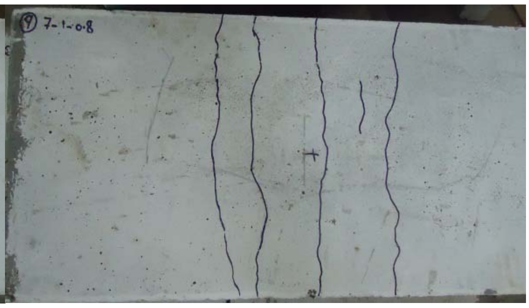

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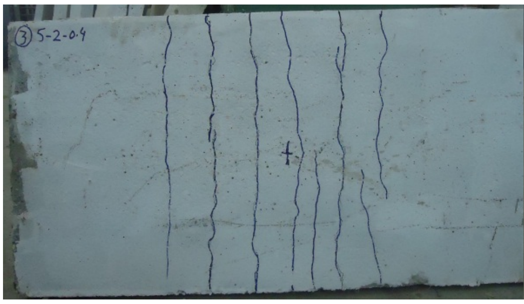
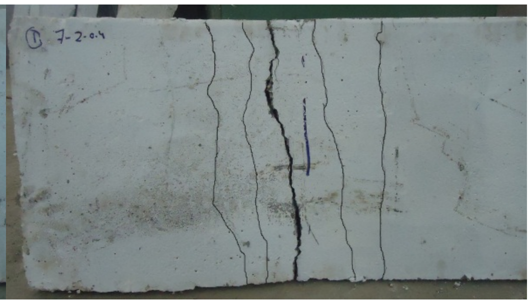
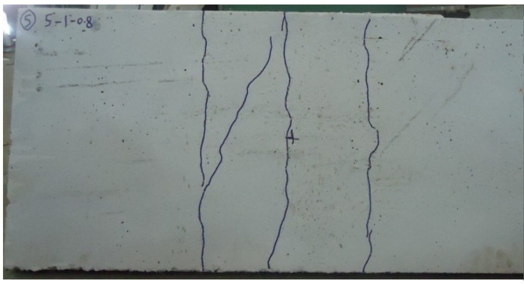
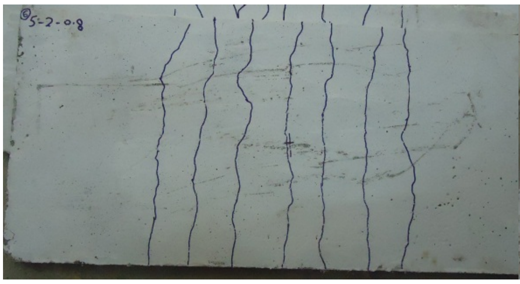
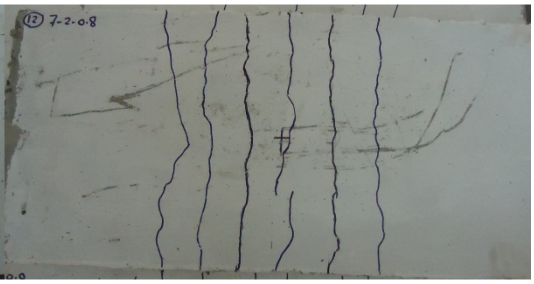



S2-0.4-5 **S2-0.4-7**




S1-0.8-5 **S1-0.8-7**

S2-0.8-5 **S2-0.8-7**

Figure (13) Crack patterns of the tested slabs

CONCLUSIONS

Based on the experimental results of the present work, the following conclusions can be drawn:

1- Using steel fiber in self compacting concrete (SCC) up to 0.8% reduces SCC filling and passing abilities but it still satisfies the requirements of EFNARC[14] and ACI-237R-07[3] specifications for SCC. In contrast, steel fiber increase compressive strength and modulus of rupture of SCC up to 10% and 60%, respectively.

2- SCC one way slabs show, generally; better structural performance in terms of higher ultimate loads and lower deflections as compared to conventional concrete (CC) slabs.

3- Within the ranges used in this work, slab thickness (t) was the most effective factor in increasing ultimate load (P_u) of SCC slabs (up to 111%) as compared to the longitudinal steel ratio (ρ) and steel fiber ratio (V_f) with ΔP_u up to 64% and 75%, respectively.

4- Increasing slab thickness (t) from 50 to 70 mm enhanced ultimate loads of nonfibrous SCC slabs by about 63-111% which is higher ratios than corresponding ones of 43-85% for fibrous SCC slabs.

5- Increasing longitudinal steel ratio (ρ) from 0.5% to 1% and from 0.33% to 0.66% for 50 and 70 mm thickness slabs, respectively; was more effective in nonfibrous SCC slabs (ΔP_u =27-64%) than fibrous ones (ΔP_u =19-55%).

6- Using steel fiber increases P_u of all SCC slabs with more evident effect in slabs of lower t (50 mm) and ρ (0.5%) where ΔP_u was about 33% and 75% for V_f = 0.4% and 0.8%, respectively, while ΔP_u for other SCC slabs of higher t and/or ρ was about 10-30%.

7- Increasing slab thickness (t), longitudinal steel ratio (ρ) and steel fiber ratio (V_f) stiffens load-deflection curves of CC and SCC slabs leading to smaller deflections at a certain load. Higher toughness and more ductile failure were also observed in load-deflection curves with the increases of t, ρ or V_f.

8- Increasing longitudinal steel ratio (ρ) increases number of cracks and reduced their widths and spacing, while increasing slab thickness (t) or steel fiber ratio (V_f) had marginal effect on crack patterns of the tested slabs.

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