Experimental study of Circular Short Columns made from Reactive Powder Concrete

Dr. Asmaa Ali Ahmad
Building and Construction Engineering Department, University of Technology/ Baghdad
Email:Asmaali313@yahoo.com
Dr. Faidhi Abdul- Rahman Alkhazraji
Building and Construction Engineering Department, University of Technology/ Baghdad
Sarah Mohammed Omar
Building and Construction Engineering Department, University of Technology/ Baghdad

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ABSTRACT

This research studies the behavior of reactive powder concrete (RPC) circular short columns with and without steel fibers of different types, as well as change of the reinforcement kinds of lateral (hoops and spiral) and the spacing between them.

The experimental work consist study of fifteen short column specimens having an overall height of 1 m with circular cross-section of 150 mm diameter are loaded at ends with concentric loads. Six of the specimens are cast with the inclusion of steel fibers with aspect ratio of 75 (group 1), and six of other specimens are cast with the inclusion of steel fibers with aspect ratio of 100 (group 2), and the other three specimens is without steel fibers, with hybrid steel fibers and high strength concrete. The concrete mix of fiber-reinforced samples contains 1% by volume of steel fibers of variable reinforcement longitudinal and lateral (hoops and spiral reinforcement).

Experimental data for strength, failure mode, lateral, and the ductility were obtained for each test.

The work concluded that the using of steel fibers in RPC was an effective way to prevent spalling of the concrete cover and increase the ductility and the using of high ratio of longitudinal reinforcement delays the pickling of the columns and increase strength.

The ultimate load capacity of RPC columns of spiral lateral reinforcement is greater than the load of RPC columns of tied lateral reinforcement by about 1.25 to 1.35 times for the two groups.

Keywords: Concentric load, Ductility, High strength concrete, Reactive powder concrete, short columns.

INTRODUCTION

Reactive Powder Concrete (RPC) is an ultra-high strength and high ductility composite material with advanced mechanical properties. RPC is a fiber reinforced, superplasticized, silica fume-cement mixture with very low water-Cement ratio (w/c) characterized by the presence of very fine quartzes and (0.15-0.6mm) instead of ordinary aggregate [1].

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

In this research, two types of RPC columns have been studied. The first type columns are reinforced with longitudinal bars and lateral ties of circular shape. The columns of the second types are reinforced with longitudinal bars and closely spaced spirals.
The objective of this research is to study the behavior of RPC columns with two types of steel fiber for tied and spiral columns and to find the increasing in bearing capacity. A comparison had been made between RPC columns of above types with HSC column.

Experimental Program

The experimental program in the current work includes testing of fifteen circular short columns, subjected to monotonically increasing of concentric axial compressions to extend the data base for steel fiber [2, 3] reinforced concrete columns, and to evaluate the effect of the inclusion of steel fibers into the concrete mix on the behavior of tied and spiral reinforced concrete columns in terms of strength and ductility.

Details of Test Specimens

A total of fifteen short column specimens having an overall height of 1 m with circular cross-section of 150 mm diameter are loaded at ends with concentric loads. six of the specimens are cast with the inclusion of steel fibers with aspect ratio of 75, and six of the specimens are cast with the inclusion of steel fibers with aspect ratio of 100 [see Fig.(1)] ,and the other three specimens is without steel fibers, with hybrid steel fibers with mixing ratio (0.5% of aspect ratio 100 and 0.5% of aspect ratio 75) and high strength concrete.

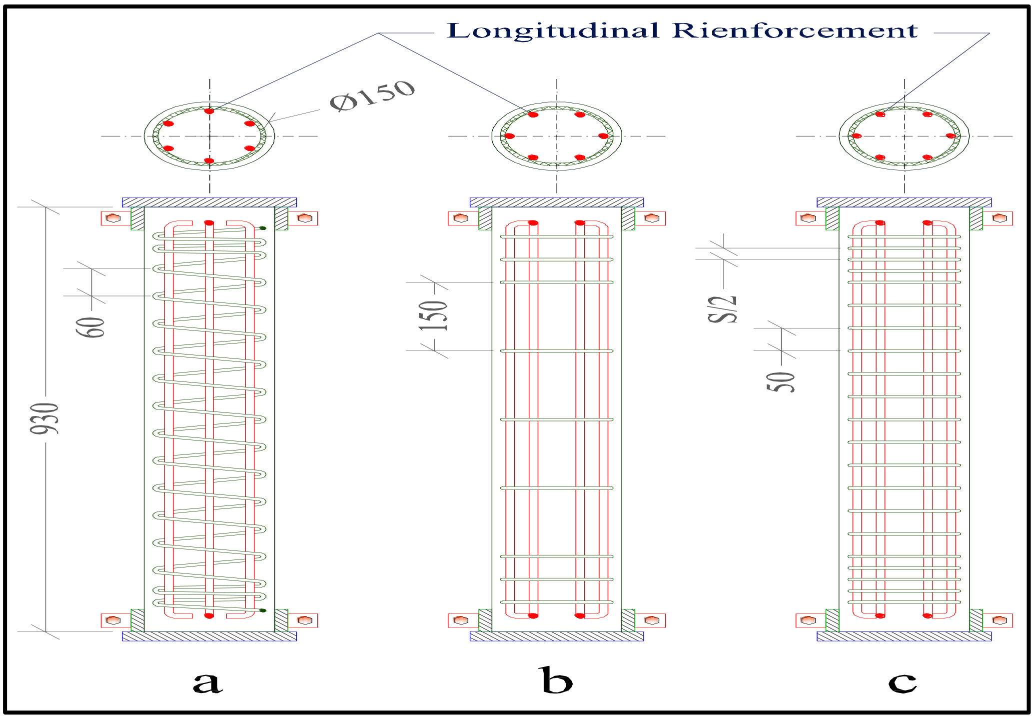
Figure. (1) Types of the steel fiber

The concrete mix of fiber-reinforced samples contains 1% by volume of end hooked steel fibers. The column specimens are divided depending on the inclusion of fibers and its type, as well as the lateral reinforcement and the longitudinal reinforcement. Two types of longitudinal reinforcement are used (*6 bar Φ 8*) and (*6* bar *Φ 6*) and three types of lateral reinforcement (hoops of Φ 6 @ 150mm and of Φ 6 @ 50mm) and spiral of Φ 6 @60mm.
The columns are tested to investigate the parameters of confinement, including and spacing of transverse reinforcement, strength of concrete with and without fibers. Concrete cover of 25 mm is provided in all confined specimens. In all specimens, the ratio of the gross area of the column cross section (Ag) to the core area (Ac) measured to the outside of the lateral reinforcement is 1.3. Longitudinal reinforcement is provided in all column specimens. Figure (2) and Table (1) appear

the various properties of longitudinal and lateral reinforcement. The $f`c$ given in Table (1) represents the type of concrete, steel fiber types, longitudinal steel reinforcement (number and size of bar, and ratio ρ_{l}), and the lateral reinforcement (number and size of bar, and spacing and volumetric ratio of hoops steel and spiral steel ρ_s).

The volumetric ratio of spiral reinforcement, ρ_s was either 0.6% or 1.5% or 1.8% [Figure (2) and (3)]. To avoid crushing of concrete near the loaded ends, spacing of the lateral reinforcement is reduced to 6 mm for specimens of spiral pitch, and 50 and 150 mm for specimens of hoops pitch, respectively.

Fig. (2) and Fig. (3) shows the various properties of longitudinal and transverse reinforcement.



Figure(2) Reinforcement details of columns with spiral confinement and hoops

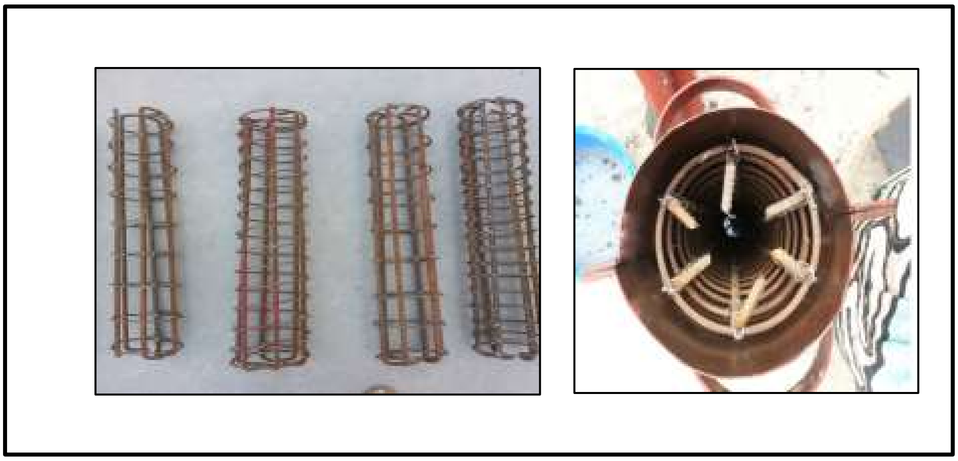


Figure (3) Assembled reinforcement cages for columns

Table (1) represents the type of concrete, steel fiber types, longitudinal steel reinforcement (number and size of bar, and ratio ρ_l), and the lateral reinforcement (number and size of bar, and spacing and volumetric ratio of hoops steel and spiral steel ρ_s).

Table (1) Details of test specimens

Columns designations		steel fiber* aspect ratio (length,*mm*)	Longitudinal Reinforcement		Lateral Reinforcement		
			No. & Size (*mm*)	ρ_l (%)	No. & Size (*mm*)	Spacing (*mm*)	ρ_s (%)
RPC group1	Column1	100(30)	6Ø8	0.012	9Ø6	150	0.6
	Column2		6Ø8	0.012	17Ø6	50	1.8
	Column3		6Ø8	0.012	Ø6	60	1.5
	Column4		6Ø10	0.027	9Ø6	150	0.6
	Column5		6Ø10	0.027	17Ø6	50	1.8
	Column6		6Ø10	0.027	Ø6	60	1.5
RPC group2	Column7	75(12)	6Ø8	0.012	9Ø6	150	0.6
	Column8		6Ø8	0.012	17Ø6	50	1.8
	Column9		6Ø8	0.012	Ø6	60	1.5
	Column10		6Ø10	0.027	9Ø6	150	0.6
	Column11		6Ø10	0.027	17Ø6	50	1.8
	Column12		6Ø10	0.027	Ø6	60	1.5
RPC	Column13	100-75	6Ø10	0.027	9Ø6	150	0.6
	Column14	0	6Ø10	0.027	9Ø6	150	0.6
HSC	Column15	0	6Ø10	0.027	9Ø6	150	0.6

*Volumetric Ratio of steel fiber (ρf) = 1%

Materials and Mix Design

Ordinary Portland cement (Type I) manufactured in Iraq with trade mark of A1 – mass has been used throughout the test work of this study for both high strength concrete and RPC. The test results showed that the cement conforms to the *Iraqi* Standard Specification No.5/1984 [4]. 20% of cement weight is used in the mix (as addition, not as replacement of cement) for RPC.

Fine silica sand is used in the RPC mix. The end-hooked steel fibers were used in RPC mix with volume fraction (Vf) of 1%.Crushed river gravel was used as coarse aggregate with maximum size 10 mm for high strength concrete only . RPC by definition has no coarse aggregate. The grading of the used coarse aggregate in high strength concrete conforms to the Iraqi Standard specification No. 45/1984[5]. Glenium 51 was used as high range water reducer to produce RPC in this study. Tap water was used in all mixes and in the curing of the specimens. Reinforcing steel bars used as longitudinal bars, spirals and hoops in reinforced concrete columns meet the ASTM 996M-05 [6] requirements. Grade 50 and 40 steel bars, provided by (ArcelorMittal) Company which is of Ukrainian origin are used for both longitudinal and transverse reinforcement for test specimens. 10 mm and 8mm diameter deformed steel bars and 6 mm diameter plain steel bars are used for longitudinal, spiral and hoops reinforcement, respectively. A High strength concrete mix consisting of cement, fine aggregate, coarse aggregate and water was used to cast the short circular column. The w/c ratio of this mix was 0.3 and the proportions of cement, fine aggregate, coarse aggregate were 1:1.5:3 (by weight) respectively. A reactive powder concrete mix consisting of cement, fine aggregate, silica fume, superplasticizer, steel fiber and water was used to cast the RPC short circular columns, with a w/c ratio of (0.17). Steel fibers and the high cement content are used to improve tensile properties of RPC mixes. Superplasticizer using to enhance workability of this mix and silica fume used to increase strength. Weight of the materials used in producing ($1m^3$) of RPC [see table (2)].

Table (2) Mix Proportions of RPC and HSC

Material	Proportions of RPC	Proportions of HSC
	weight(Kg)	weight(Kg)
Cement (C)	880 kg	400
Sand (S)	1100 kg	600
Silica Fume (SF)	220 kg	-----
Steel Fiber (V_f)	(1 %) 156 kg	-----
W/C	0.17	0.3
HRWRA	1.5 %	1%

Mixing, Curing and Fabrication

Mixing was done for HSC first by mixing gravel and sand for 2 minutes then cement was added to the dry components and mixing for about 3 minutes. During mixing, water was added during about 3 minutes to obtain a homogeneous mixture.

Several trial mixes were made for RPC to get the appropriate mix that used in this study. Superplasticizer was added to the water and stirred before the mixing process. Dry materials (cement and silica fume) were first mixed for 3 minutes, then sand was added to the dry materials and all were mixed for 3 minutes. (80-85)% of the liquid (superplasticizer and water) was added to the dry mix and all were mixed for 4 minutes, then the remaining of the liquid was added and mixed until the RPC paste was processed which took additional (4-8) minutes. Steel fibers were added in (5-6) patches by hand. Each patch took (1-2) minutes while mixing was incorporated. The total mixing time was about 25 minutes. After 24 hour from casting, RPC specimens placed in water tanks and leaving the specimens in water under normal curing condition till age of (28) days.

Test Procedure

The concentrically loaded column specimens are tested under monotonically increasing axial compressive loading condition. The column specimens' surfaces are prepared, the positions of the demec points are marked and the demec points are fixed on the specimens [7, 8, 9]. A thin layer of rubber caps are used at the top and the bottom

ends of each column to eliminate unevenness at the ends and ensure uniform distribution of the applied load on the cross section.
All the specimens are externally confined by 15 mm thick and 50 mm height steel collars at both ends of the columns to avoid premature failure in the end regions of the columns throughout the test. Then, the column specimen is placed in its position for testing and the dial gauge is fixed in its position. A trial test is performed on a single column prior to testing the actual column specimens. In the trial test, the column is loaded up to failure. After performing the trial test, the actual tests are carried out.
Initially a load of 5 kN is applied and released three times to set and check the dial gauge. Initial readings of strain gauges as well as the dial gauge are taken and recorded before loading. The rate of loading is kept constant at an average of 2 kN/Sec. from the beginning up to failure. The dial gauge readings and the axial compression strain at mid-height length are recorded at every increment until to column fails.

Ultimate loads and Failure Mode

Table (3) shows the magnitude of tested concrete compressive strength (average value of three concrete cylinders) and the ultimate failure load (P test) for each column.

Table (3) Load of test specimens

Columns	compressive strength, f'^{*}_{c} (*MPa*)	Failure Load P_{test} (kN)
Col.1	90.77	1000
Col.2		1080
Col.3		1180
Col.4		1050
Col.5		1140
Col.6		1300
Col.7	100.55	1300
Col.8		1400
Col.9		1700
Col.10		1480
Col.11		1720
Col.12		2000
Col.13	94.64	1300
Col.14	80.63	900
Col.15	50.68	830

*$f'c$:Average value of three concrete cylinders.

Fig. (4) shows the failure modes of some Column Specimens. The tied columns fail at ultimate load by crushing of the concrete accompanied by shearing out warding along on inclined plane and buckling of longitudinal steel out ward between the ties. In the spiral columns, the longitudinal steel and concrete within the core are prevented from failing out ward by the spiral and only the outer shell spalls off.

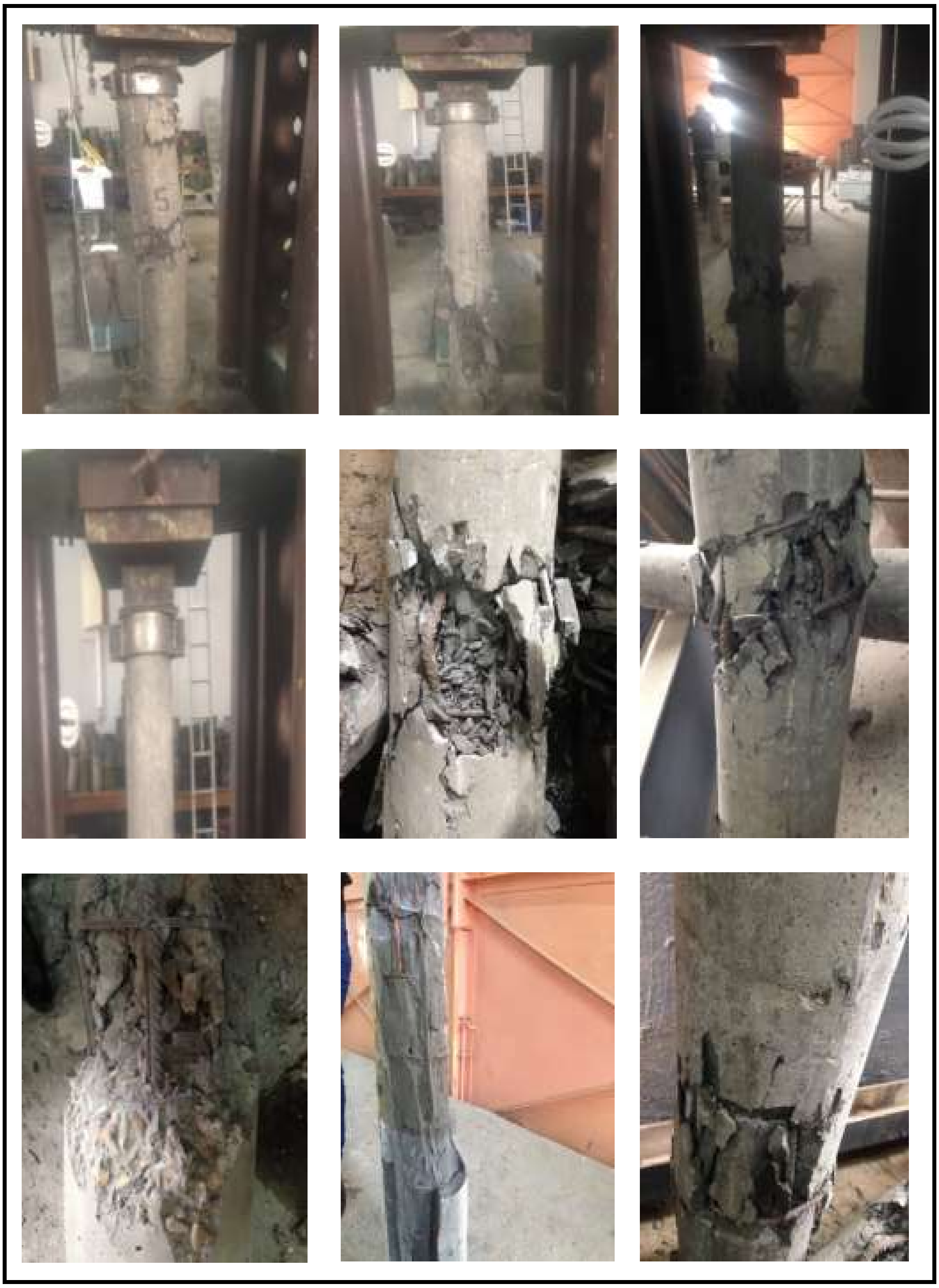


Figure (4) Failure modes of some column specimens

Load (P) – Displacement (Δ) Relationship of Columns

Typical load (P)-displacement (Δ) curves of circular RPC columns with and without steel fiber for two types of steel fiber measured using axial demec devices[10, 11] are shown in figures below [Fig.(5-a) for group one, Fig.(5-b) for group two, and Fig.(4-c) for columns have the same lateral and longitudinal reinforcement] .

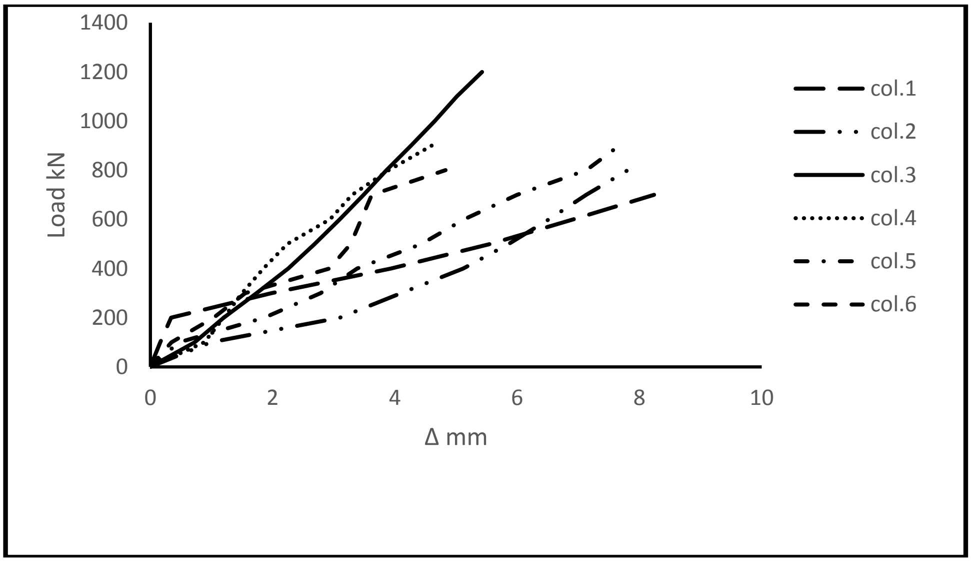


Figure (5-a) Load - displacement relationship for RPC with steel fiber of aspect ratio=100(Group 1)

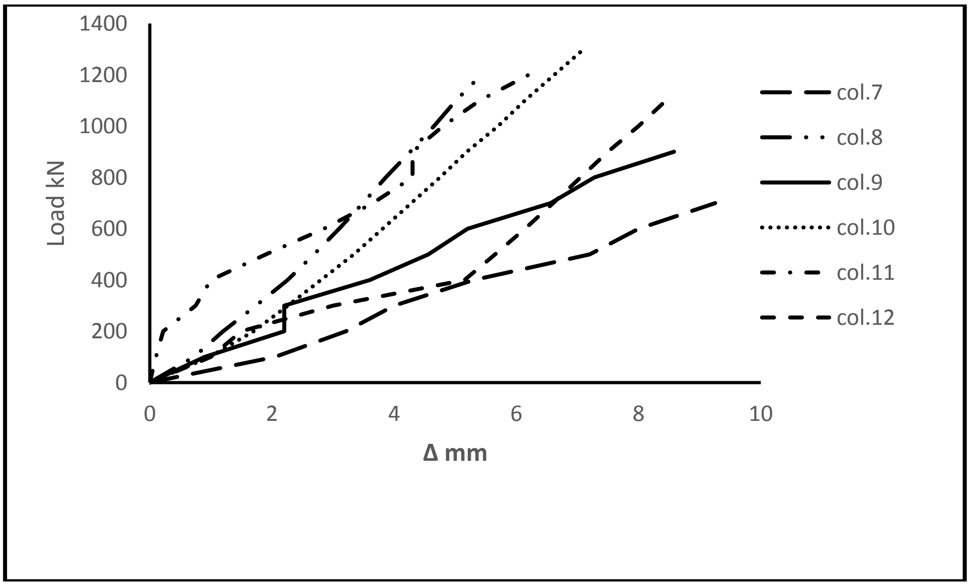


Figure (5-b) Load - displacement relationship for RPC with steel fiber of aspect ratio=75 (Group 2)

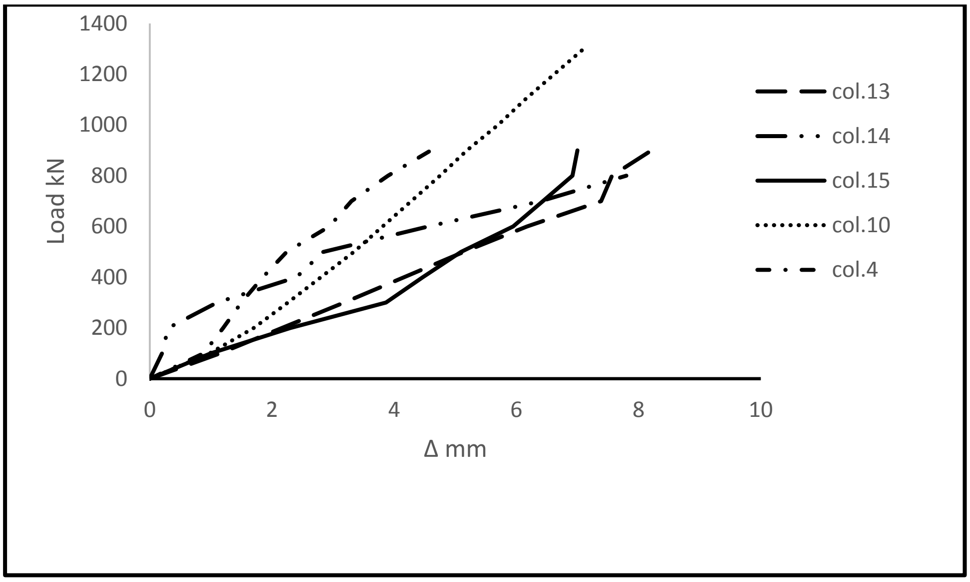


Figure (5-c) Load - displacement relationship for RPC columns with and without steel fiber and HSC column

Figure (6) shows the effect of (type and the ratio of steel fiber) on the ultimate loads

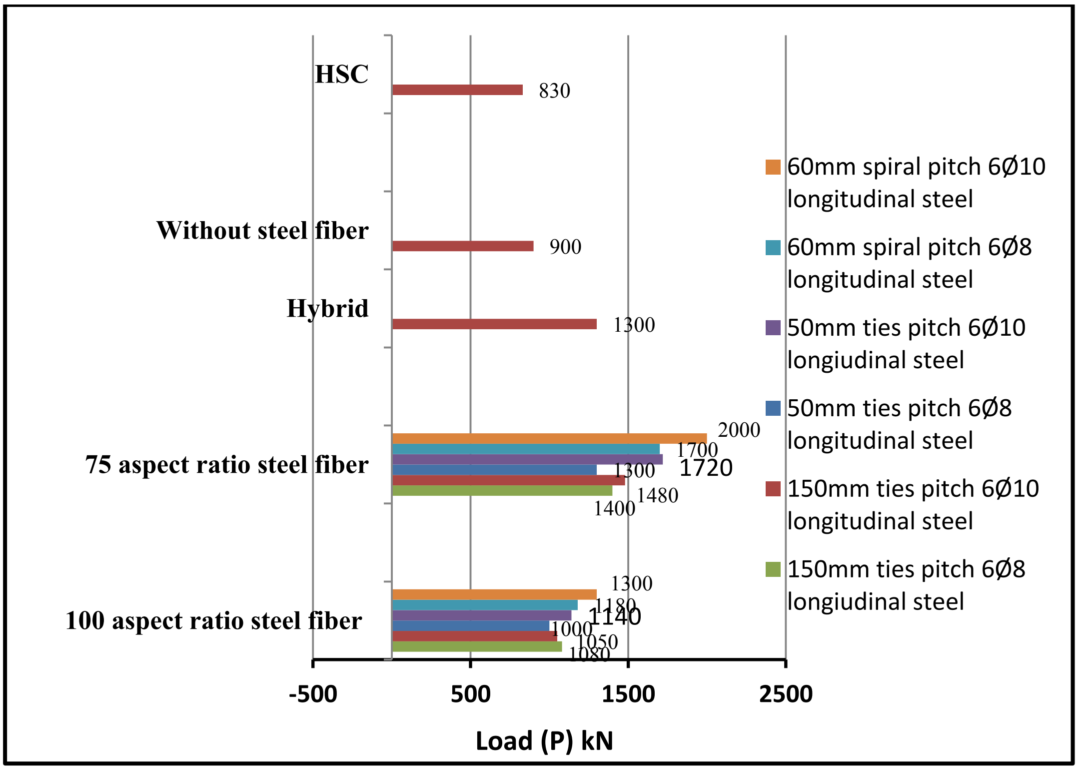


Figure (6) Ultimate experimental load capacities P_{max} for all the tested columns

Also the effect of (steel fiber type and compressive strength $f'c$) on the ultimate load (P) for RPC [0% steel fiber (col.14), hybrid (col.13), group one (col. 4), and group two (col. 10)] and the HSC column (col.15) (all these columns have the same longitudinal and lateral reinforcement) shown in fig.(7). It can be seen that the RPC column (col. 10) of group 2 has the maximum value of ultimate load (P).

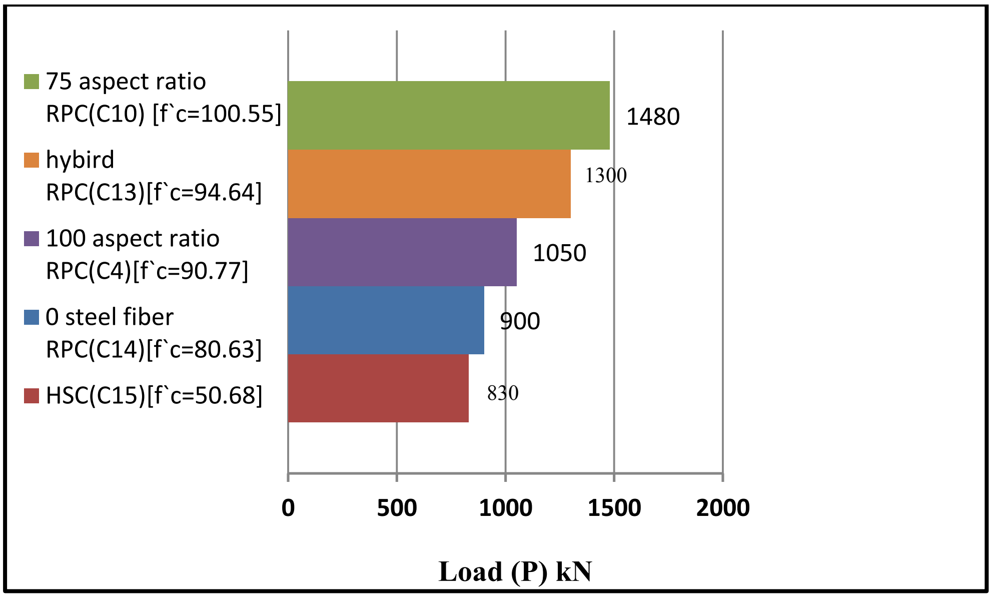


Figure (7) Ultimate experimental load capacities P_{max} for tested columns of same longitudinal and lateral reinforcement

Figure (8) shows the line of increasing the load with increasing the compressive strength f`*c* (all these columns have the same longitudinal and lateral reinforcement). The load increases from 600 kN to 1300 kN for *f`c* ranging from 50 MPa to 100 MPa respectively at an average rise of 140% for each 10 MPa of strength.

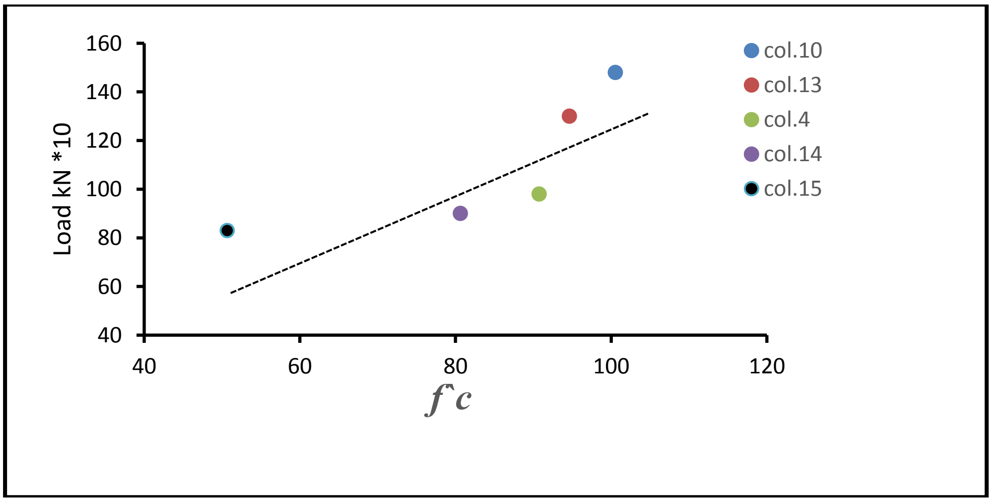


Figure (8) Effect of *f`c* on load of columns with the same reinforcement

Figs.(9-a and 9-b) show the effect of ratio and types of stirrup reinforcement on the ultimate load (P) with the variable of longitudinal reinforcement . That seems the column of higher longitudinal reinforcement and spiral lateral reinforcement (*S=60mm*) has the maximum value of P for group one and two.

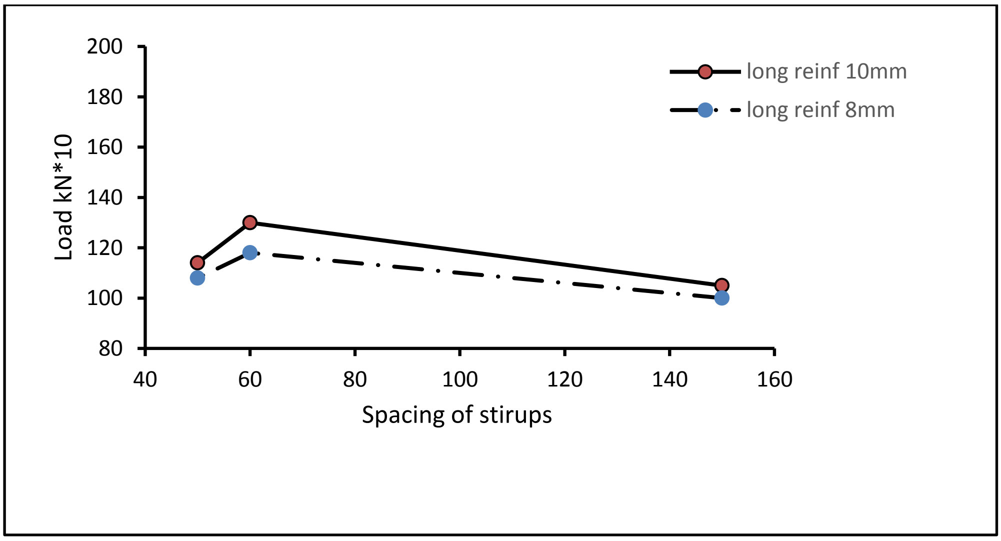


Figure (9-a) Effect the type and ratio of stirrups on load of RPC Columns (group1)

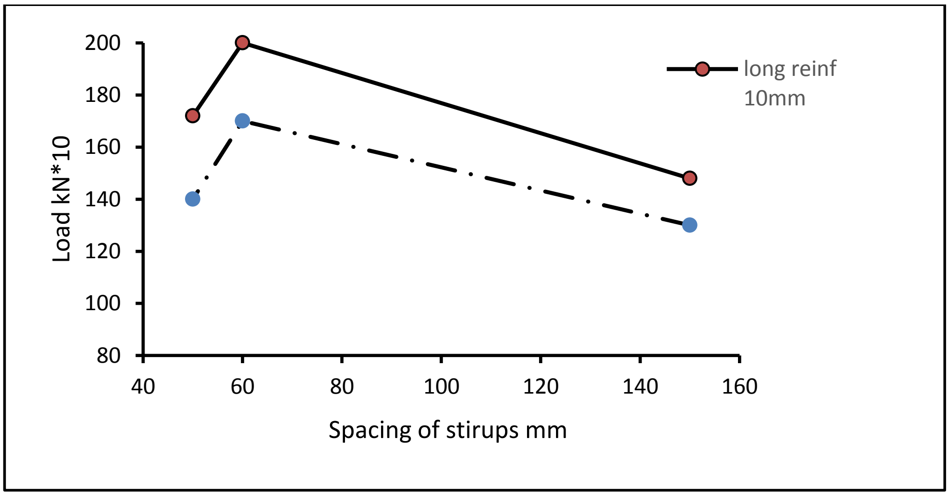


Figure (9-b) Effect the type and ratio of stirrups on load of RPC Columns (group2)

Figs.(10-a and 10-b) show effect of fiber steel type of aspect ratio [*75*(*12mm* length) and *100* (*30 mm* length)] on the ultimate load (P) with variable types of stirrups for longitudinal reinforcement of Ø8 and Ø10. The Ratio of increasing strength is about 40%- 44% for longitudinal reinforcement of diameter 8 mm (ρ_l = 0.012), while this ratio becomes to be 51%-53% for longitudinal reinforcement of diameter 10 mm (ρ_l = 0.027).

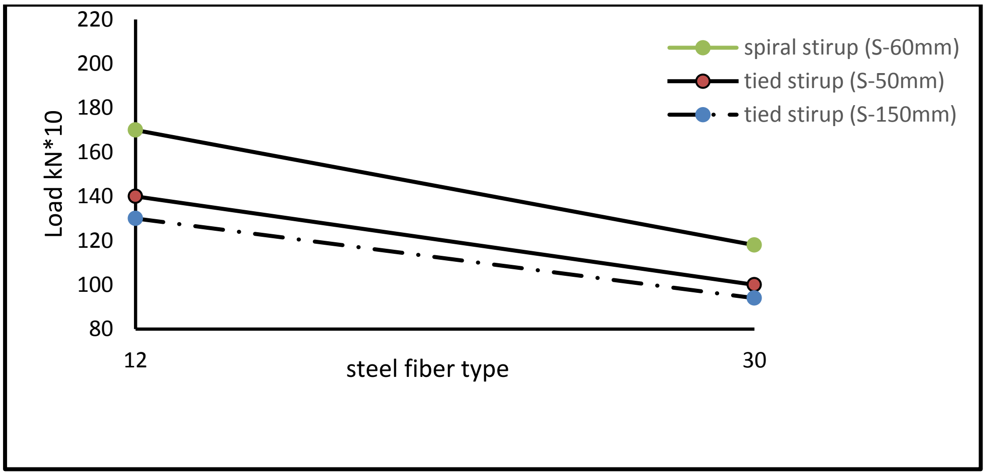


Figure (10-a) Effect of steel fibers type on load of RPC columns (long reinf. dia.8mm)

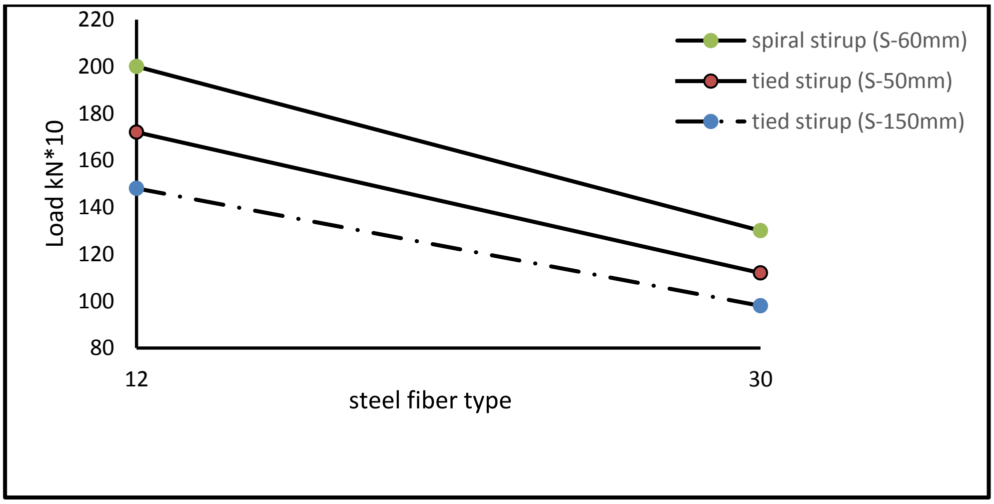


Figure (10-b) Effect of steel fiber type on load of RPC (long reinf. dia.10mm)

CONCLUSIONS

1. The tied columns fail at ultimate load by crushing of the concrete accompanied by shearing out warding along on inclined plane and buckling of longitudinal steel out ward between the ties.
2. In the spiral columns, the longitudinal steel and concrete within the core are prevented from failing out ward by the spiral and only the outer shell spalls off.
3. The ultimate load of RPC columns with steel fiber of group 1 and 2 is greater than the carrying capacity of RPC columns without steel fiber by about 1.1 to 1.65 respectively.
4. The ultimate load capacity of RPC columns of spiral lateral reinforcement is greater than the load of RPC columns of tied lateral reinforcement by about 1.25 to 1.35 times for the two groups.
5. The bearing capacity of RPC columns is more than the bearing capacity of HSC column by about 1.8 times

6. The spiral lateral reinforcement columns have the maximum value of load (P) with minimum displacement (Δ).
7. The ratio of increasing load with increasing the compressive strength ($f'c$) is about 1.4.

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