Effect of Steel Fiber on Punching Shear Strength of Non-Rectangular Reactive Powder Concrete Slabs

Tamara Adnan Qasim Al-Shaikhli
Hayway and Transportation Department, Faculty of Engineering, Al-Mustansiriyah University, Baghdad, Iraq
Email: tadnan_sh@yahoo.com

***Abstract*—This study presents an experimental investigation of punching shear strength of Reactive Powder Concrete (RPC) square and triangular flat slabs. Reactive powder concrete is an ultra-high strength and high ductility composite materials in form of a superplasticized cement mixture with silica fume and steel fibers. Six reduced scale reinforced concrete slab specimens divided into two groups (square and triangular slabs) were casted and tested in this study. Each group consists of three specimens which are identical in size and shape but contains different percentages of steel fibers (0, 0.5 and 1%) of total volume. Results indicated that, punching shear strength increases by about (37%) and (100%) in square slabs containing 0.5% and 1% of steel fibers respectively. While this increment is about (53%) and (100%) in triangular slabs which containing steel fiber by 0.5% and 1% by the total volume.**

***Index Terms*—punching shear, steel fiber, flat plat slab, reactive powder concrete**

I. Introduction

Reinforced concrete slabs may be carried directly by the columns without using beams or girders. Such slabs are described as flat plates. Since the depth (thickness) of a typical slab is relatively small, its capacity to transfer loads to the columns by shear is often low. As a result, most failure cases of flat plates are initiated by overstress in shear at the columns. These failures are termed as Punching-Shear failures [1].

Punching shear failure of slabs is usually sudden and leads to progressive failure of flat plate structures; therefore, caution is needed in the design of such slabs and attention should be given to avoid the sudden failure conditions [1].

Punching shear of rectangular (or square) shaped slabs were interested by several researches [1]-[4] and several experimental investigations were conducted to increase the punching shear strength of slabs by using steel fiber reinforced concrete, high strength concrete or concrete polymer composite [5]. Conventional shear reinforcement can also be used to increase the punching shear strength of slabs [6], however, shear reinforcement cannot be used in this slabs.

A new type of concrete that can be used to increase punching shear strength is called reactive powder concrete. Reactive powder concrete is an ultra-high strength and high ductility composite materials with enhanced mechanical properties if compared with conventional types of concrete. Therefore, this study is aimed to investigate the effect of reactive powder concrete on punching shear strength of square and triangular shaped flat slabs.

Sometimes, and for architectural purposes, the flat slabs made with non-uniform or irregular shaped, such as circular, triangular, trapezoidal,…etc.

The main objective of this study is to investigate experimentally punching shear and flexural strengths of reactive powder concrete slabs, square and triangular shaped slabs.

II. Experimental Work

Two test slab groups were casted and tested, each of which consisted of three slab specimens identical in size but different in constituent's properties. Square shaped slabs, having dimensions of (450 x 450mm), and thickness of (50mm). While, triangular shaped, having a width of (500mm), hight of (810mm) and thickness of (50mm).

Each group consists of three specimens containing three percentages of steel fiber (0, 0.5 and 1%) of total volume.

All slabs are simply supported along all edges and subjected to single point load applied at the center of gravity of each slab. The applied load is transformed from testing machine through a central column of dimensions (40 x 40mm).

III. Materials

A. Cement

Tasluoja Ordinary Portland cement (Type I) was used in this work. It was stored in suitable condition to avoid any exposure to hazard conditions. Table I and Table II show respectively the chemical and physical compositions of cement.

Test results indicate that the used cement conformed to the Iraqi specification No.5 / 1984 [7].

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TABLE I. CHEMICAL COMPOSITION AND MAIN COMPOUNDS OF CEMENT

Oxides Composition	Content%	Limits of Iraqi Specification No.5/1984
CaO	62.96	---
Sio_2	21.04	----
Al_2O_3	5.20	----
Fe_2O_3	2.68	----
MgO	1.77	<5.00
SO3	2.40	<2.80
L.O.I.	3.32	<4.00
Insoluble residue (I.R)	1.32	<1.50
Lime saturation factor(L.S.F)	0.93	0.66-1.02
Main compounds(bougue's equations)		
C_3S	57.04	
C_2S	14.83	---
C_3A	9.25	---
C_4AF	10.95	---

TABLE II. PHYSICAL PROPERTIES OF CEMENT

Physical Properties	Test Results	Limits of Iraqi Specification No.5/1984
Specific Surface Area (Blaine Method), cm^2/g	2985	Not less than 230
Setting Time (Vicat Apparatatus), Initial Setting, (min) final setting, (min)	166 255	Not less than 45 min Not greater than 10 hr.
Compressive strength, MPa at 3 days Compressive strength, MPa at 7 days	18.76 26.81	≥ 15.00 ≥ 21.00
Soundness (autoclave Method), %	0.35	≤ 0.8

B. Fine Aggregates

Al-Ekhaider natural sand of 4.75mm maximum size was used as fine aggregate. Results indicate that the fine aggregate grading is within the requirements of the Iraqi specification No.45/1984 [8]. For reactive powder concrete, very fine sand with maximum size 600 μm is used. This sand is separated by sieving; its grading satisfies the fine grading in accordance with the Iraqi specification No.45/1984 [8]. Table III shows the Grading of the separated fine sand.

TABLE III. GRADING OF THE SEPARATED FINE SAND COMPARED WITH THE REQUIREMENTS OF IRAQI SPECIFICATION NO.45/1984 [8]

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1984
4.75	100	100
2.36	100	100
1.18	100	100
0.600	100	100
0.300	45	15 – 50
0.150	11	0 – 15

C. Silica Fume

One percentage of silica fumes was used (25%(by mass of cementitious material). The chemical composition and properties of silica fume are given in Table IV. The silica fume used in this work conforms to the chemical and physical requirements of ASTM C1240-03 [9] as shown in Table V and Table VI respectively.

TABLE IV. COMPOSITION AND PROPERTIES OF SILICA FUME

Composition (%) Property	Silica Fume
SiO_2	98.87
Al_2O_3	0.01
Fe_2O_3	0.01
CaO	0.23
MgO	0.01
K_2O	0.08
Na_2O	0.00
Blaine fineness (m^2/kg)	20000

TABLE V. CHEMICAL REQUIREMENTS OF SILICA FUME (SF) ASTM C1240-03 [9]

Oxide Composition	Silica Fume	Limit of Specification Requirement ASTM C1240
SiO_2, min. Percent	90.0	> 85.o
Moisture Content, Max. %	0.68	< 3.0
Loss on Ignition, Max. %	2.86	< 6.0

TABLE VI. PHYSICAL REQUIREMENTS OF SILICA FUME ACCORDING TO ASTM C1240-03 [9]

Physical Properties	Silica Fume	Limit of Specification Requirement ASTM C1240
Percent Retained on 45μm (No.325) Sieve, Max.	7	< 10
Accelerated Pozzolanic Strength Activity Index with Portland Cement at 7 days, Min. Percent of Control	128.6	> 105
Specific Surface, Min, m^2/g	21	> 15

D. Steel Fibers

RPC is characterized by the inclusion of steel fibers and the absence of large aggregates. Steel fiber-reinforced concrete is basically a cheaper and easier to use form of reinforced concrete. Steel fibers aids in converting the brittle characteristics of concrete to a ductile one. The principal role of fibers is resisting the formation and growth of cracks by providing pinching forces at crack tips [10].

The steel fibers used in this test program were straight steel fibers manufactured by Bekaert Corporation in China.

The fibers have the properties described in Table VII and Fig. 1 shows steel fibers used in this study.

Figure 1. Silica fume

TABLE VII. PROPERTIES OF STEEL FIBERS

length (mm)	Diameter (mm)	Density (kg/m^3)	Tensile strength (MPa)	Aspect ratio
13	0.2	7800	2600	65

Figure 2. Steel fibers

E. Mixing Water

Tap water was used for casting and curing all the specimens.

F. Steel Reinforcement

The steel reinforcement mesh consists of Welded Wire Fabric (WWF); each wire have yield strength (f_y) of (360MPa) and (6mm) in diameter at (75 mm) c/c spacing in each direction for square and triangular slabs. A clear cover of (5mm) was provided below the mesh. It may be noted that, for both square and triangular shaped slabs, the steel reinforcement were designed to ensure the tested specimens to fail in punching shear.

G. Superplasticizer

For the production of high strength conventional concrete with steel fiber, superplasticizer (High Water Reducing Agent HWRA) based on polycarboxylic ether is used [11]. The typical properties of Glenium 51 are shown in Table VIII. Glenium 51 is free of chlorides and complies with ASTM C494, type A and type F. It is compatible with all Portland cements that meet the recognized international standards.

TABLE VIII. TYPICAL PROPERTIES OF GLENIUM 51

Form	Viscous Liquid
Colour	Light Brown
Relative Density	1.1 @ 20 ^{0}C
pH	6.6
Viscosity	128+/-30 cps @ 20 ^{0}C
Transport	Not Classified as Dangerous
Labeling	No Hazard Label Required

IV. CONCRETE MIXES

Several trial mixes were made, finally the following mixes, shown in Table IX, were used in this study.

TABLE IX. CONCRETE MIXES

Mix Type	Cement kg/m^3	Sand kg/m^3	Silica Fume kg/m^3	w/c	Super plasticizer L/m^3	Steel fiber content %
*S0.0	1000	1000	250	0.2	3.0	0
*G0.0	1000	1000	250	0.2	3.0	0
S0.5	1000	1000	250	0.2	3.0	0.5
G0.5	1000	1000	250	0.2	3.0	39
S1.0	1000	1000	250	0.2	3.0	1
G1.0	1000	1000	250	0.2	3.0	78

*Where: S/ Square slab, G/ Triangular Slab

V. MIXING PROCEDURE

Initially the small trial batch mixing was prepared using a small rotary mixer of $0.01m^3$ capacity. Later on, all mixes were prepared in a large horizontal rotary mixer of 0.15 m^3 capacity, Fig. 2.

The procedure followed in preparing an RPC mix was as follows: the desired quantity of silica fume was mixed in dry state with the required quantity of cement. This operation was continued to 5 minutes to ensure that silica fume powder was thoroughly dispersed between cement particles. Then, fine sand was put in the mixer and mixed for 10 minutes. Then, the superplasticizer was dissolved in water and the solution of water and superplasticizer was added to the rotary mixer and the whole mix ingredients were mixed for a sufficient time. The mixer was stopped and mixing was continued manually especially for the portions not reached by the blades of the mixer. The mixer then was operated for 5 minutes to attain reasonable fluidity. Fibers were uniformly distributed into the mix slowly in 5 minutes during mixing process, and then the mixing process continued for additional 2-3 minutes. In total, the mixing of one batch requires approximately 25- 30 minutes.

Several effects were noticed when adding the fibers to the concrete matrix, the most striking of which is the great reduction in workability, which is reduced as the fiber content is increased.

The compressive strength and dimensions of tested slabs are shown in Table X.

Figure 3. Stage of mixing properties and description of tested slabs

TABLE X. PROPERTIES AND DESCRIPTION OF TESTED SLABS

Slab Shape	Slab Symbol	Compressive strength (MPa)	Thickness (mm)	Width (mm)	Length (mm)	Reinforcement
Square	S0	87.7	50	450	450	ϕ6mm@75 c/c
	S0.5	102.7	50	450	450	
	S1.0	113.2	50	450	450	
Triangular	G0	87.7	50	500	810	
	G0.5	102.7	50	500	810	
	G1.0	113.2	50	500	810	

VI. TEST PROCEDURE

Setup of tested specimens is shown in Fig. 3. All slab specimens were tested using universal testing machine (MFL system) with monotonic loading to ultimate states. The tested slabs were simply supported and loaded with a single-point load. The slabs have been tested at ages of 28 days. The slab specimens were placed on the testing machine and adjusted so that the centerline, supports, point load and dial gauge were in their correct or best locations.

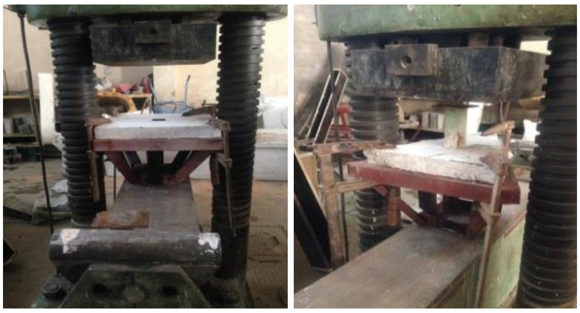


Figure 4. Test procedure

Loading was applied slowly in successive increments; the applied load is transformed from testing machine through a central column of dimensions (40x40mm). At the end of each load increment, observations and measurements were recorded for the mid-span deflection and crack development and propagation on the slab surface. When the slab reached advanced stage of loading, smaller increments were applied until failure, where the load indicator stopped recording anymore and the deflections increased very fast without any increase in applied load. The developments of cracks (crack pattern) were marked with a pencil at each load increment.

VII. RESULTS AND DISCUSSION

Photographs of the tested slabs are shown in Fig. 4 and test results are given in Table XI and Fig. 5. The groups of tested slabs were designed to fail in punching shear. The use of steel fiber has a clear effect on compressive strength of RPC. The compressive strength of RPC is increased by about 17.1% and by 29.1% by using steel fiber by 0.5 and 1% respectively, if compared with reference mix without steel fibers. Generally, as the load was increased, radial cracks started to appear and extended from that perimeter toward the slab edges. At the same time, the cracks increased in number at the center regain of the slab. A complete failure occurred by increasing the load.

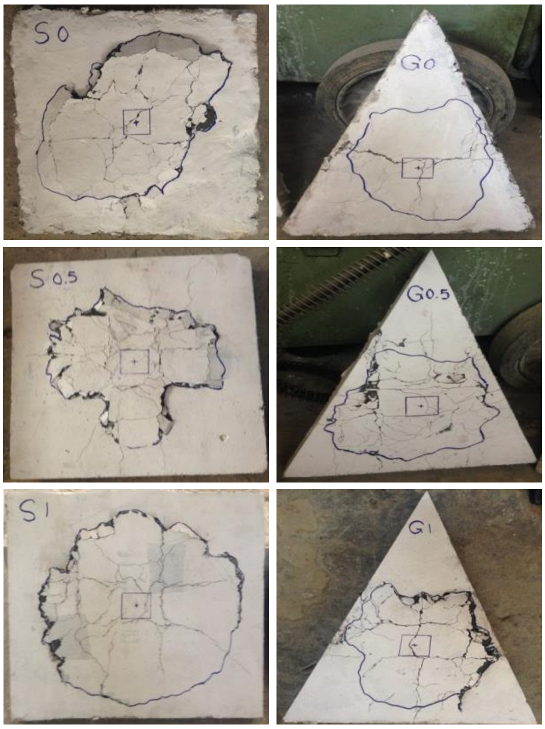


Figure 5. The test specimens

The cracking pattern depends on the longitudinal, transverse steel spacing and the quantity of fibers. During the test, it was observed that the slab without steel fiber reinforcement failed shortly after the formation of the critical diagonal crack. However, in fibrous RPC slabs, multiple cracks were seen to form soon after initial cracking and the rate of crack growth on the fiber volumetric content. The cracks propagated at a faster rate in specimens with lower quantities of fibers All the tested specimens were failed in punching shear, the punching shear failure occurred by developing of cracks and this cracks progressed rapidly and announced an imminent failure and as a result crushing of the concrete was occurred. The first crack appears around the sides of the column on the tension face of the slab and other cracks form at the central region of the slab. By increasing the load, these cracks were widen and increased in number. At ultimate load, punching shear failure occurs suddenly. Fig. 4 illustrate crack patterns and failure modes of Square and triangular shaped slab.

Ultimate load capacity, failure characteristics and failure modes of Square and triangular specimens are reported and presented in Table XI.

Generally, the experimental results show that the ultimate capacity increased with increasing in compressive strength and increasing the percentage of steel fiber this result is compatible with Munahey [12], Ramadane [13], and Zhang [14]. The ultimate load increased by about 37% and 100% in square specimens which contain steel fiber by 0.5% and 1%, of the total volume, respectively while this percentage is about 59% and 100% in triangular slabs containing steel fiber by 0.5 and 1% respectively. These results are compatible to the researchers [15] and [16]. The use of steel fiber improves the punching shear resistance and allowing higher forces to be transferred through the slab-column connection. As a result, the ultimate capacity depends on both content of steel fiber and shape of slab.

It is evident from Table XII and Fig. 5 That the deflection (Δ_o) at ultimate load is considerably increased by the presence of steel fibers. The addition of steel fibers to RPC square slab at volume fractions of 0.5% and 1.0% are (19.5 and 99%) respectively, while these percentages in triangular slabs are (3.4 and 13%) respectively as compared to Δ_o of the nonferrous RPC slab.

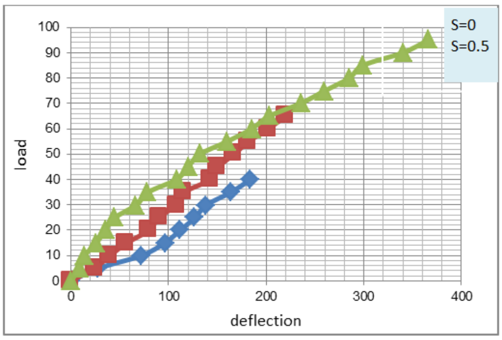
It is clear from Table XII that the ductility ratio also increased by the presence of steel fibers. The ductility ratio in square slabs increased from 8.1 to 16.6 when the steel fibers ratio increased from 0.5 to 1%, and in triangular slabs the ductility increased from 3.75 to 6.1 when the steel fibers ratio increased from 0.5 to 1%. This is expected since the presence of fibers causes a reduction in the deflection at cracking load and increases the deflection at ultimate load. Also, from Table XII and Fig. 5, it can be concluded that the square shape slabs are more ductile than triangular slabs.

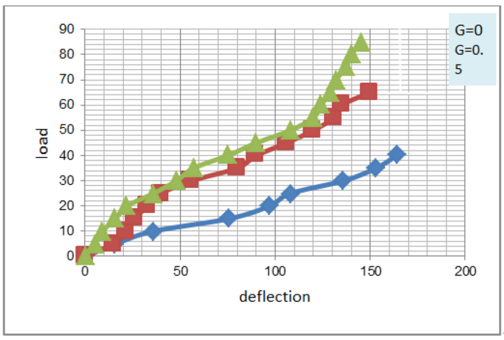
TABLE XI. ULTIMATE, CRACKED LOAD AND TYPE OF FAILURE OF TESTED SLABS

Slab Shape	Slab Symbol	P_u (kN)	P_{ui}/P_{ur}	P_{cr} (kN)	P_{cr}/P_u	Failure Perimeter (mm)	Maximum Diameter (mm)	Failure Mode
Square	S0.0	47.5	1.00	16.0	0.34	126.5	26	Punching Shear
	S0.5	65.0	1.37	17.5	0.27	137	28	
	S1.0	85.0	1.79	20.0	0.24	148.5	32.5	
Triangular	G0.0	42.5	1.00	17.5	0.41	104	21	
	G0.5	65.0	1.53	22.5	0.35	109.5	22	
	G1.0	95.0	2.24	25.0	0.26	116	23	

TABLE XII. RESULTS OF DEFLECTION

RPC slabs	Deflection at first crack load Δ_{cr} (mm)	Deflection at Ultimate load Δ_o (mm)	Ductility ratio (Ψ)
S0	88	184	2.1
S0.5	27	220	8.1
S1	22	366	16.6
G0	72	145	2.0
G0.5	40	150	3.75
G1	27	164	6.1





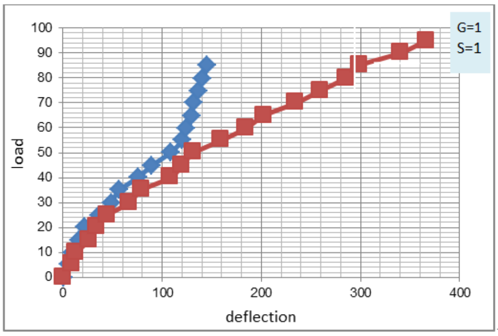


Figure 6. Load – Deflection curve of Square (S) and triangular (G) specimens

Note: each value of deflection is multiplied by 10^{-3}

VIII. CONCLUSIONS

(1) The use of steel fiber has a clear effect on compressive strength of RPC. The compressive strength of RPC is increased by about 17.1% and by 29.1% by using steel fiber by 0.5 and 1% respectively, if compared with reference mix without steel fibers.

(2) The ultimate capacity increased with increasing the percentage of steel fiber. The ultimate load increased by about 37% and 100% in square specimens which contain steel fiber by 0.5% and 1%, of the total volume, respectively while this percentage is about 59% and 100% in triangular slabs containing steel fiber by 0.5 and 1% respectively. The use of steel fiber improves the punching shear resistance and allowing higher forces to be transferred through the slab-column connection. As a result, the ultimate capacity depends on both content of steel fiber and shape of slab.

(3) The deflection (Δ_o) at ultimate load is considerably increased by the presence of steel fibers. The addition of steel fibers to RPC square slab at volume fractions of 0.5% and 1.0% are (19.5 and 99%) respectively, while these percentages in triangular slabs are (3.4 and 13%) respectively as compared to Δ_o of the nonferrous RPC slab.

(4) The ductility ratio also increased by the presence of steel fibers. The ductility ratio in square slabs increased from 8.1 to 16.6 when the steel fibers ratio increased from 0.5 to 1%, and in triangular slabs the ductility increased from 3.75 to 6.1 when the steel fibers ratio increased from 0.5 to 1%. This is expected since the presence of fibers causes a reduction in the deflection at cracking load and increases the deflection at ultimate load

(5) It is concluded that the square shape slabs are more ductile than triangular slabs.

For future studies, the fiber type effect need to be observed, carbon, glass and composite can be added to the concrete slab under punching shear.

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Tamara Adnan Qasim Al-Shaikhli was born in the capital of Iraq Baghdad 1982. She finished her master degree from Al-Mustansiriyah University, College of Engineering. She is currently assistant lecturer in the same university and college. She has carried out lots of works in structure.