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Punching Shear Failure Characteristics Of Flat Slabs Using Reactive And Modified Powder Concrete With Steel Fibers

Prof. Dr. Kaiss F. Sarsam
Building& Construction Eng. Dept.
University of Technology, Baghdad, Iraq

Lecturer. Dr. Hassan F. Hassan
Civil Eng. Dept., College of Eng.
Al-Mustansiriya University, Baghdad,

Abstract :

This work is devoted to study the mechanical properties of reactive powder concrete(RPC) and modified reactive powder concrete (MRPC) as a material as well as studying the punching shear behavior of RPC and MRPC slabs. The experimental program includes investigating the effect of steel fiber volumetric ratio (V_f) and absence of coarse aggregates on some important mechanical properties of RPC and MRPC such as compressive strength, modulus of elasticity (E), splitting tensile strength and modulus of rupture. Additional experimental tests are also conducted to study the effect of V_f, steel reinforcement ratio (ρ) and slab thickness on the failure characteristics of the punching shear (in terms of observation of failure, shape of the failure zone, size of the failure zone, failure angles, critical section perimeters and ultimate punching shear stress) of simply supported reinforced RPC slabs having dimensions of 1000×1000× 50 or 70 mm under concentrated load at the center of the slab.

Keywords: punching shear, flat slab, reactive powder concrete, flexural behavior

خصائص فشل القص الثاقب للبلاطات المسطحة باستخدام خرسانة المساحيق الفعالة الاعتيادية والمطورة والألياف الحديدية

أ.د. قيس فؤاد سرسم
قسم هندسة البناء والإنشاءات
الجامعة التكنولوجية

م.د. حسن فلاح حسن
قسم الهندسة المدنية
الجامعة المستنصرية

الخلاصــــــة :

يهتم البحث الحالي بدراسة الخواص الميكانيكية لخرسانة المساحيق الفعالة (RPC) وخرسانة المساحيق الفعالة المعدلة (MRPC) كمادة إضافة إلى دراسة تصرف القص الثاقب (Punching Shear) للبلاطات المصنعة من هذه الخرسانة. يتركز البرنامج العملي من البحث على دراسة واستقصاء تأثير النسبة الحجمية للألياف الفولاذية ووجود الركام الخشن على بعض الخواص الميكانيكية المهمة لخلطة خرسانة المساحيق الفعالة مثل مقاومة الانضغاط للخرسانة ومقاومة شد الانشطار ومنحني الإجهاد-الانفعال تحت تأثير انضغاط أحادي المحور ومعامل الانثناء. يتضمن البحث أيضا دراسة تأثير نسبة حديد التسليح وسمك البلاطات إضافة إلى المتغيرات أعلاه على خصائص الفشل للقص الثاقب (بدلالة مساحة الفشل، زاوية الفشل، محيط المنطقة الحرجة والانفعال الأقصى للقص الثاقب) لبلاطات مصنعة من خرسانة المساحيق الفعالة بأبعاد (50X 1000X1000أو 70) مم ذات إسناد بسيط تحت تأثير حمل مركز في منتصف البلاطة.

1. Introduction :

Reinforced concrete slabs may be carried directly by the columns without using beams, drop panels or columns capitals. Such slabs are described as "flat plates". This type of structures has more space in addition to its pleasant appearance. Flat plates have been widely used due to the reduced construction cost. They are also economical in their formwork and lead to simpler arrangement of flexural reinforcement. An additional advantage of a flat plate is reduced building storey heights that result in more usable space in buildings for a given or limited height. Many other advantages can be achieved by flat plates, such as a reduction in dead loads on the columns and foundations [1].

One of the major problems in such structures is the punching shear failure (also known as two-way action shear) that takes place when a plug of concrete is pushed out from the slab immediately above the columns. The pushed plug takes the from of a frustum cone or a cutoff pyramid with a minimum cross section at least as large as the loaded area[2]. 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 slabs and attention should be given to avoid the sudden failure condition.

2. Reactive Powder Concrete

Research over the past decade has yielded a new classification of concrete called Reactive Powder Concrete (RPC) now labeled and classified as Ultra-High Performance Concrete (UHPC). UHPC tends to exhibit superior properties such as advanced strength, durability and long-term stability that make it well suited for use in a wide variety of structural and nonstructural applications.[3]

The RPC concept is used on the principle that a material with a minimum defect, such as micro cracks and inside voids reveals high resistance and durability. Thus, RPC will possess a greater load carrying capacity and greater durability.

This can be possible according to the following concept [4] .

1) **Eliminating all the coarse aggregates.**

   The homogeneity of the concrete material can be improved by eliminating all the coarse aggregates and making, as much as possible the dry components material of the same particle size. All the dry components used in RPC are less than 0.6 mm in particle size.

2) **Very low water- cement ratio.**

   The water cement ratio used in RPC ranges approximately from 0.15 to 0.23. This range of w/c ratio produces not only the highest range of strength, but also ensures that all the water in the mixture will be combined in producing calcium silicate hydrate (C-S-H) [5].

3) **The microsilica or another suitable pozzolanic material**. In RPC materials with high silica content are necessary for optimum performance.
4) **Very fine sand.**
   The largest particles size in RPC are in the aggregate which is the sand (300 – 600 μm), the next largest particle size is cement (100 μm), the smallest particles size are silica fume, which are in the order of (0.1 μm) in diameter. The volumes of these particles are selected to achieve the greatest particle packing and hence the greatest density of the paste **[6].**
5) **The steel fibers.**
   They are used in order to increase the concrete ductility and improve its tension, splitting and rupture strength **[7].**
6) **Applying the pressure and heat treatment.**
   They may be helpful to get rid of excess water and to increase the paste density, and can improve chemical process and strength gain.

The above composition and casting lead to the following properties of RPC:

1- Ultra high compressive strength (200-800 MPa) combined with higher shear capacity.
2- Static Young's modulus higher than ordinary concrete and can range from 29 – 74 GPa **[8].**
3- Tensile strength ranging from 20 to 50 MPa, twice as strong as normal concrete in compression **[9].**
4- Fracture energies ranging from 20000 to 40000 J/ m^2 **[10].**
5- Flexural strength ranging from 30 to 141 MPa[10].
6- Its low and non-interconnected porosity makes penetration of liquids, gases or radioactive elements nearly nonexistent.
7- Enhanced abrasion resistance provides extended life for bridge decks and industrial floors **[11].**
8- Superior corrosion resistance provides protection from de-icing chemicals and continuous exposition to humid environments **[12].**

3. Experimental Program

In the experimental work, control specimens were cast which were three cylinders and four cubes for compression test, one cylinder for compressive stress-strain diagram, three cylinders for splitting 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
Compression	3 cylinders	100X200
	3 cubes	100X100
Compression stress strain	1 cylinder	150X300
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 RPC slabs. These variables are:

1. Percentage of steel fibers.

2. Flexural steel reinforcement ratio.

3. Thickness of the slab.

4. Type of concrete (RPC &MRPC) .

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	Flexural steel reinforcement	Steel reinforcement ratio (ρ)	Steel fibers % by volume	Slab thickness (mm)
Group One (Normal concrete slabs as reference slabs) (NSC)	S1	Ø 4mm @ 100mm c/c	0.0033	0	50
	S2	Ø 6mm @ 150mm c/c	0.0033	0	70
	S3	Ø 4mm @ 50mm c/c	0.0066	0	50
	S4	Ø 6mm @ 75mm c/c	0.0066	0	70
Group Two (RPC0)	S5	Ø 4mm @ 50mm c/c	0.0066	0	50
	S6	Ø 4mm @ 100mm c/c	0.0033	0	50
	S7	Ø 6mm @ 75mm c/c	0.0066	0	70
	S8	Ø 6mm @ 150mm c/c	0.0033	0	70
Group Three (RPC1)	S9	Ø 6mm @ 150mm c/c	0.0033	1	70
	S10	Ø 6mm @ 75mm c/c	0.0066	1	70
	S11	Ø 4mm @ 50mm c/c	0.0066	1	50
	S12	Ø 4mm @ 100mm c/c	0.0033	1	50
Group Four (RPC2)	S13	Ø 6mm @ 75mm c/c	0.0066	2	70
	S14	Ø 4mm @ 50mm c/c	0.0066	2	50
	S15	Ø 4mm @ 100mm c/c	0.0033	2	50
	S16	Ø 6mm @ 150mm c/c	0.0033	2	70
Group Five (MRPC2)	S17	Ø 6mm @ 75mm c/c	0.0066	2	70
	S18	Ø 6mm @ 150mm c/c	0.0033	2	70
	S19	Ø 4mm @ 50mm c/c	0.0066	2	50
	S20	Ø 4mm @ 100mm c/c	0.0033	2	50

4. Mixing Procedure

In this study, mixing was performed by using 0.19 m^3 capacity horizontal rotary mixer. Before using the mixer, any remaining concrete from previous batch was cleaned off. A damp cloth was used to wipe the pan and the blades of the mixer. The silica fume powder was mixed in dry state with the required quantity of sand for 5 minutes to ensure uniform dispersion of the reactive powder particles throughout the sand particles. Then, cement was fed to the mixer and mixed for another 5 minutes. The required amount of tap water was added to the rotary mixer within 1 minute, then all the super plasticizers were added and mixed for an additional 5 minutes . Finally when steel fibers were used, they were introduced, and dispersed uniformly. These were added slowly to the rotary mixer after the rest of the materials had been properly mixed and the concrete had a wet appearance and mixed for an additional 2 minutes. Also hand mixing was done after adding the required quantity of fibers to prevent the segregation or balling of fibers during mixing. This procedure is similar to the method used by **Wille et al** [13] which had been used successfully to produce RPC with compressive strength exceeding 150MPa without using heat curing-this is a major factor in the process of production, especially in this country.

5. Results and Discussion

5.1 Concrete Compressive Strength

The test results of RPC and MRPC cube and cylinder compressive strength are shown in **Figures (1)** and **(2)** in which it is clear that increasing the steel fiber volumetric ratio content increases the compressive strength. The percentage increase in the cube compressive strength (f_{cu}) is higher for higher ratios of steel fibers reaching up to (176.57%) for volume ratio of steel fibers that equals 2 %. This is significantly higher for (f'_c), where it is (214.66%) with 2% steel fibers volume ratio.

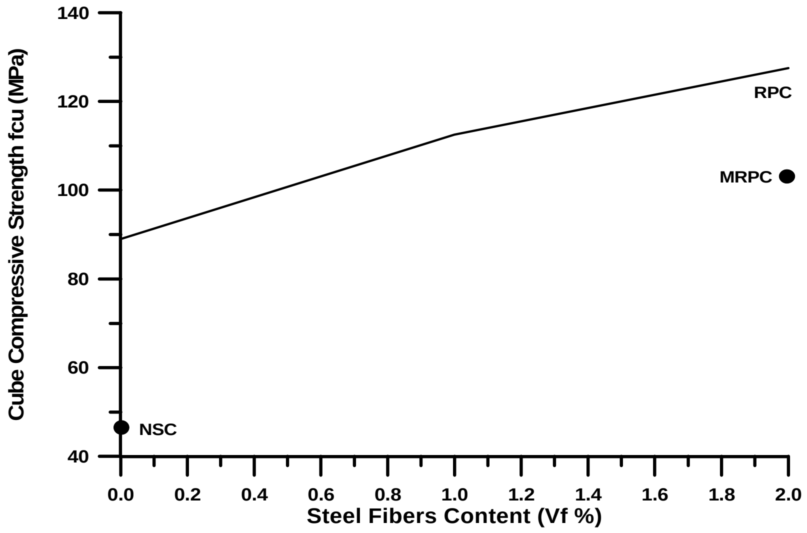


Fig. (1): Effect of steel fibers content on cube compressive strength

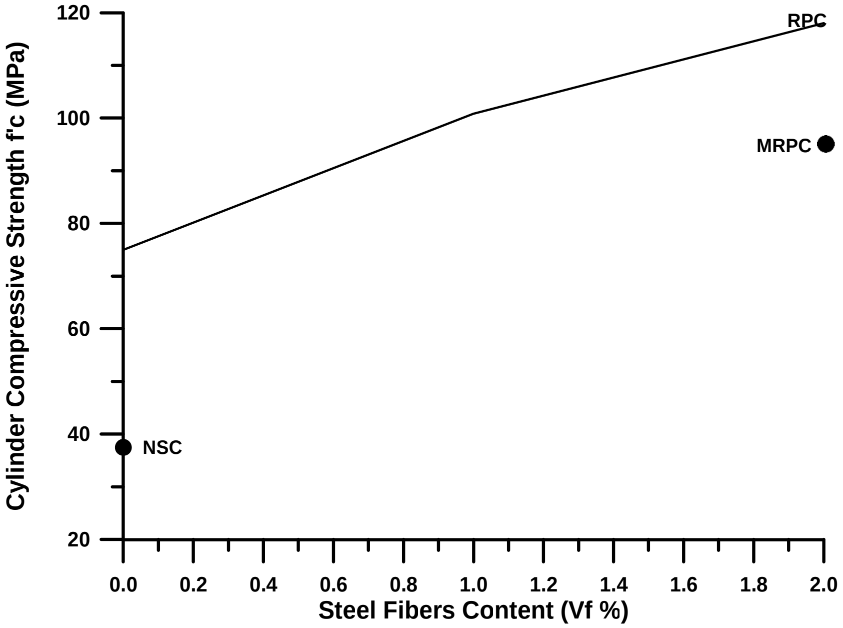


Fig. (2): Effect of steel fibers content on cylinder compressive strength

5.2 Splitting Tensile Strength

The contribution of steel fibers to the improvement of splitting tensile strength of RPC is significantly higher than its contribution to the improvement of compressive strength. Referring to Figure (3) , the splitting tensile strength of RPC cylinders can be increased up to (308.26%) as steel fibers volume ratio increases from 0 to 2%.

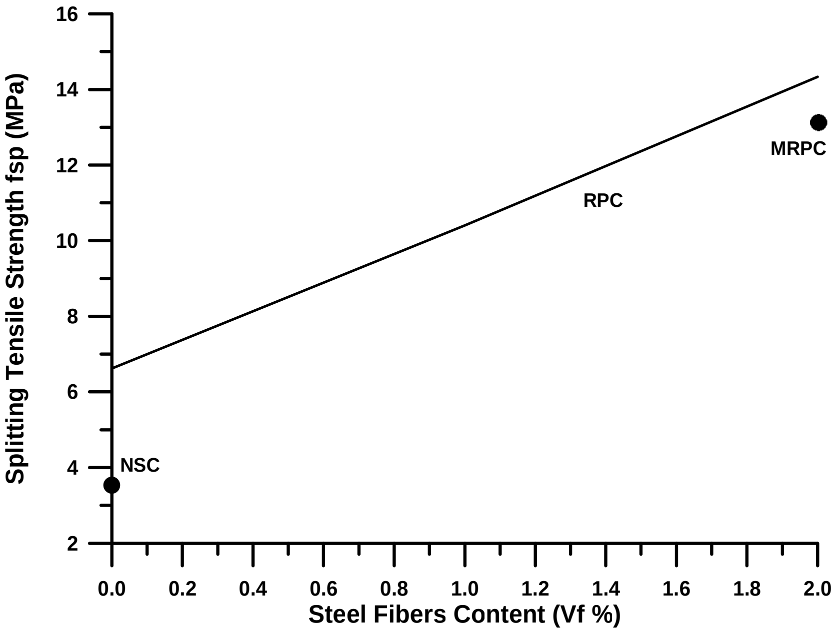


Fig. (3): Effect of steel fibers content on splitting tensile strength

5.3 Modulus of Rupture

Figure (4) shows the effect of changing the steel fiber volumetric ratio on the modulus of rupture of RPC, where it is clear that changing steel fibers ratio from 0 to 2% increases the modulus of rupture by 405.54% .

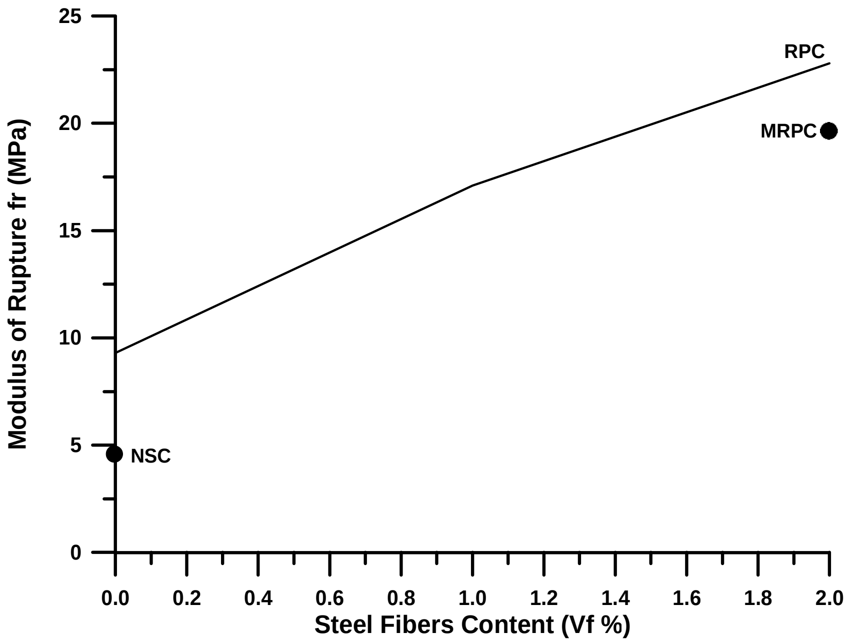


Fig.(4): Effect of steel fibers content on modulus of rupture

5.4 Modulus of Elasticity

The effect of increasing the steel fiber volumetric ratio on modulus of elasticity is shown in Figure (5). In general increasing steel fiber ratio increases the modulus of elasticity, and this can be attributed to the fact that the ascending part of the stress-strain curve becomes steeper as the steel fiber ratio increases.

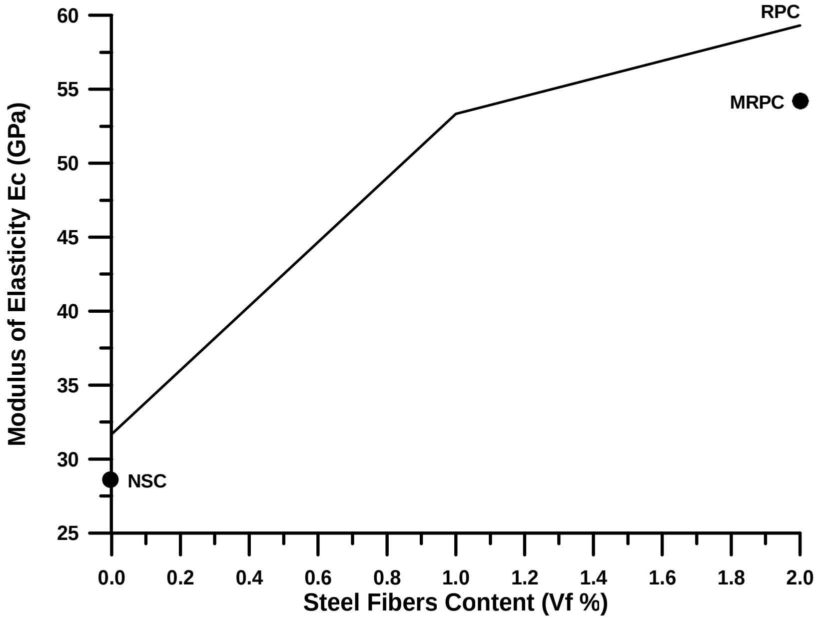


Fig. (5): Effect of steel fibers content on modulus of elasticity

5.5 Failure Characteristics

5.5.1 Observation of Failure

Punching shear failure had occurred suddenly in all the tested slabs without steel fibers. There is no sign of warning before the occurrence of failure, except the rapid movement of dial gage.

The failure of the reference slabs and RPC slabs without steel fibers was sudden and very brittle as compared to those with steel fibers in which failure was in a gradual manner.

In the case of sudden failure, the dial gage faced a sudden shock and moved from its position in some slabs and a plug of concrete is pushed out from the slab immediately, especially those slabs of group 1&2. In the others, the dial gage recorded fast movement
before failure.

5.5.2 Shape of the Failure Zone

It was observed that the shape of the failure zone in plane is ranging from a circle to a square with round corners. The shapes can be modeled similar to that proposed by the **ACI 318M-11[14].**

5.5.3 Size of the Failure Zone and Failure Angles

The punching failure mode was typically in the shape of pyramid making an angle Ø with the bottom face of the slab. The failure angles and the failure punching zone of the punching pyramid were measured by indicating the dimensions of the crushed zone at the center line passing through the loaded area. It was observed that the angle of failure was about 17.5° for reference slabs. The steel fibers, also angle was gradually decreased to about 15° for RPC without the angle was increased to 18.5°,20° and 19.15 for RPC (with 1% steel fibers), RPC(with 2% steel fibers) and MRPC(with 2% steel fibers) respectively.

Since the failure angle was more in slabs with steel fibers, the failure pyramid that was pushed out in slabs without steel fibers has a much wider base than that in slabs with steel fibers as shown in the figures of crack patterns. This indicates that steel fibers help to prevent the disintegration of concrete cover under the flexural steel reinforcement, and tend to integrate the hole section.

Figures (6) to (10) and **Table (3)** show the value of the punching failure angle Ø for all tested slabs**. Table (3)** also includes the area of the failure punching zone calculated after measuring the dimensions of the crushed zone at the center line passing through the loaded area.

Table (3) Failure area and angle of failure of the tested slabs

Slab NO.	Type Of concrete	f'_c (MPa)	Steel fiber% by vol.	Thickness (mm)	Steel reinforcement ratio (ρ)	Measured Failure Area (mm^2)	Failure Angle Ø°
SN1-5	NSC	37.5	0	50	0.0033	89207	17.35
SN1-7	NSC		0	70	0.0033	211004	17.65
SN2-5	NSC		0	50	0.0066	101603	16.99
SN2-7	NSC		0	70	0.0066	244029	17.3
SR2-5	RPC	75	0	50	0.0066	124651	14.23
SR1-5	RPC		0	50	0.0033	108869	14.08
SR2-7	RPC		0	70	0.0066	267211	15.88
SR1-7	RPC		0	70	0.0033	230874	16.05
SR1F1-7	RPC	100.8	1	70	0.0033	198829	18.89
SR2F1-7	RPC		1	70	0.0066	220789	18.16
SR2F1-5	RPC		1	50	0.0066	92102	18.29
SR1F1-5	RPC		1	50	0.0033	78989	18.64
SR2F2-7	RPC	118	2	70	0.0066	199205	18.88
SR2F2-5	RPC		2	50	0.0066	80798	19.9
SR1F2-5	RPC		2	50	0.0033	67205	20.09
SR1F2-7	RPC		2	70	0.0033	172211	20.85
SMR2F2-7	MRPC	105.3	2	70	0.0066	208012	18.41
SMR1F2-7	MRPC		2	70	0.0033	181504	19.44
SMR2F2-5	MRPC		2	50	0.0066	85660	19.03
SMR1F2-5	MRPC		2	50	0.0033	73100	19.68

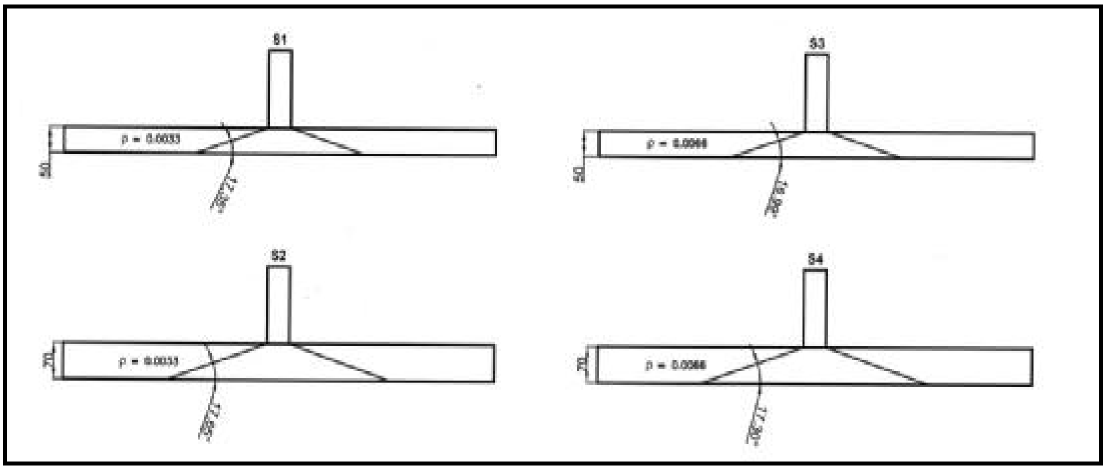


Fig. (6) Angle of failure of slabs of group 1 (NSC)

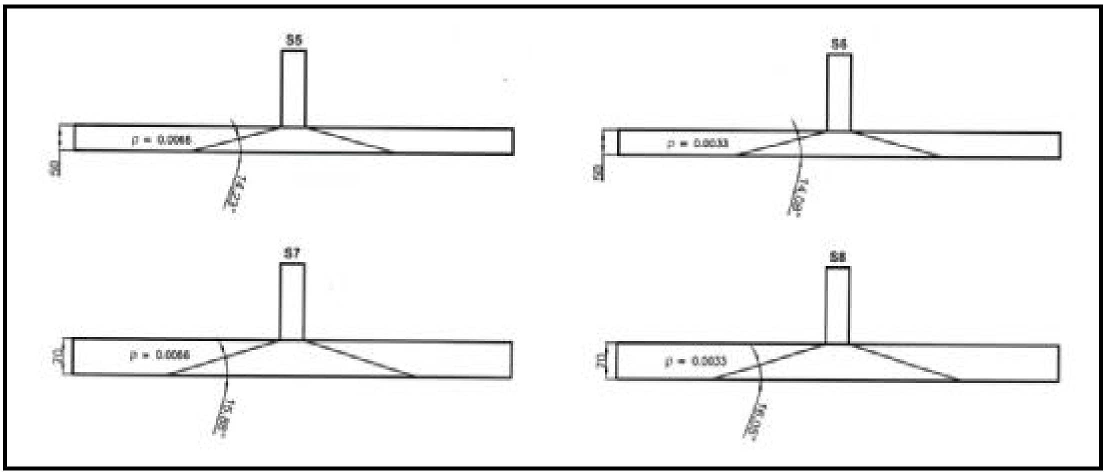


Fig. (7) Angle of failure of slabs of group 2 (RPC0%)

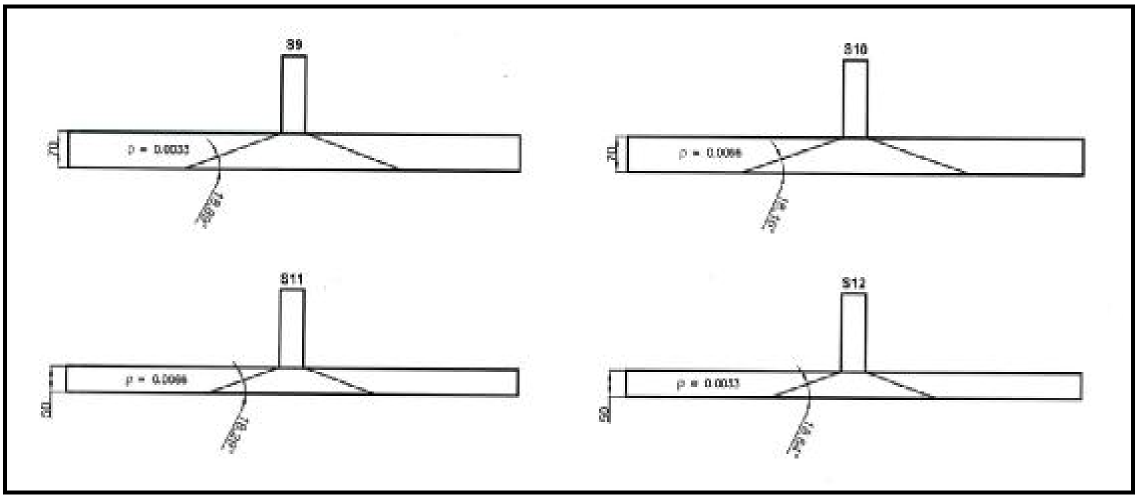


Fig. (8) Angle of failure of slabs of group 3 (RPC1%)

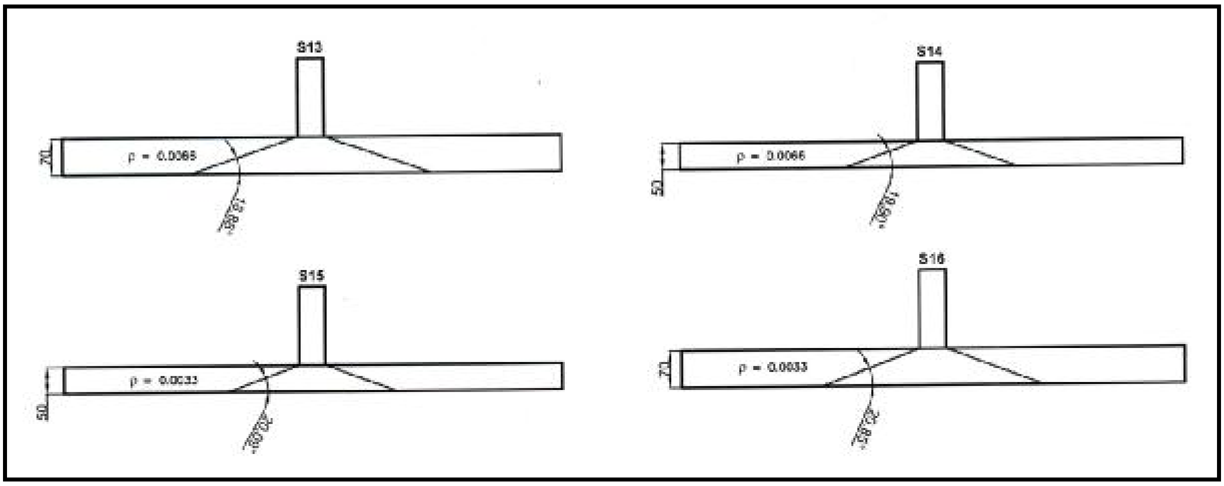


Fig.(9) Angle of failure of slabs of group 4 (RPC2%)

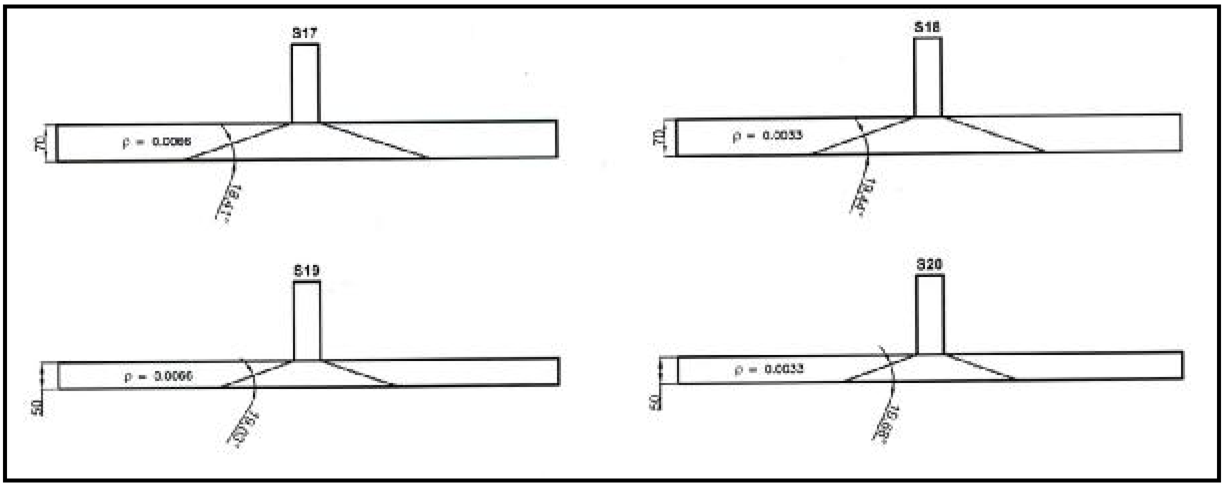


Fig. (10) Angle of failure of slabs of group 5 (MRPC2%)

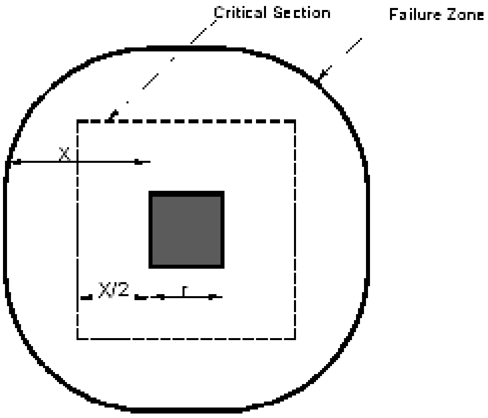
Previous tests [15] had shown that the angle of failure was about 19° for slabs without steel fibers and gradually increased to 24° in slabs with 1% crimped steel fibers content.

The present test shows also a similar trend in principle that the size of failure zone decreased by addition of steel fibers in slabs of group 3,4 and 5.

5.5.4 Critical Section Perimeters

The distance of the critical section for the slabs tested in this investigation is considered as half the distance between the end of the failure surface and the face of the column. The calculated distances are based on the measured area. Figure (11) shows the method used to calculate the critical sections for the tested slabs.

In **ACI 318M-11**[14] and **BS8110**[16] codes, the critical punching shear section is assumed to be located at distance d/2 and 1.5d from the column face, respectively (where d is the effective depth of the slab). **Tuan**[17] showed that the critical section perimeters equal to (2d) for high strength concrete and this conformed with **CEB-FIPMC-90**[18]**.**
Previous research[15] showed that the critical section perimeter ranged from 1.16h to 1.5h for slabs without steel fibers and 1.06h to 1.25h for slabs with steel fibers. Table (4) lists the calculated distances and the critical section for each group of the tested slabs.



$A= r^2 + 4rx + p\, x^2$

$p\, x^2 + 4rx + (r^2 - A) = 0$

$$X = \frac{-4r + \sqrt{(4r)^2 - 4 \times p \times (r^2 - A)}}{2 \times p}$$

Fig. (11) Method Used to Calculate the Critical Sections

where:

A: Area of failure zone in (mm^2).
r: Side length of square column.
x: Distance between the end of failure surface and the face of the column.

Table (4) Location of the punching shear section (distance of critical section from face of column)

Slab NO.	Type Of concrete	ƒ´c (MPa)	Steel fiber % by vol.	Thickness (mm)	Measured Failure Area (mm^2)	X (mm) See figure (4-63)	Location of punching shear section from face of column			
							Present test@ x/2	ACI 318 @ d/2	B.S.8110 @1.5d	CEB-FIP MC-90 @2d
SN1-5	NSC	37.5	0	50	89207	137.36	68.68	20	60	80
SN1-7	NSC		0	70	211004	227.8	113.9	29	87	116
SN2-5	NSC		0	50	101603	148.64	74.32	20	60	80
SN2-7	NSC		0	70	244029	247.32	123.66	29	87	116
SR2-5	RPC	75	0	50	124651	167.94	83.97	20	60	80
SR1-5	RPC		0	50	108869	154.94	77.47	20	60	80
SR2-7	RPC		0	70	267211	260.24	130.12	29	87	116
SR1-7	RPC		0	70	230874	239.72	119.86	29	87	116
SR1F1-7	RPC	100.8	1	70	198829	220.22	110.11	29	87	116
SR2F1-7	RPC		1	70	220789	233.74	116.87	29	87	116
SR2F1-5	RPC		1	50	92102	140.06	70.03	20	60	80
SR1F1-5	RPC		1	50	78989	127.44	63.72	20	60	80
SR2F2-7	RPC	118	2	70	199205	216	108	29	87	116
SR2F2-5	RPC		2	50	80798	129.24	64.62	20	60	80
SR1F2-5	RPC		2	50	67205	115.2	57.6	20	60	80
SR1F2-7	RPC		2	70	172211	202.8	101.4	29	87	116
SMR2F2-7	MRPC	105.3	2	70	208012	225.96	112.98	29	87	116
SMR1F2-7	MRPC		2	70	181504	209.04	104.52	29	87	116
SMR2F2-5	MRPC		2	50	85660	133.98	66.99	20	60	80
SMR1F2-5	MRPC		2	50	73100	121.44	60.72	20	60	80

The results in **Table (4)** show that the critical section of the RPC and MRPC slabs is located at a distance between 1.6d to 1.9d from the face of column. Also results indicate that as the content of steel fibers becomes higher the critical punching shear section becomes closer to the face of the column indicating that the punching shear area becomes smaller. This does not mean that the punching shear force will be smaller too, but on the contrary it will be greater since a larger punching shear force is usually required to cut or pull out the higher amount of fibers.

Increasing slab thickness or flexural steel reinforcement ratio lead to a shift in the punching shear section away from the face of the column. This obviously leads to a larger punching shear area and eventually a higher punching shear force.

5.5.5 Ultimate Punching Shear Stress

It can be seen from the test results in Table (5), that by increasing the volume
4, the ultimate punching fraction of fibers from 0% in group2, 1% in group3 and 2% in group

shear stress was increased by (27.51%, 74.38% and 134.89%) respectively for slabs with 50mm thickness, as compared with reference slabs of group1.

One can see from the results also that by increasing the volume fraction of fibers from 0% in group2, 1% in group3 and 2% in group4, the ultimate punching shear stress was increased by (40.95%, 100.1% and 181.53%) respectively for slabs with 70mm thickness, as compared with reference slabs of group1. This means that, although the perimeter and effective depth are greater for the 70mm slabs than the 50mm ones, the ultimate punching shear stress is still higher in the former than the latter.

Results also show that the presence of coarse aggregate in MRPC slabs of group 5 with 2% steel fibers content leads to decreasing ultimate punching shear stress by (10.37% and 14.43%) for slabs with thickness (50mm and 70mm) respectively as compared with RPC slabs with 2% steel fibers content.

The increased flexural steel reinforcement ratio leads to decreasing percentage rise in the ultimate punching shear stress due to the use of fibers. One can see this drop clearly when increasing the volume fraction of fibers from 0% to 2%. Table (5) shows all results of the ultimate punching shear stress for all tested slabs.

Table (5) Ultimate punching shear stress in slabs

Group No.	Slab Designation	Ultimate Load (kN)	Effective Depth(d) (mm)	Perimeter of the critical punched section@ x/2 (mm)	Ultimate Punching Shear Stress (MPa)
Group One reference slabs (NSC)	SN1-5	NSC	40	749.44	1.75
	SN1-7	NSC	58	1111.2	1.05
	SN2-5	NSC	40	794.56	1.81
	SN2-7	NSC	58	1189.28	1.56
Group Two (RPC) (R0)	SR2-5	RPC	40	871.76	2.32
	SR1-5	RPC	40	819.76	2.22
	SR2-7	RPC	58	1240.96	2.08
	SR1-7	RPC	58	1158.88	1.56
Group Three (RPC) (R1)	SR1F1-7	RPC	58	1080.88	2.31
	SR2F1-7	RPC	58	1134.96	2.81
	SR2F1-5	RPC	40	760.24	3.22
	SR1F1-5	RPC	40	709.76	2.99
Group Four (RPC) (R2)	SR2F2-7	RPC	58	1064	3.97
	SR2F2-5	RPC	40	716.96	4.79
	SR1F2-5	RPC	40	660.8	3.59
	SR1F2-7	RPC	58	1011.2	3.24
Group Five (MRPC) (MR2	SMR2F2-7	MRPC	58	1103.84	3.51
	SMR1F2-7	MRPC	58	1036.16	2.68
	SMR2F2-5	MRPC	40	735.92	4.41
	SMR1F2-5	MRPC	40	685.76	3.13

6. Conclusions

1. The mixing procedure used in this study presents a successful way to produce RPC with a cylinder compressive strength exceeding 115 MPa without using the heat curing, as found in previous research.
2. The inclusion of steel fibers in all RPC and MRPC slabs resulted in a significant enhanced ductility which made the slabs fail gradually in a ductile manner, unlike nonfibrous slabs and/or conventional concrete slabs which showed lesser ductility at failure.
3. The inclusion of steel fibers in RPC and MRPC slabs resulted in an enhanced stiffness, reduced crack width, reduced rate of crack propagation and preserving the whole section together after reaching failure. Most of the steel fibers were observed to pullout of the cement matrix rather than snap.
4. The failure angle of RPC slabs was found to increase with increasing V_f. The highest value was 20.85^o for RPC slab with 2% steel fibers, while the lowest value was 14.08^o for RPC slab without fibers. This indicates that the size of failure zone can be reduced by adding fibers to the RPC slabs thus helping to prevent the disintegration of concrete cover under the flexural steel reinforcement.
5. Increasing the volume fraction of steel fiber(V_f) leads to decreased perimeter of the punching shear section. Also increasing slab thickness leads to increased length of such perimeter. The results of the present investigation show that the distance between the face of the column and the critical punching shear section is about (2d) for RPC slabs with fibers.

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