# *Experimental Study Of Fibrous High Strength Self-Compacting Concrete One-Way Slabs*

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## Abstract

*The experimental work of this study includes testing sixteen reinforced concrete one-way slabs cast using high strength self-compacting concrete (HSSCC) with using steel fibers to evaluate their flexural behavior and strength. The slabs were subjected to concentrated transverse loads (loads were distributed across the entire width of the slab) at the third points. All tested slabs have dimensions of 1000×450×50 or 70 mm. The parameters considered are slab thickness, steel reinforcement ratio (ρ) and steel fiber volumetric ratio ($V_f$). The effect of these parameters on the behavior of the tested slabs included investigation of deflection, failure mode, and ultimate loads. Two different failure modes were predicted either flexural tension mode or flexural shear mode or a combination of these two.*

*Key words: Self- compacting concrete, Fiber reinforced concrete, One-way slab.*

# دراسة عملية للبلاطات الخرسانة أحادية الاتجاه ذاتية الرص عالية المقاومة والمسلحة بالألياف

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## الخلاصة :

يتضمن البرنامج العملي لهذه الدراسة فحص ست عشرة بلاطة احادية الاتجاه والمصنوعة من الخرسانة عالية المقاومة ذاتية الرص والمسلحة بالالياف الفولاذية لتقييم سلوك ومقاومة الانحناء لها. كل البلاطات ذات ابعاد 1000×450×50 أو 70 ملم. المتغيرات التي تم دراستها في هذا البحث هي سمك البلاطة، نسبة حديد التسليح ونسبة الالياف الفولاذية. تم دراسة تأثير هذه المتغيرات على الهطول،شكل الفشل والحمل الاقصى. تم ملاحظة نوعين من الفشل للبلاطات وهي اما فشل شد الانثناء او فشل القص او حالة مركبة من كلا النوعين من الفشل.

الكلمات المرشدة:الخرسانة ذاتية الرص،الخرسانة المسلحة بالالياف، البلاطات احادية الاتجاه.

## 1. Introduction

Concrete that is able to flow and consolidate under its own weight, completely fill the formwork of any shape, even in the presence of dense reinforcement, while maintaining homogeneity and without the need for any additional compaction. Fibers reinforcement can extend the technical benefits of SCC by also providing crack bridging ability, higher toughness and long-term durability. The use of steel and synthetic fibers however is known to alter the flow properties of fresh concrete. In recent times, few attempts have been made to include steel fibers in plain SCC. But these studies are limited to small scale specimen such as cubes, prisms and cylinders. The present investigation is made to study the flexural behavior of large scale structural elements, an attempt has been made to develop cast and test HSSCC slab elements [1].

Since the idea of utilizing fiber reinforced cementations composites in structural elements has been increased exponentially over the past decade, it is necessary to have the concept introduced in the provisions of the concrete codes. It is necessary to conduct laboratory investigations on various types of structural components under different loading conditions to have a precise understanding of their behavior. As on date, there are limited investigations on the flexural behavior of slabs cast with steel fiber reinforced self-compacting concrete [2].

## 2. Research Significance

The paper presents unique experimental results of sixteen HSSCC one-way concrete slabs tested under static loading conditions up to failure. The research describes the various limit states behavior including modes of failure due to variation of the slab thickness, steel fibers content and the reinforcement ratio. The behavior of HSSCC slabs is compared to conventional concrete slabs. The information gathered throughout this investigation is valuable for future development of design guidelines for one-way HSSCC concrete slabs.

## 3. Experimental Program

In the experimental work, control specimens were casted which were three cylinders and four cubes for compressive strength, three cylinders for splitting tensile strength and three prisms for modulus of rupture. Details of these control specimens are shown in **Table (1).**

**Table .(1) Specifications of the control specimens**

| Type of test | Number and type of specimens | Specimens dimension mm |
|---|---|---|
| Compressive strength | 3 cylinders | 100X200 |
| Splitting tensile strength | 3 cylinders | 100X200 |
| Modulus of rupture | 3 prisms | 100X100X500 |

Four variables are investigated in this study to show their effects on the punching shear strength of the HSSCC slabs. These variables are:

**1.** Percentage of steel fibers volumetric ratio.

**2.** Flexural steel reinforcement ratio.

**3.** Thickness of slab.

**4.** Type of concrete [conventional concrete (CC) &HSSCC].

**Table (2)** illustrates the details of all the test slabs.

**Table .(2) Details of all the test slabs of the present investigation**

| Group No. | Slab Designation | Steel reinforcement ratio (ρ) | Steel fibers % by volume | Slab thickness (mm) |
|---|---|---|---|---|
| Group One (conventional concrete slabs as reference slabs) (CC) | CCS1-0-5 | 0.0033 | 0 | 50 |
| | CCS1-0-7 | 0.0033 | 0 | 70 |
| | CCS2-0-5 | 0.0066 | 0 | 50 |
| | CCS2-0-7 | 0.0066 | 0 | 70 |
| Group Two (HSSCC0) | HSSCC1-0-5 | 0.0033 | 0 | 50 |
| | HSSCC1-0-7 | 0.0033 | 0 | 70 |
| | HSSCC2-0-5 | 0.0066 | 0 | 50 |
| | HSSCC2-0-7 | 0.0066 | 0 | 70 |
| Group Three (HSSCC-0.4) | HSSCC1-0.4-5 | 0.0033 | 0.4 | 50 |
| | HSSCC1-0.4-7 | 0.0033 | 0.4 | 70 |
| | HSSCC2-0.4-5 | 0.0066 | 0.4 | 50 |
| | HSSCC2-0.4-7 | 0.0066 | 0.4 | 70 |
| Group Four (HSSCC-0.8) | HSSCC1-0.8-5 | 0.0033 | 0.8 | 50 |
| | HSSCC1-0.8-7 | 0.0033 | 0.8 | 70 |
| | HSSCC2-0.8-5 | 0.0066 | 0.8 | 50 |
| | HSSCC2-0.8-7 | 0.0066 | 0.8 | 70 |

Slabs designations were as following:

1st symbol (H) from high.

2nd symbol (S) from strength.

3rd symbol (S) from self.

4th symbol (C) from compacting.

5th symbol (C) from concrete.

$6^{th}$ symbol (1 and 2) from $\rho_1$=0.0033 or $\rho_2$=0.0066.

$7^{th}$ symbol (0, 0.4 and 0.8) from steel fibers content $V_f$=0, 0.4 or 0.8%.

$8^{th}$ symbol (5 and 7) from slab thickness 50 or 70 mm.

## 3.1 Materials:

### 3.1.1 Cement

Ordinary Portland cement (type I) of Tasluja Factory is used in the present study. Test results of chemical composition and physical properties of the used cement tested by National Center for Construction Laboratories and Researches in Baghdad comply with the requirements of I.Q.S. No.5, 1984[3].

### 3.1.2 Fine Aggregate

Al-Ukhaider natural sand is used in concrete mix. Before using it, the sieve analysis is performed at Material Laboratory in Engineering College of Al- Mustansiriya University to ensure its validity for mixing. The fineness modulus, depending on this analysis, is 2.78. The sieve analysis results of the sand comply with the limits of the Iraqi Specification No.45/1984[4].

### 3.1.3 Coarse Aggregate (Gravel)

Crushed river gravel with maximum particle size of 10mm was used as coarse aggregate for CC mixes only while coarse aggregate with maximum particle size of 5mm was used for UHPC mixes. . The grading of this aggregate conforms to the Iraqi specification No.45/1984[4].

### 3.1.4 Limestone Powder

Limestone powder is locally named “Al-Gubra” brought from Al-Mousel district and has been used as filler for concrete production for many years. The particle size of the limestone powder is less than 0.125 mm, which satisfies EFNARC 2002[5] recommendations.

### 3.1.5 Superplasticizer

A superplasticizer commercially named Sika Visco Crete PC-20 was used as an admixture to produce HSSCC in this study

### 3.1.6 Steel Reinforcement

Deformed steel bar of nominal diameter 6 mm was used as slab reinforcement. Two reinforcement ratios (ρ) are used in each group of the tested slabs. The yield strength of used bar was 435 N/mm$^2$. The result of testing this bar meet the **ASTM A615** [6] requirements for Grade 60 steel.

### 3.1.7 Steel Fibers

Micro straight steel fibers with aspect ratio (L/d) of 52 were used in UHPC mixes. Sample of the used steel fibers is shown in **Figure (1)** and their properties are listed in **Table(3).**

**Fig .(1) Sample of micro steel fibers used in present investigation**

**Table .(3) Properties of steel fibers used***

| | |
|---|---|
| **Type of steel** | Straight |
| **Relative Density** | 7800 kg/m$^3$ |
| **Yield strength** | 1130 MPa |
| **Modulus of Elasticity** | 205 000 MPa |
| **Strain at proportion limit** | 5650*10-6 |
| **Poisson's ratio** | 0.28 |
| **Average length (L)** | 13.1 mm |
| **Nominal diameter (d)** | 0.25 |
| **Aspect ratio (length/diameter)** | 52 |

*According to manufacturer editions.

### 3.2 Mix Proportions

**Table (4)** gives mix proportions of CC and HSSCC mixes used in different beams. Based on several trial mixes, one CC mix and three HSSCC mixes that differ from each other only in volumetric steel fibers ratio ($V_f$) were adopted in this study.

**Table .(4) Mix proportions of CC and HSSCC**

| Concrete Type | CC | HSSCC | | |
|---|---|---|---|---|
| Cement (C) (kg/m$^3$) | 400 | 550 | | |
| Sand (S) (kg/m$^3$) | 600 | 855 | | |
| Gravel (G) (kg/m$^3$) | 1200 | 767 | | |
| Limestone powder (LSP) (kg/m$^3$) | - | 50 | | |
| Superplasticizer (SP) (kg/m$^3$) | - | 22.5 | | |
| Water (W) (kg/m$^3$) | 200 | 165 | | |
| W/C | 0.5 | 0. 3 | | |
| Steel Fibers (kg/m$^3$) | 0 | 0 | 31.4 | 62.8 |
| $V_f$ ( %) | 0 | 0 | 0.4 | 0.8 |

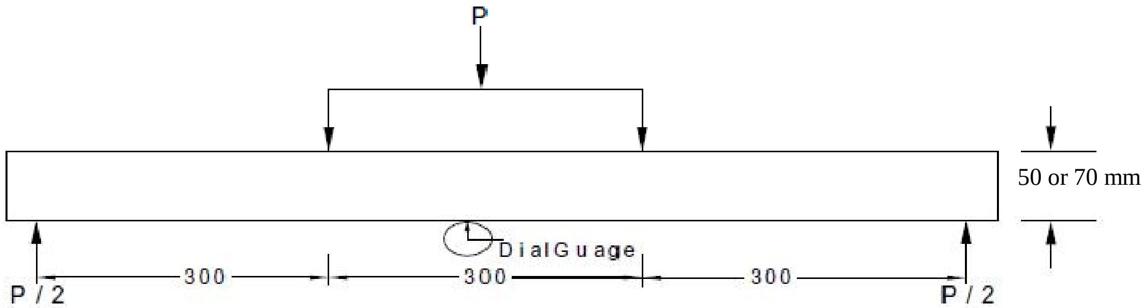
## 4. Mixing

The procedure of mixing is stated as follows:

1. The fine aggregate is added to the mixer with 1/3 quantity of water and mixed for 1 minute.
2. The cement and limestone powder are added with another 1/3 quantity of water. Then, the mixture is mixed for 1 minute.
3. The coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of super plasticizer, and the mixing time lasts for 1½ minutes then the mixer is left for 1/2 minute to rest.
4. Then, the 2/3 of the leftover of the dosage of super plasticizer is added and mixed for 1½ minutes.
5. The concrete is then discharged for performing fresh properties and casting.
6. However, for mixes containing steel fibers, the fibers are added during step 4 and mixed for 2 minutes to achieve homogenous distribution of fibers.

## 5. Details and Designation of Beams

Sixteen slabs of dimensions (1000mm×450mm×50 or 70mm) were cast and tested in flexure in this study. Four of these slabs are made with CC and twelve with HSSCC, during loading the slabs were simply supported at their ends on steel beams which formed part of a rigid steel frame. A dial gauge was arranged to measure the central deflection of the slabs. Two line loads were applied at the third points of the slab by means of a hydraulic jack **(Figure 2).** The test procedure included crack monitoring and central deflection measurements for load increments of 5 kN.




(A)

(B)

**Fig .(2) A- Schematic sketch of typical experimental set-up. B- Specimen and Loading Instrumentation.**

## 6. Fresh HSSCC Properties Results

**Table (5)** illustrates the results of these three tests that carried out on HSSCC mixes and the comparisons with the standard limitations are also presented. From this table, one can notice that the results of all mixes tests satisfy the requirements of EFNARC[5] specifications except the last mix (HSCC-0.8) which exceeds the limitations by small margins in slump flow test and $T_{50}$ slump flow test. The deviation is acceptable according ACI-237R-07[7] which gives limitation of 450-760 mm for slump flow test and according to Advanced Concrete Masonry Center which suggests a value of > 600 mm for slump flow and a value of < 7 sec for $T_{50}$ slump flow test for mixes which are designed with characteristic cube strength not less than 60 MPa.

**Table .(5) Tests results of fresh properties for HSSCC**

| Mix name | Slump flow (mm) | $T_{50}$ (sec) | L – box ($H_2/H_1$) |
|---|---|---|---|
| HSSCC-0 | 730 | 4 | 0.92 |
| HSCC-0.4 | 690 | 4.5 | 0.88 |
| HSSCC-0.8 | 640 | 6 | 0.81 |
| Limits of EFNARC[5] | 650-800 | 2-5 | 0.8-1 |

## 7. Hardened HSSCC Mechanical Properties Results

**Table (6)** shows test results of mechanical properties obtained for the four mixes. These properties are concrete compressive strength ($f'_c$), splitting tensile strength ($f_t$) and modulus of rupture ($f_r$). Each value presented in this table represents the average value of three specimens.

**Table .(6) Tests results of mechanical properties for hardened CC & HSSCC**

| Mix name | $f'_c$ (MPa) | $f_t$ (MPa) | $f_r$ (MPa) |
|---|---|---|---|
| **CC** | **33** | **3.12** | **4.41** |
| **HSCC** | **66** | **4.56** | **6.80** |
| **HSCC-0.4** | **70** | **5.43** | **8.21** |
| **HSCC-0.8** | **72** | **6.23** | **9.05** |

The effect of steel fibers on concrete compressive strength seems to be very small for HSSCC. The splitting tensile strength and modulus of rupture are significantly affected by using steel fibers.

## 8. Test Results of HSSCC One-Way Slabs

**Table (7)** summarizes the results of first cracking load ($P_{cr}$), ultimate load ($P_u$) and mode of failure for all tested slabs together with their deflection.

**Table .(7) Tests results of HSSCC one-way slabs**

| Slab Designation | Steel reinforcement ratio (ρ) | Steel fibers % by volume | Slab thickness (mm) | $P_u$ kN | $D_u$ (mm) | Mode of failure |
|---|---|---|---|---|---|---|
| CC1-0-5 | 0.0033 | 0 | 50 | 29 | 2.38 | F.T. |
| CC1-0-7 | 0.0033 | 0 | 70 | 41 | 3.79 | F.T. |
| CC2-0-5 | 0.0066 | 0 | 50 | 42 | 2.93 | F.S. |
| CC2-0-7 | 0.0066 | 0 | 70 | 56.5 | 6.5 | F.S. |
| HSSCC1-0-5 | 0.0033 | 0 | 50 | 47.5 | 3.77 | F.T. |
| HSSCC1-0-7 | 0.0033 | 0 | 70 | 65 | 4.2 | F.T. |
| HSSCC2-0-5 | 0.0066 | 0 | 50 | 72.5 | 4.91 | F.T.+F.S. |
| HSSCC2-0-7 | 0.0066 | 0 | 70 | 92.5 | 6.4 | F.T.+F.S. |
| HSSCC1-0.4-5 | 0.0033 | 0.4 | 50 | 62.5 | 4.9 | F.T. |
| HSSCC1-0.4-7 | 0.0033 | 0.4 | 70 | 102 | 7.2 | F.T. |
| HSSCC2-0.4-5 | 0.0066 | 0.4 | 50 | 87.5 | 5.8 | F.T.+F.S. |
| HSSCC2-0.4-7 | 0.0066 | 0.4 | 70 | 122.5 | 9.7 | F.T.+F.S. |
| HSSCC1-0.8-5 | 0.0033 | 0.8 | 50 | 90.5 | 5.24 | F.T.+F.S. |
| HSSCC1-0.8-7 | 0.0033 | 0.8 | 70 | 118 | 8.7 | F.T.+F.S. |
| HSSCC2-0.8-5 | 0.0066 | 0.8 | 50 | 107.5 | 7.38 | F.T.+F.S. |
| HSSCC2-0.8-7 | 0.0066 | 0.8 | 70 | 137.5 | 9.85 | F.T.+F.S. |

- F.T.: Flexural Tension.

-F.S.: Flexural Shear.

## 9. Discussion of Test Results

### 9.1 Deflections

The load-deflection relationships for the tested slabs are shown in **Figures (3) To (6).** Initial loading of the slabs showed approximately linear elastic characteristics until the cracking load Pcr was exceeded and the first crack developed 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 steel reinforced 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.

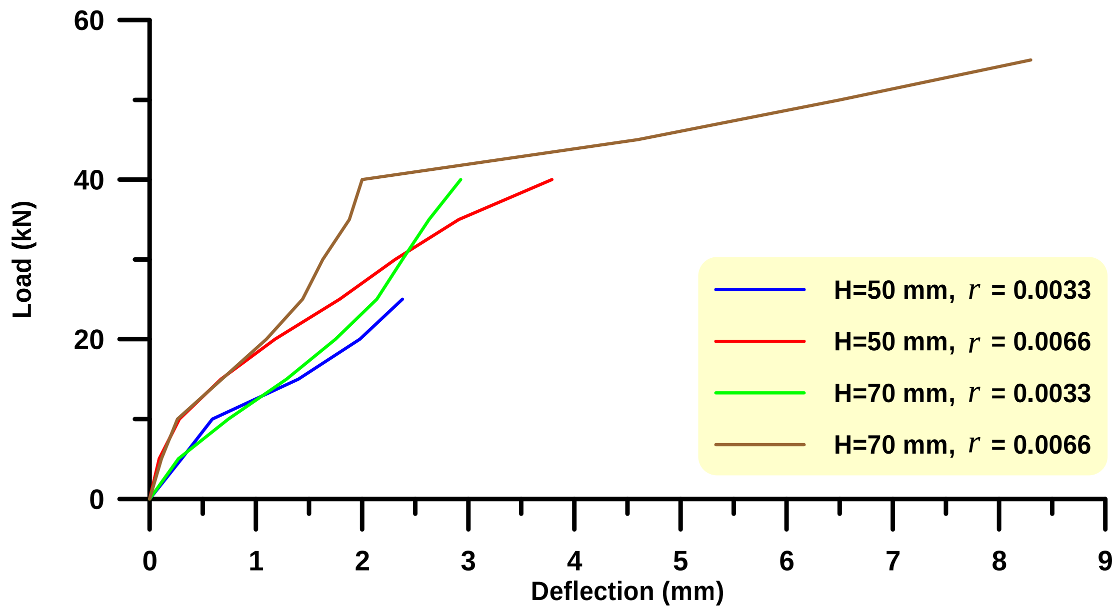



Fig .(3) Load-deflection curves of C.C. slabs

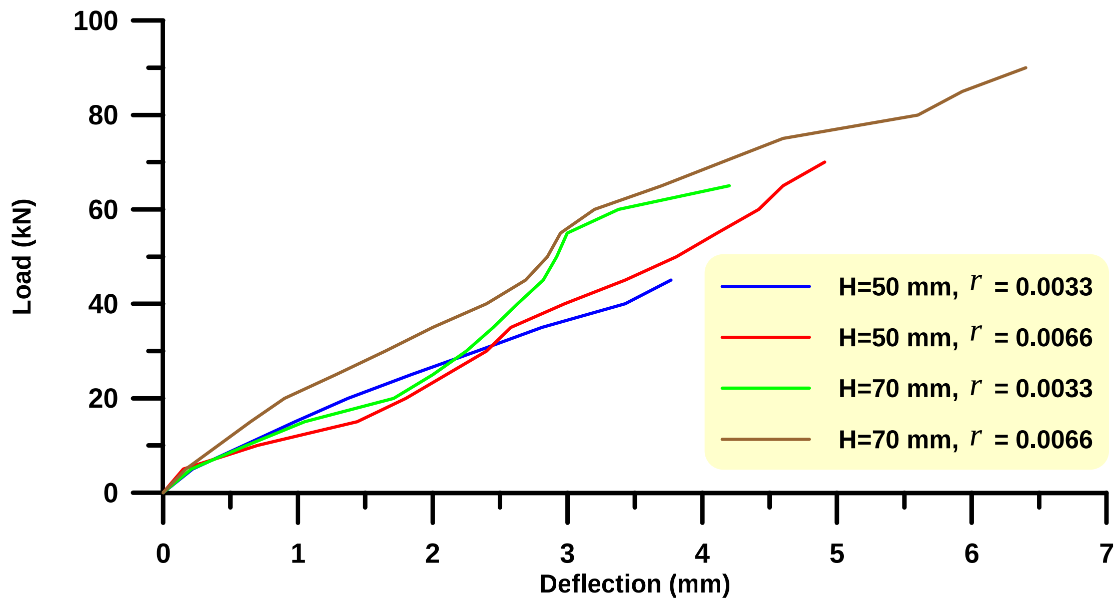



Fig .(4) Load-deflection curves of HSSCC slabs with $V_f$=0%

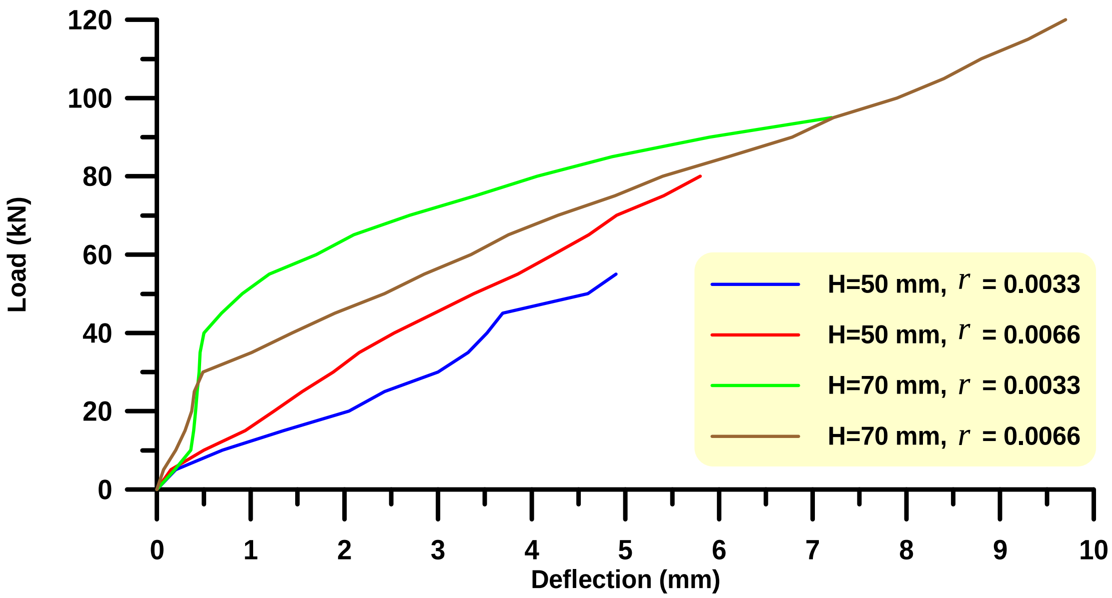



**Fig .(5) Load-deflection curves of HSSCC slabs with Vf=0.4%**

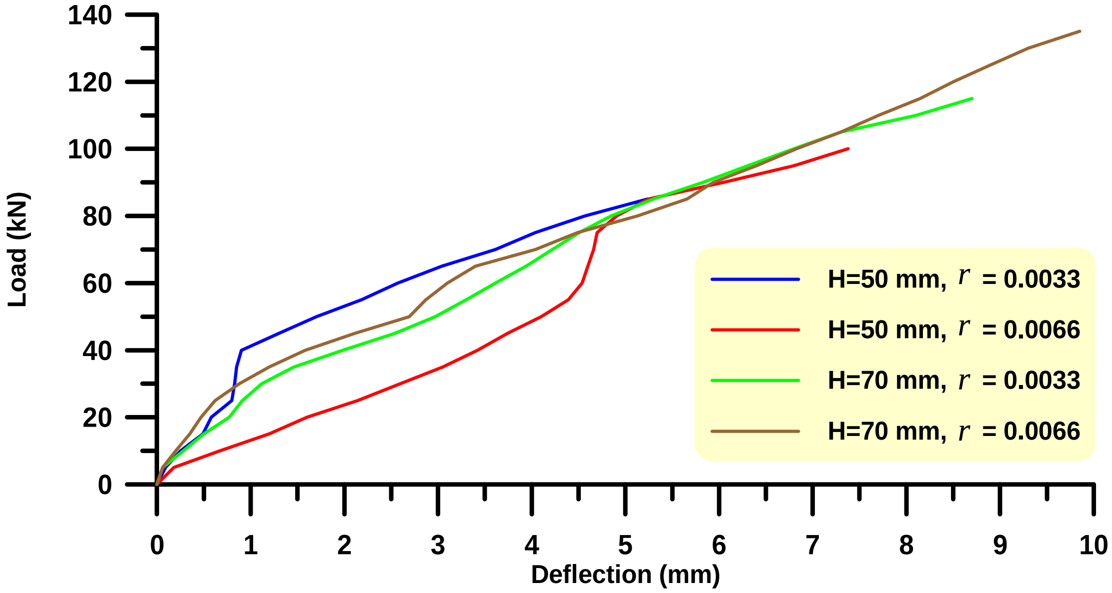



**Fig .(6) Load-deflection curves of HSSCC slabs with Vf=0.8%**

## 9.2 First Cracking and ultimate failure load

At low level of load, the slab behavior was linear elastic with no crack occurrence. As load level increase, the extreme fiber concrete stress reach it's limiting concrete tensile stress and hair fine flexure cracks occur.

As the load increase above the first cracking load, the cracks seem to widen and start to propagate, and generally extend (to be initiated) and deviate towards the slab free sides up to failure.

The cracking loads for all of the tested slabs observed to be at 20 up to 60% of the slab failure load. In general, the first crack load for all the tested slabs appeared under the loading point. The cracking load and ultimate load for all tested slabs are listed in **Table (8).**

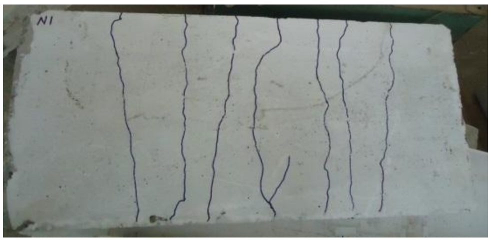
**Table .(8) Ultimate & first crack loads**

| Slab Designation | f′c (MPa) | $D_{cr}$ (mm) | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}$/ $P_u$ | Stiffness* $P_{cr}/D_{cr}$ |
|---|---|---|---|---|---|---|
| CCS1-0-5 | 33 | 1.0 | 12.5 | 29 | 0.43 | 12.5 |
| CCS1-0-7 | 33 | 0.67 | 15 | 41 | 0.36 | 22.4 |
| CCS2-0-5 | 33 | 0.8 | 13.5 | 42 | 0.32 | 16.9 |
| CCS2-0-7 | 33 | 0.89 | 17 | 56.5 | 0.3 | 19.1 |
| HSSCC1-0-5 | 66 | 1.37 | 20 | 47.5 | 0.42 | 14.6 |
| HSSCC1-0-7 | 66 | 2.25 | 30 | 65 | 0.46 | 13.33 |
| HSSCC2-0-5 | 66 | 2.4 | 32 | 72.5 | 0.44 | 13.33 |
| HSSCC2-0-7 | 66 | 2.69 | 45 | 92.5 | 0.48 | 16.7 |
| HSSCC1-0.4-5 | 70 | 3.32 | 35 | 62.5 | 0.56 | 10.5 |
| HSSCC1-0.4-7 | 70 | 2.7 | 52 | 102 | 0.51 | 19.2 |
| HSSCC2-0.4-5 | 70 | 2.16 | 40 | 87.5 | 0.46 | 18.5 |
| HSSCC2-0.4-7 | 70 | 3.1 | 67.5 | 122.5 | 0.55 | 21.77 |
| HSSCC1-0.8-5 | 72 | 1.3 | 45 | 90.5 | 0.49 | 34.6 |
| HSSCC1-0.8-7 | 72 | 3.65 | 61.5 | 118 | 0.52 | 16.85 |
| HSSCC2-0.8-5 | 72 | 4.2 | 52.5 | 107.5 | 0.48 | 12.5 |
| HSSCC2-0.8-7 | 72 | 3.2 | 61.5 | 137.5 | 0.45 | 19.2 |

*Stiffness corresponding to the slope of load deflection curve.

## 9.3 Modes of failure

For a simply supported one-way slab subjected to equal transverse loads at the third points, the middle third of the span is subjected to pure bending (such that it is under zero shear and maximum bending moment); whilst the remaining sections experience maximum shear force and varying bending moment. The middle third experiences the largest strains and therefore the concrete beneath undergoes cracking first. However, many of the slabs failed by combined modes of flexural tension and flexural shear. Each of the slabs developed at least one shear crack. The shear cracks developed after several flexural cracks had developed. Typical crack configurations have been illustrated in **Figure (7).**

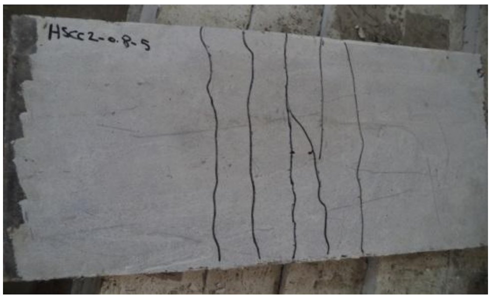


**CCS1-0-5**

**HSSCC1-0-5**

**HSSCC1-0.4-5**

**HSSCC1-0.4-7**



**HSSCC2-0.8-5**

**HSSCC2-0.4-7**

**Fig .(7) Crack configuration of tested slabs**

## 10. Effect of Concrete Compressive Strength (f'c)

Effect of (f′c) on cracking and ultimate loads and the ratio between them for all tested slabs are detailed in **Table (9).** The improving in ultimate load due to doubling the (f′c) value ranges from 58.5 % to 72.6 % (average increase is 64.7 %). It is clear that the increase in ($f'_c$) value reduces the deflection for all load stages. The reduction in deflection as a result of rising ($f'_c$) is insignificant. The increase in ($f'_c$) value results in higher modulus of elasticity then result in higher flexural rigidity (EI), therefore, the deflection is smaller (positive action).

**Table .(9) Effect of (f'c) on cracking and ultimate loads**

| Slab Designation | f′c (MPa) | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}/P_u$ | D$P_{cr}$ % | D$P_u$ % |
|---|---|---|---|---|---|---|
| CCS1-0-5 | 33 | 12.5 | 29 | 0.43 | 60 | 63.8 |
| HSSCC1-0-5 | 66 | 20 | 47.5 | 0.42 | | |
| CCS1-0-7 | 33 | 15 | 41 | 0.36 | 100 | 58.5 |
| HSSCC1-0-7 | 66 | 30 | 65 | 0.46 | | |
| CCS2-0-5 | 33 | 13.5 | 42 | 0.26 | 137 | 72.6 |
| HSSCC2-0-5 | 66 | 32 | 72.5 | 0.44 | | |
| CCS2-0-7 | 33 | 17 | 56.5 | 0.22 | 164.7 | 63.7 |
| HSSCC2-0-7 | 66 | 45 | 92.5 | 0.48 | | |

## 11. Effect of volumetric steel fiber ratio ($V_f$)

Effect of ($V_f$) on cracking and ultimate loads and the ratio of them for all tested slabs are detailed and **Tables (10)** and **(11).** The improvement in ultimate load value due to increasing ($V_f$) from 0 % to 0.4 % ranges from 20.7 % to 56.9 % (average increase is 35.4 %). The improvement becomes larger as the slab thickness increases. The improvement in ultimate load due to increasing ($V_f$) from 0 % to 0.8 % ranges from 48.3 % to 90.5 % (67.23 % as a typical average improvement for all cases). This improvement becomes larger as the steel reinforcement ratio decreases.

The improvement in cracking load due to increasing ($V_f$) from 0.0 % to 0.4 % ranges from 25 % to 75 % (55.83 % as a typical average improvement for all cases). The improvement becomes higher as the slab thickness increases. The improvement in cracking load due to increasing ($V_f$) from 0 % to 0.8 % ranges from 36.7 % to 125 % (82.7 % as typical average improvement for all cases).

The presence of steel fibers results in a delay in crack initiation and propagation where they hold concrete particles and prevent them from initial separation. Therefore, the first crack in fibrous concrete slabs appears at a load level appreciably higher than the load which causes crack initiation in non-fibrous concrete slabs. After cracking, the steel fibers prevent the crack widening and delay its growth by absorption a portion of tension stresses carried by concrete i.e., this action reduces the tension stresses applied to concrete. Therefore, the failure takes place in fibrous concrete slabs at a load level higher than that causing the failure load of non-fibrous concrete slabs. The ratio between cracking and ultimate loads increases with increasing steel fiber ratio, where it ranges from 0.3 to 0.48 for non-fibrous concrete slabs and ranges from 0.46 to 0.56 for fibrous concrete beams with 0.4 % of steel fibers. While the ratio ranges from 0.45 to 0.52 for fibrous concrete slabs with 0.8 % of steel fibers.

**Table .(10) Effect of using0.4% steel fibers on cracking and ultimate loads**

| Slab Designation | $V_f$% | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}/P_u$ | $DP_{cr}$ % | $DP_u$ % |
|---|---|---|---|---|---|---|
| HSSCC1-0-5 | 0 | 20 | 47.5 | 0.42 | 75 | 31.6 |
| HSSCC1-0.4-5 | 0.4 | 35 | 62.5 | 0.56 | | |
| HSSCC1-0-7 | 0 | 30 | 65 | 0.46 | 73.33 | 56.9 |
| HSSCC1-0.4-7 | 0.4 | 52 | 102 | 0.51 | | |
| HSSCC2-0-5 | 0 | 32 | 72.5 | 0.44 | 25 | 20.7 |
| HSSCC2-0.4-5 | 0.4 | 40 | 87.5 | 0.40 | | |
| HSSCC2-0-7 | 0 | 45 | 92.5 | 0.48 | 50 | 32.4 |
| HSSCC2-0.4-7 | 0.4 | 67.5 | 122.5 | 0.55 | | |

**Table .(11) Effect of using0.8% steel fibers on cracking and ultimate loads**

| Slab Designation | $V_f$% | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}/P_u$ | $DP_{cr}$ % | $DP_u$ % |
|---|---|---|---|---|---|---|
| HSSCC1-0-5 | 0 | 20 | 47.5 | 0.42 | 125 | 90.5 |
| HSSCC1-0.8-5 | 0.4 | 45 | 90.5 | 0.5 | | |
| HSSCC1-0-7 | 0 | 30 | 65 | 0.46 | 105 | 81.5 |
| HSSCC1-0.8-7 | 0.4 | 61.5 | 118 | 0.52 | | |
| HSSCC2-0-5 | 0 | 32 | 72.5 | 0.44 | 64 | 48.3 |
| HSSCC2-0.8-5 | 0.4 | 52.5 | 107.5 | 0.49 | | |
| HSSCC2-0-7 | 0 | 45 | 92.5 | 0.48 | 36.7 | 48.6 |
| HSSCC2-0.8-7 | 0.4 | 61.5 | 137.5 | 0.45 | | |

## 12. Effect of flexural steel reinforcement (ρ)

Generally, the ultimate flexural capacity increases with the addition of steel reinforcement.

For conventional concrete increasing flexural steel reinforcement from 0.0033 to 0.0066 increases the ultimate failure load by (44.8 and 37.8%) for slabs with (50 and 70mm) thicknesses, respectively.

The percentages increase of the ultimate failure load in slabs with 50mm thickness were increased to (52.6, 40 and 18.8%) for HSSCC slabs with steel fibers content (0, 0.4 and 0.8%), respectively. On the other hand, the percentages of increase of the ultimate failure load in slabs with 70mm thickness by (42.3, 20 and 16.5%) for HSSCC slabs with steel fibers content (0, 0.4 and 0.8%), respectively. **Table (12)** shows the effect of flexural steel reinforcement ratio on the ultimate failure load.

**Table .(12) Effect of flexural steel reinforcement ratio on the ultimate failure load**

| Slab Designation | ρ | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}$/ $P_u$ | $DP_{cr}$ % | $DP_u$ % |
|---|---|---|---|---|---|---|
| CCS1-0-5 | 0.0033 | 12.5 | 29 | 0.43 | 8 | 44.8 |
| CCS2-0-5 | 0.0066 | 13.5 | 42 | 0.26 | | |
| CCS1-0-7 | 0.0033 | 15 | 41 | 0.36 | 13.3 | 37.8 |
| CCS2-0-7 | 0.0066 | 17 | 56.5 | 0.22 | | |
| HSSCC1-0-5 | 0.0033 | 20 | 47.5 | 0.42 | 60 | 52.6 |
| HSSCC2-0-5 | 0.0066 | 32 | 72.5 | 0.44 | | |
| HSSCC1-0-7 | 0.0033 | 30 | 65 | 0.46 | 50 | 42.3 |
| HSSCC2-0-7 | 0.0066 | 45 | 92.5 | 0.48 | | |
| HSSCC1-0.4-5 | 0.0033 | 35 | 62.5 | 0.56 | 14.3 | 40 |
| HSSCC2-0.4-5 | 0.0066 | 40 | 87.5 | 0.40 | | |
| HSSCC1-0.4-7 | 0.0033 | 52 | 102 | 0.51 | 29.8 | 20 |
| HSSCC2-0.4-7 | 0.0066 | 67.5 | 122.5 | 0.55 | | |
| HSSCC1-0.8-5 | 0.0033 | 45 | 90.5 | 0.5 | 16.7 | 18.8 |
| HSSCC2-0.8-5 | 0.0066 | 52.5 | 107.5 | 0.49 | | |
| HSSCC1-0.8-7 | 0.0033 | 61.5 | 118 | 0.52 | 0 | 16.5 |
| HSSCC2-0.8-7 | 0.0066 | 61.5 | 137.5 | 0.45 | | |

## 13. Effect of slab thickness

Generally, the ultimate flexural capacity increases with the increase of slab thickness.

For conventional concrete increasing slab thickness from 50mm to 70mm increases the ultimate failure load by (41.4 and 34.5%) for slabs with (0.0033 and 0.0066) flexural steel reinforcement ratio respectively.

The percentages increase of the ultimate failure load in slabs with 0.0033 flexural steel reinforcement were more by (36.8, 63.2 and 30.4%) for HSSCC slabs with steel fibers content (0, 0.4 and 0.8%), respectively.

While the percentages increase of the ultimate failure load in slabs with 0.0066 flexural steel reinforcement were (27.6, 40 and 34.4%) for HSSCC slabs with steel fibers content (0, 0.4 and 0.8%), respectively. These seem to be close to the values for the reference slabs. **Table (13)** shows the effect of slab thickness on the ultimate failure load.

From the results in **Table (13),** one can see that there are clear differences in the percentages of increasing in the ultimate failure load for slabs with 0.0033 flexural steel reinforcement ratio which was varied between 41.4% in reference slabs to 63.2% in HSSCC slabs with 0.4% steel fibers content. This variation in the percentage increase of the ultimate failure load between slabs with flexural steel reinforcement ratio 0.0033 and 0.0066 was because the addition of steel fibers in slabs with 0.0033 flexural steel reinforcement ratio changes the mode of failure from (flexural tension) to (flexural shear), while the mode of failure in slabs with 0.0066 flexural steel reinforcement ratio was already (flexural shear).

**Table .(13) Effect of slab thickness on the ultimate failure load**

| Slab Designation | Slab Thickness (mm) | $P_{cr}$ (kN) | $P_u$ (kN) | $P_{cr}/P_u$ | $DP_{cr}$ % | $DP_u$ % |
|---|---|---|---|---|---|---|
| CCS1-0-5 | 50 | 12.5 | 29 | 0.43 | 20 | 41.4 |
| CCS1-0-7 | 70 | 15 | 41 | 0.36 | | |
| CCS2-0-5 | 50 | 13.5 | 42 | 0.26 | 26 | 34.5 |
| CCS2-0-7 | 70 | 17 | 56.5 | 0.22 | | |
| HSSCC1-0-5 | 50 | 20 | 47.5 | 0.42 | 50 | 36.8 |
| HSSCC1-0-7 | 70 | 30 | 65 | 0.46 | | |
| HSSCC2-0-5 | 50 | 32 | 72.5 | 0.44 | 40.6 | 27.6 |
| HSSCC2-0-7 | 70 | 45 | 92.5 | 0.48 | | |
| HSSCC1-0.4-5 | 50 | 35 | 62.5 | 0.56 | 48.6 | 63.2 |
| HSSCC1-0.4-7 | 70 | 52 | 102 | 0.51 | | |
| HSSCC2-0.4-5 | 50 | 40 | 87.5 | 0.40 | 68.9 | 40 |
| HSSCC2-0.4-7 | 70 | 67.5 | 122.5 | 0.55 | | |
| HSSCC1-0.8-5 | 50 | 45 | 90.5 | 0.5 | 36.7 | 30.4 |
| HSSCC1-0.8-7 | 70 | 61.5 | 118 | 0.52 | | |
| HSSCC2-0.8-5 | 50 | 52.5 | 107.5 | 0.49 | 17.2 | 34.4 |
| HSSCC2-0.8-7 | 70 | 61.5 | 137.5 | 0.45 | | |

## 14. Conclusions

1. For the case of 50mm slabs, it was found that, with ρ=0.0033, the percentage of increase in the ultimate failure load of HSSCC slabs exceeded that of CC ones by (63.8, 115.5 and 212%) when HSCC slabs had $V_f$ of (0, 0.4 and 0.8%) respectively, and of the order (72.6, 108.3 and 156%), for HSSCC slabs with ρ=0.0066.
2. For the case of 70mm slabs it was found that, with ρ=0.0033 the percentage of increase in the ultimate failure load of HSSCC slabs exceeded that of CC ones by (58.5, 148.8 and 187.8%), when HSSCC slabs had $V_f$ of (0, 0.4 and 0.8%) respectively, and of the order (63.7, 116.8 and 143.4%), for HSSCC slabs with ρ=0.0066.
3. The inclusion of steel fibers in all HSSCC slabs resulted in a significantly enhanced ductility which made the slabs fail gradually in a ductile manner, unlike non-fibrous slabs and/or conventional concrete slabs which showed lesser ductility at failure.
4. The inclusion of steel fibers in HSSCC slabs resulted in an enhanced stiffness, reduced crack width, reduced rate of crack propagation and preserved the whole section together after reaching failure. Most of the steel fibers were observed to pullout of the cement matrix rather than snap.

5. Generally, the ultimate flexural capacity increases with the increase of slab thickness and flexural steel reinforcement ratio, but increasing slab thickness still plays a major role on the ultimate failure load. It was found that for HSSCC with 0.8% $V_f$ increasing the slab thickness from 50mm to 70mm increases the ultimate failure load by (30.4 and 34.4)% for slabs with ($\rho$=0.0033 and 0.0066), respectively. In contrast, increasing flexural reinforcement ratio has a small effect as compared with the increases of slab thickness. It was found that increases of 0.8% steel fibers HSSCC slab reinforcement ratio from 0.0033 to 0.0066 increased the ultimate failure load by (18.8 and 16.5)% for slabs with 50mm and 70 mm thicknesses, respectively.
6. Generally, the ultimate flexural capacity increases with the increase of slab thickness and flexural steel reinforcement ratio, but increasing steel reinforcement ratio plays a major role on the ultimate failure load for non-fibrous slabs, while the increasing slab thickness plays a major role on the ultimate failure load for fibrous slabs.

## 15. References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