Fiber Reinforced Reactive Powder Concrete Columns' Behavior after Exposure to Fire and Improvements Made To Improve Column Resistance against Fire

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ABSTRACT: *This paper offers a test examination of the fiber strengthened responsive powder solid sections' conduct after introduction to fire and upgrades made to improve segment opposition against fire. This examination is for the most part meant to contemplate the test conduct of mixture strengthened segments created by receptive solid powder (RPC) and presentation to the fire of fire at one side and exposed to erratic burden. The test technique comprises of sixteen RC segments that sorted out into four gatherings dependent on the factors utilized in this examination: (SF) steel strands, (PP) polypropylene filaments, (HB) half and half filaments, (PPC-SF) crossover cross-segment (steel fiber responsive powder solid center with polypropylene fiber receptive powder solid spread). All sections were tried under 60 mm capricious burden and the consume segments were presented to fire for various length (1, 1.5 and 2) hours. The outcomes showed that (SF-RPC, PP-RPC, HB-RPC, PPC-SFRPC) sections presented to a fire for the period 2 hours, lost from their heap limit by about (54.39, 40.03, 34.69 and 30.68) % separately. The primary finish of this paper is that the best imperviousness to fire of the segment acquired when utilizing a half breed cross-area (steel fiber responsive powder solid center with polypropylene fiber receptive powder solid spread).*
Keywords: Reactive Powder Concrete (RPC); Hybrid Cross Section Column; Hybrid Fibers (HB); Exposed to Fire and Eccentric Load.

I. INTRODUCTION

The reinforced concrete column is a structural member utilized mainly for standing compressive loads, consisting of concrete with an embedded steel frame for reinforcement purposes. There are rarely axially loaded columns in practice since there is always some bending. The moments that happened in the continuous construction along with unavoidable building imperfections will cause eccentricities and then caused a bending in the member. The strength of the column is controlled by the strength of the used material (in particular, the compression strength of the concrete) and the cross-section geometry [1]. The demand for stronger, products with lower space-consuming has increased as construction and material costs increase. Newly, in Bouygues, France, developed a very high strength and high ductility cement-based composite, known as reactive powder concrete (RPC) [2]. RPC is a cemented material characterized by high-performance characteristics for example low shrinkage creep and permeability, ultra-high strength and increased protection against corrosion [3]. However, the need for high-strength structures always comes with an issue in fire resistance for the structure. It was disclosed collectively that the greater strength of the blend will cause a reduction in the composition's fire resistance. In high temperature, the high-performance concrete compositions which are usually denser tend to be more likely to fail because of their high brittleness. High performance concrete shows greater deterioration than ordinary strength concrete, for example concrete spalling and cracking [4]. Nowadays, many fire accidents have occurred around the world, with the use of fresh cement developments (lately RPC) to build load-carrying members for high-rise structures composed of beams and columns, and the fire safety design of these structures has become crucial. This is because the fire resistance of these members is the recent line defense, if other means is failed in extinguish the fire [5]. Also, secure constructions must be designed with a minimum danger for both individuals and property as potential [6, 7].

Nevertheless, the previous study concentrated only on the efficiency of the concrete columns during the fire, whereas the performance of these columns after cooling was very crucial since most concrete buildings subjected to fire circumstances did not collapse and could be recycled using appropriate methods for repairing [8]. In spite of that, it is not easy to decide whether it is more economical to repair the fire-exposed buildings or to demolish and repair them. This choice requires a full understanding of the conduct of these constructions after exposure to fire to determine whether the residual load-bearing capability of the load-bearing members is adequate. The previous researches indicated that the main cause of the crash was steel reinforcement failure for most of the concrete buildings that were damaged by fire [9, 10]. The reason is that the position of the reinforcement is generally near to the surface of the concrete member. Therefore, the steel reinforcement initially deteriorates due to its higher transfer rate of heat compared to the concrete

[10].   The tests were carried out as the most critical situation on four sides fired concrete columns. Concrete columns may be exposed to fire from various sides in actual fire events based on the construction's architecture and structural design [11, 12]. For instance, a wall could operate as a column obstacle exposing only one, two or three sides of the column to fire. On the other side, a column can be situated in the center of a space thus exposing all four sides of the column to fire.

        In this research improvements made to improve column resistance against fire. One of the improvements is to make a model in which the main component of the column Steel fiber strengthened RPC (SF-RPC) in the (core) and protected using polypropylene fiber strengthened RPC (PP-RPC) in the (cover). In this case, the core column is not significantly affected, the designer that can used after burning by the rehabilitation of the column through maintenance on the cover only. Also hybrid fibers are used in optimal proportions to differ from previous researches columns to obtain a column with elevated burn resistance and it has compared to columns casted, containing only steel fibers or polypropylene fibers. Figure 1 show the research methodology.
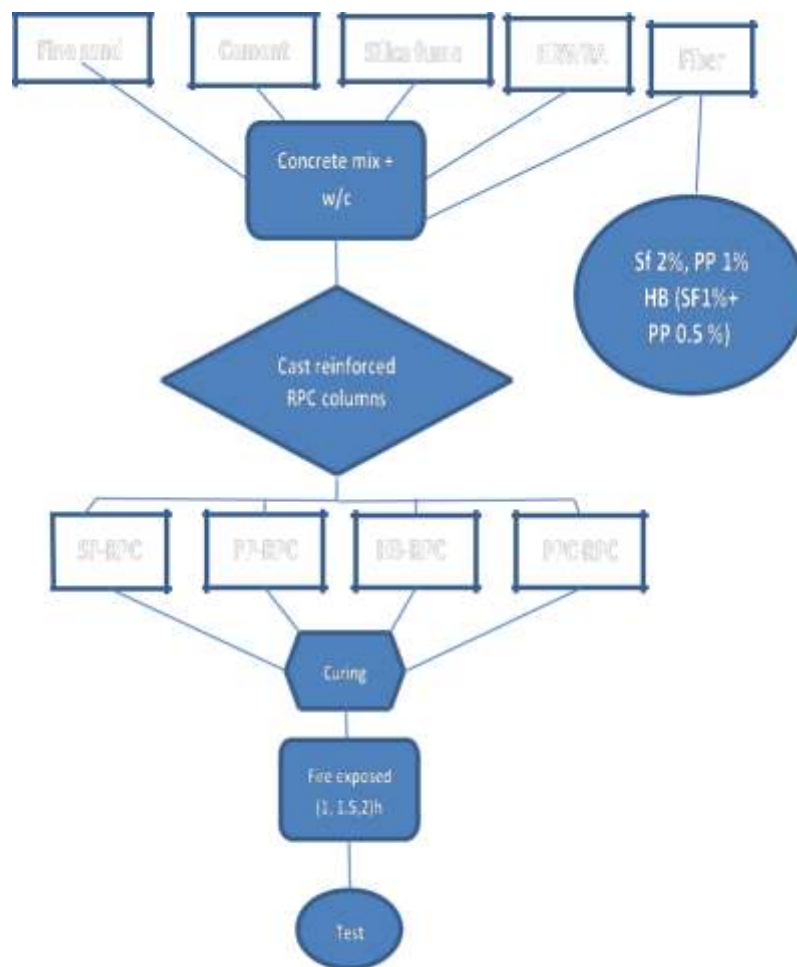

Figure 1. Flow chart of the project of research

II.   EXPERIMENTAL PROGRAM

2.1. Material
2.1.1. Cement
The cement that utilized in this study is Ordinary Portland cement (Type I), cement produced in Iraqi north and known of commercially as Karasta.

2.1.2. Fine Aggregate

Very fine sand with maximum particle size (600 μm) was utilized as a fine aggregate for reactive powder. In compatible with Iraqi Specification requirements IQS No.45/1984. Figure 2 shows the natural sand grading curve.
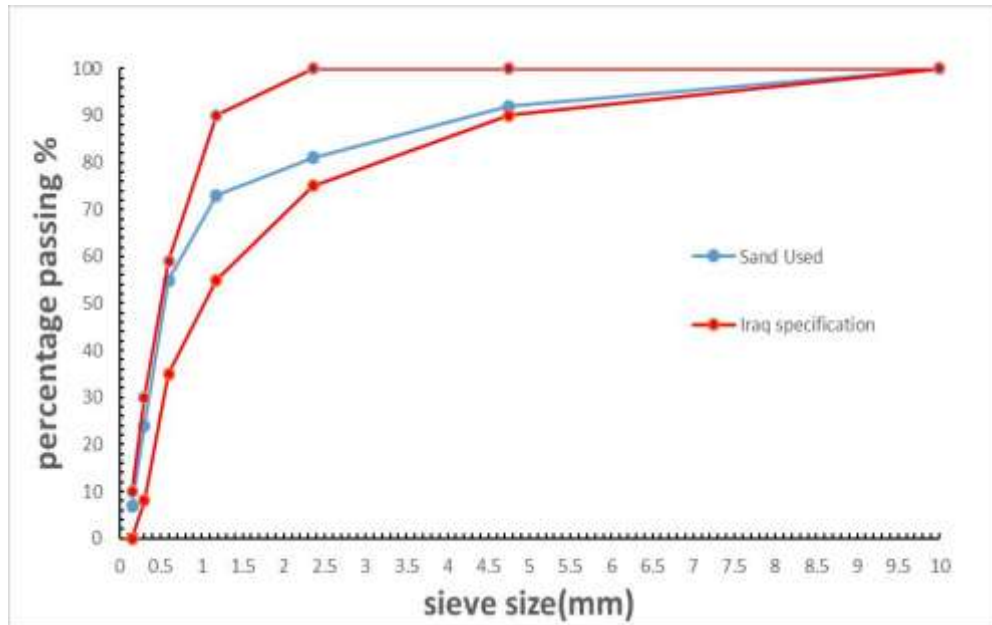

Figure 2. Grading curves for fine sand

2.1.3. Micro Silica Fume

RPC mixtures contain densified micro silica which is a pozzolanic material with particle size ranging from 0.1 to 1 μm. In terms of particle diameter, the average particle size is about 100 times smaller compared to Portland cement. The silica fume is manufactured in accordance with the requirements (ASTM C 1240/2005).

2.1.4. Fibers

In this research, uses of two kinds of fibers, Micro Steel Fiber (SF) and Micro Polypropylene Fibers (PP) having (13±1) and (12) mm length, (0.2±0.05) and (0.032) mm diameter, (2400) and (600-700) MPa Tensile Strength, (7825) and (910) Kg/m^3 density respectively.

Figure 3. Sample of Micro polypropylene and steel fibers

2.1.5. High-range Water Reducing Admixture (HRWRA)

In this research, superplasticizer type (Hyperplast PC200) conform with (ASTM C494, 2017, Type, G, F) was used which is chloride-free polycarboxylic polymers with long chains.

2.1.6. Steel Reinforcement Bars

There are three types of steel reinforcing bars used in this research: First: deformed steel bar Ø8 mm nominal diameter within all columns as longitudinal reinforcing (Ukrainian production). Second: deformed steel bar Ø10mm nominal diameter within all corbels reinforcement. (Ukrainian production). Third: deformed steel bar Ø6mm nominal diameter as transverse ties in the corbels and columns. (Turkish production).

2.2. Concrete Mix Design

Based on the previous researches, many trials RPC mixes were made to gain the higher compressive strength and flow (110%±5) according to (ASTM C109, 2016 and ASTM C1437, 2015) respectively . In the present research, three kinds of RPC mixes were used, as shown in the table (1).The variable used in these mixes was, fiber type (steel fibers, polypropylene fibers and hybrid fibers).

Table 1. The concrete mixtures used for this study

Mix No.	Mix ID	Cement Kg/m^3	Sand Kg/m^3	Silica Fume Kg/m^3	SF%	PP%	W/Cm	Super Plasticizer by wt. of Cementitious (%)	Compressive Strength fcu (MPa) in test day
1	SF-RPC	950	1050	237.5	2	-	0.18	7	141.64
2	PP-RPC	950	1050	237.5	-	1	0.18	7	121.7
3	HB-RPC	950	1050	237.5	1	0.5	0.18	7	137.3

2.3. Mixing Procedures

The specimens' mixes were carried out in a pan mixer of (0.09m3) for RPC. In this research, RPC was produce in a simple method without accelerated cure systems to simulate the practical site conditions. At the beginning of the mixing process, silica fumes and fine sand were mixed for 3 minutes, then for 2 minutes the cement and dry components were mixed until the uniform color was obtained. The superplasticizer was added to the water then mixed liquid was added to the dry mix for another 4 minutes during the mixer rotation. Fibers were lastly added by hand within 5 minutes during blending.

2.4. Specimens Details

All the columns have the same size and nominal dimensions. The model dimensions were a square section of 120×120mm and 1000 mm total length and 500 mm length localize between the corbel (middle part). The constant eccentricity value e = (60) was assumed. The corbels were reinforced by additional steel bars to avoid early failure in this part of the specimens during the tests and to concentrate the failure in mid part, as shown in Figure 4. Depending on the following variables, the columns were organized into four groups: steel fibers, polypropylene fibers, hybrid fibers and hybrid cross-section steel fiber reactive powder concrete core with polypropylene fiber reactive powder concrete cover. Each group consists of four reinforced reactive powder concrete columns. The test program and specimen details are summarized in Table 2, Symbols defined each column are (SF) refers to the steel fiber, (PP) refers to polypropylene Fiber, (HB) refers to hybrid fibers mixture (Steel fiber polypropylene Fiber). (RPC) refer to reactive powder concrete, (PPC) refer to use polypropylene fiber in cover and (SFRPC) refer to use the steel fiber in the core. The symbol (1, 1.5 and 2) refers to the duration of fire exposure (hour).
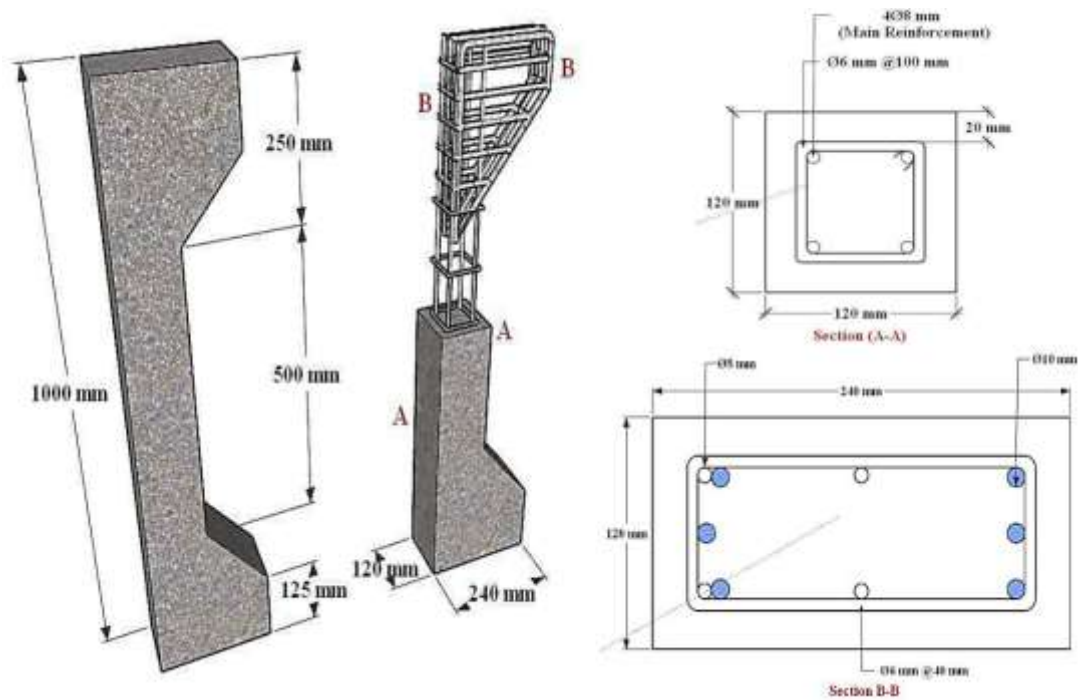
Figure 4. The dimensions and details of column specimens

Table 2. Details of the tested columns' specimens

GROUP NO.	Columns Symbol	The type of concrete		Volume Fraction of Steel Fiber %	Volume Fraction of Vfpolypropylene Fiber Vf %	Fire Duration (hr.)
		Concrete Core	Concrete Cover			
GROUP ONE	SF-RPC					0
	SF-RPC-1					1
		SF	SF	2%	0	
	SF-RPC-1.5					1.5
	SF-RPC-2					2
GROUP TWO	PP-RPC					0
	PP-RPC-1					1
		PP	PP	0	1%	
	PP-RPC-1.5					1.5
	PP-RPC-2					2
GROUP THREE	HB-RPC					0
	HB-RPC-1					1
		HB (SF+PP)	HB (SF+PP)	1%	0.5%	
	HB-RPC-1.5					1.5
	HB-RPC-2					2
	PPC-SFRPC					0

	PPC-SFRPC-1				1
GROUP		SF	PP	2%	1%
FOUR					
	PPC-SFRPC-1.5				1.5
	PPC-SFRPC-2				2

2.5. Casting Procedures

Steel molds were used. The fresh concrete was placed in three layers of column specimens (SF_RPC, PP_RPC, and HB_RPC). After putting each layer, the vibrator was used to compact the layer and ensure that the trapped air was removed and left for 24 hours until it was hardened. The samples were got out of the molds and cured with saturated wet coverings using burlap but column specimens (PPC-SFRPC) were cast in a different method: the first stage, core and corbel of the concrete mixed column cast (SF-RPC) and polystyrene foam sheet put surrounding the reinforced of the column to prevent concrete from escaping to the cover. The vibrating table was used during casting. After 24 hours, the polystyrene foam sheet was removed, then the surface of the core was cleaned and intentionally roughened to facilitate the process of bonding the new casting concrete in the after stage. The prepared sample was returned to the steel mold and casting the empty cover with PP_RPC in addition to the use of the vibrating table as mentioned before.

During the cover casting, the corbel was covering by saturated wet burlap. After 24 hours, the specimen got out of the mold and cured with saturated wet burlap, as shown in Figure 4 (a, b & c).

(a) Hybrid section column reinforcement
(b) Hybrid section mold and steel reinforcement
(c) Hybrid section after casting
**Figure 4. Method casting hybrid section columns**

2.6. Burning Process

At the college of engineering in the University of Babylon, the laboratory of concrete research, material properties and fire exposure studies were conducted there. Figure 5 (a) illustrate Furnace and equipment used in the burning process.The main structure of the furnace was produced from refractory brick and refractory mortar in addition to the presence of a small opening to provide adequate air for the burners. The main objective of the furnace compartment is to increase the temperature constantly for a required period for each type of columns as shown in Figure 5. The Sburner's network made from three methane burners, which organized in one lines at one side of exposure and their distribution were all over the column length without corbels, methane burners were connected together in one pipeline. The equipment that controlled the fire temperature and the heating process were shown in figure 5. At the age of 28 days, the curing process was finished, after that, the samples will be left for 26 days without curing and in the day 55th the will subject to burn, then the test carried out in (56 days age). The part of the concrete specimen that localized in between corbels (middle portion) were fair-faced toward methane burners. After the duration of burning was achieved (1, 1.5 or 2 hours of burning) the gas valve closed. After that, it left the specimens to cool down to the ambient temperature.

2.7. Testing Process

All RPC column specimens were tested at the age of 56 days under a calibrated electro-hydraulic testing machine with (capacity of 650 KN).An eccentricity distance of 60 mm was used in the present work. The

load was applied at a loading rate of 1 kN/s, using load control. For each increment in the load, the lateral deformation at mid-height and axial displacement were measured by two dial gauges with an accuracy of 0.01 mm per deviation and a capability of 50 mm. One dial gauge was placed on the testing machine piston and the other at the mid-height place along the vertical centerline of columns. Testing continues until failure recorded by a drop in load record.
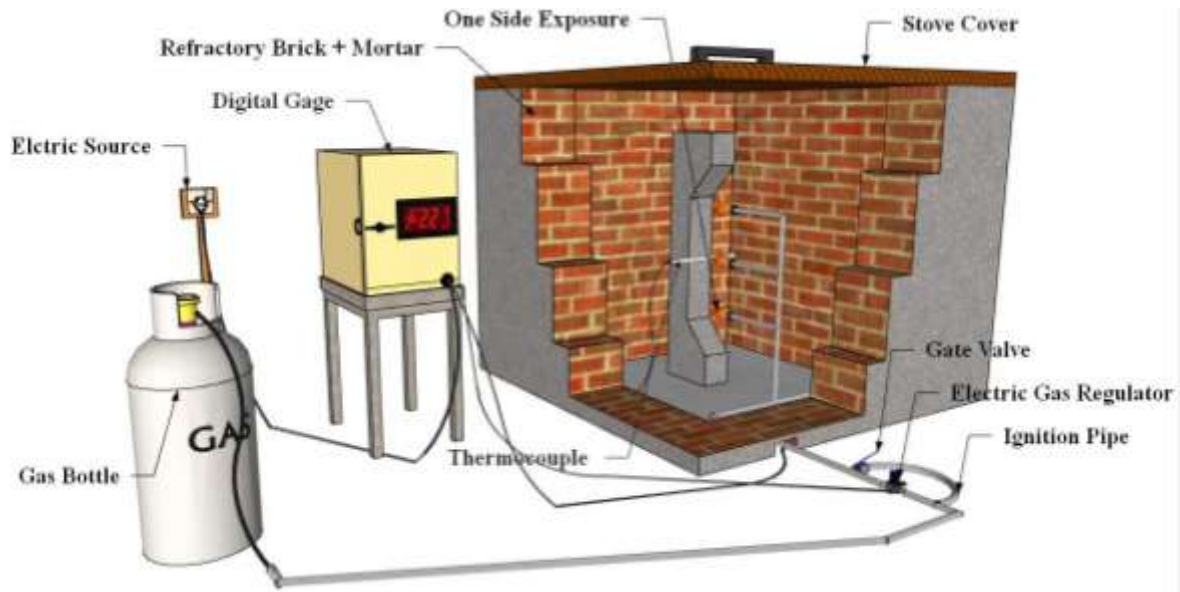
(a) Burning process
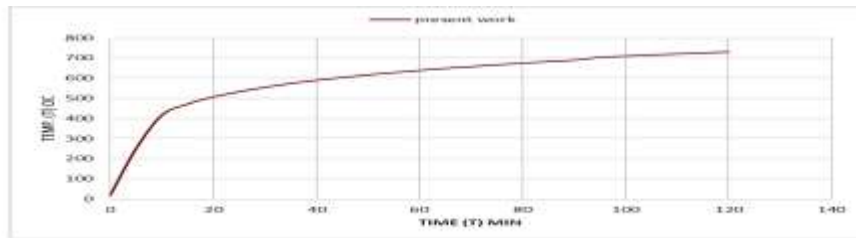
(b) Time-Temperature Curve
Figure 5. All details of the furnace and equipment and a time-temperature curve

III.   RESULTS AND DISCUSSION

The experimental results for the columns of each group are compared to each other to determine the effect of duration of fire exposure (1, 1.5 and 2 hours) then compare each group with another group to investigate the effect of fiber type. The test results of the specimen were the ultimate load carrying capacity, the first crack load, load- lateral deflection relationship, axial deformation, the cracks generated with a load of the columns, and failure mode of column samples.

Table 3. Experimental test results of column specimens

GROUP NO.	Columns Symbol	Fire Duration (hr.)	Load Carrying Capacity Pu (kN)	Percentage Decreasing Load Carrying Capacity (%)	Ultimate axial deformation (mm)	Ultimate mid-height lateral deflection (mm)	First crack load Pcr (KN)
	SF-RPC	0	320.36	Reference	7.78	9.9	83
	SF-RPC-1	1	290.03	9.46	7.79	9	66
GROUP ONE							
	SF-RPC-1.5	1.5	166.34	48.07	6.41	8.46	40

	SF-RPC-2	2	146.11	54.39	6.3	8.85	36

	PP-RPC	0	238.29	Reference	5.87	9.74	28
	PP-RPC-1	1	227.48	4.53	5.32	8.80	26
GROUP TWO							
	PP-RPC-1.5	1.5	187.9	21.14	4.84	10.4	19
	PP-RPC-2	2	142.9	40.03	5.8	17.45	16
	HB-RPC	0	315.10	Reference	7.31	11.66	75
	HB-RPC-1	1	257.15	18.39	7.03	12	52
GROUP THREE							
	HB-RPC-1.5	1.5	224.03	22.55	8.2	13.85	48
	HB-RPC-2	2	205.77	34.69	8.22	15.30	47
	PPC-SFRPC	0	294.74	Reference	5.72	14.75	87.37
	PPC-SFRPC-1	1	254.03	13.81	5.77	15	81
GROUP FOUR							
	PPC-SFRPC-1.5	1.5	232	21.28	5.25	13.44	60
	PPC-SFRPC-2	2	204.29	30.68	5.58	14.69	50

3.1. Load Carrying Capacity

The load carrying capacity reflected the ultimate load applied to tested column specimens after which a decrease in device reading occurred with a fast column deformation known as a failure. The behavior of columns tested at ambient temperature as a reference specimen for comparison to study the loading capacity remaining of columns after burning. As stated before, the columns are subdivided into groups. The results showed that the non-exposed control column of group one has more load capacity than the control column of group two while group three and four for the control column have load carrying capacity close to control column of group one. As for the columns exposed to fire for duration of fire exposure 1 hour for each group, the decrease in the load carrying capacity of (SF-RPC, PP- RPC, HB-RPC, PPC-SFRPC) columns (9.46%, 4.53%, 18.39% and 13.81%) respectively from reference in each group but the decrease in the column load carrying capacity exposed to fire for duration of fire exposure (1.5 and 2) hours for each group (SF - RPC, PP- RPC, HB-RPC, and PPC-SFRPC) columns are (48.07%, 21.14%, 22.55%, and 21.28%) and (54.39%,40.03%,34.69%and30.68%) respectively from reference column in each group as shown in figure 6. Adding polypropylene fibers considerably decreases RPC spalling during fire periods. These fibers melt and form channels to escape water vapor to relieve the inner vapor pressure of the RPC while the existence of these channels decreases the RPC strength. This is confirmed in many types of researches. However, hybrid fiber reinforced reactive powder have a more stable behavior under fire exposure and the greater residual load carrying capacity.

This is because the hybrid fiber-reinforced RPC had preferable resistance to elevated temperatures compared to (steel or polypropylene) fiber-reinforced RPC as well as a successful way to improve the resistance of RPC to explosive spilling is to add hybrid fiber (steel fiber and polypropylene fiber), which should be a main objective for improved fire resistance.

3.2. Load-Displacements Relationship of Reinforced Concrete Columns

From Figure 8 (a, b, c & d), it could be observed that the rise in duration of column fire exposure has an important impact on the mid-height lateral deflection of column specimens for all groups. Also, this comparison means that load-deflection curves for group (two and three) are more sensitive to high temperatures compared with a group (one and four). This can be ascribed to the reality that heating causes a decrease in the stiffness of the column owing to the decrease of the concrete elasticity modulus and the decrease in the effective section due to cracking.

3.3. First Crack Load

The cracks formed in the concrete if the tensile stress extents to its strength limit at the interface of cover-core. After the cover-core interface cracks advanced, the concrete cover was free to spall or buckle away. In all tested columns, the first crack was experimentally measured, in this research, the first experimental crack load for columns was visually observed by a magnifying lens while the load was gradually increased. The first crack was seen in all samples at mid-height of the column on the tension face (maximum moment region). Table 3 shows this. With growing compressive strength of concrete and fiber type, this first crack has been improved. The first crack load of RPC columns with steel and hybrid fibers, compared to RPC columns with polypropylene fibers was better by (3-2.5) times. Hence, the steel fibers are better to be used to enhance the tension, split and rupture strength of concrete. In general, the first crack load of RPC columns reductions with increasing the fire exposure's duration.

IV.   FAILURE'S MODE

The failure mechanism of all columns was caused by yielding the longitudinal steel reinforcement, which occurs after buckling and cracking that happened at the tensile face of the specimen while the crushing and deboning at a compression face of unburned specimens. Generally, this was depend on concrete compressive strength and fiber type. The columns that contain steel fiber and hybrid fiber have high ductility in compare with columns that contain only polypropylene fiber .This affect the failure mode. Also, these fibers effected preventing the exploding and spalling concrete cover even after failure.

In burned columns, the presence and spreading of cracks are faster than unburned columns. In (SF-RPC-1, SF-RPC-1.5, SF-RPC-2) columns, a crack has been started in the side of the corner of the columns then spread towards the compression zone, in (SF-RPC-1) the concrete cover's debonding and crushing was happened at this face, while there are explosive concrete spalling before testing columns in the (SF-RPC-1.5, SF-RPC-2) columns due to the high temperature in the compression face, so spread cracks and columns failure is fast [13]. The form of failure of (PP-RPC-1, PP-RPC-1.5, PP-RPC-2) columns almost similar to the failure of (SF-RPC-1, SF-RPC-1.5, SFRPC-2) but cracks appear faster and concrete spalling of the concrete cover occur after test at a compression zone in the middle third of the column. The failure mode of (HB-RPC-1, HB-RPC-1.5, HB-RPC-2) columns are similar to previous unexposed columns where no explosive concrete spalling happened before testing the columns due to high temperature and after testing columns due to high pressure at compression zone. The failure mode in PPC-RPC-1, PPC-RPC-1.5, PPC-RPC-2 is similar to (PP-RPC) that exposed to fire but the cracks spread slowly at tension face .In addition to thermal cracks due to high temperature before testing and concrete spalling after testing at compression zone in the middle third of the column, there are splitting along an area of junction between core and cover. As shown in Figure 9, the start of failure can be observed for all RPC columns by listening to the popping sound and pulling of steel fibers then gradually dropping down the load applied.

V.   DUCTILITY

In this paper, the method of (energy absorption capacity) is adopted to the study the ductility. The absorbed energy capacity of the concrete column defined as the enclosed area under the curve of load vs. displacement until the maximum load was reached [14]. The result of calculation of (ductility) is given in Figure 7. From these results and figure turns out, using steel fibers in reactive powder provide a significant enhancement for the ductility of an unexposed column (reference) in group one from other references for other groups. From these results, the residual ductility of columns for group one after burning are (93.45, 44.44, and 41.96) % to columns exposed for the duration of fire exposure (1, 1.5 and 2 hour) respectively. For columns of a group two, group three and group four (89.11, 67.96 and 74.52) %, (86.3, 84.27and 83.08) % and (84.71, 68.14 and 66.99) % for columns exposed for the duration of fire exposure (1, 1.5 and 2 hour) respectively.
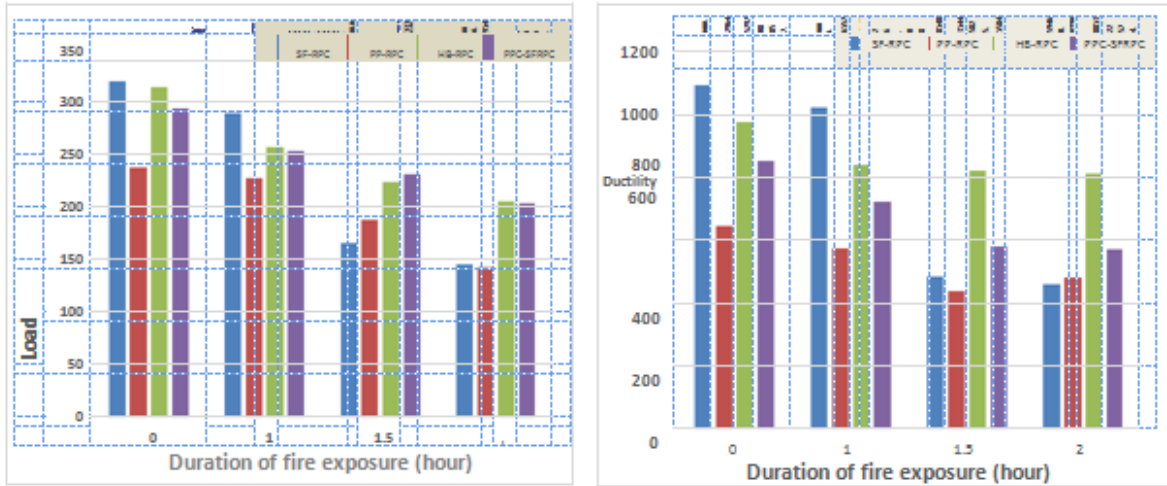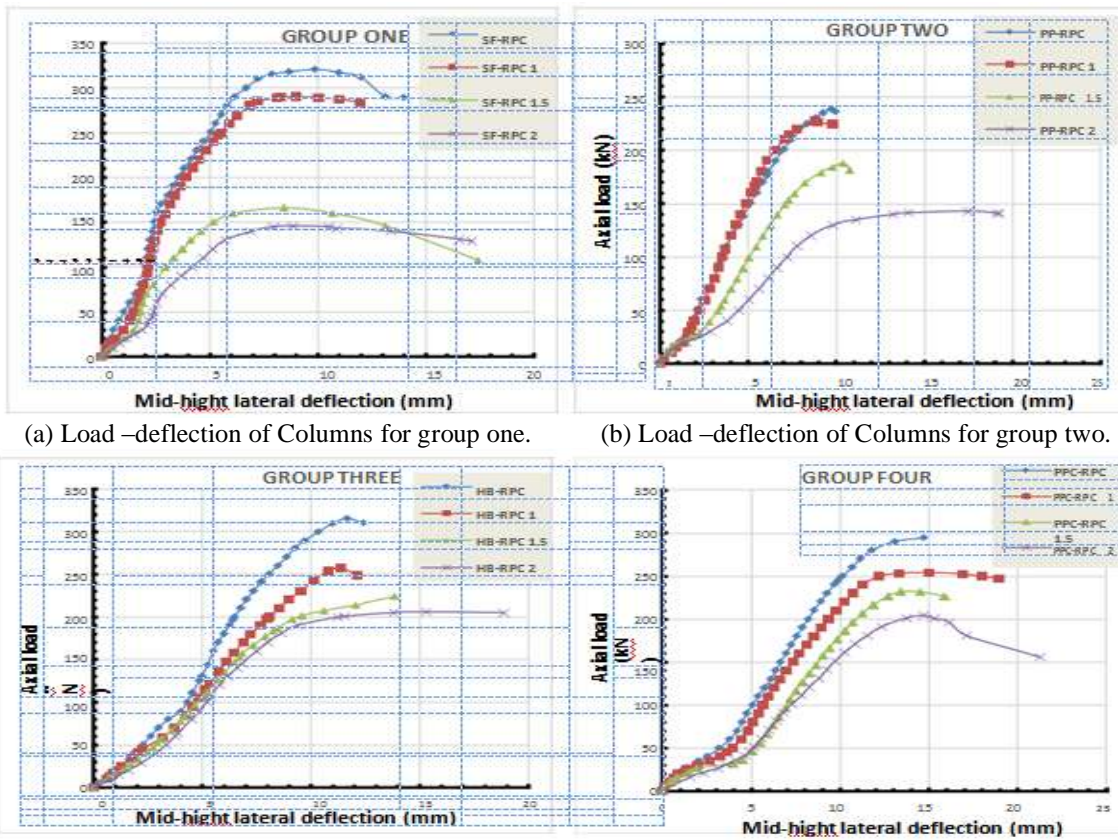
Figure 6. The percentage of load carrying capacity of columns
Figure 7. The ductility of specimens

(a) Load –deflection of Columns for group one.   (b) Load –deflection of Columns for group two.

(c) Load –deflection of Columns for group three.   (d) Load –deflection of Columns for group four.
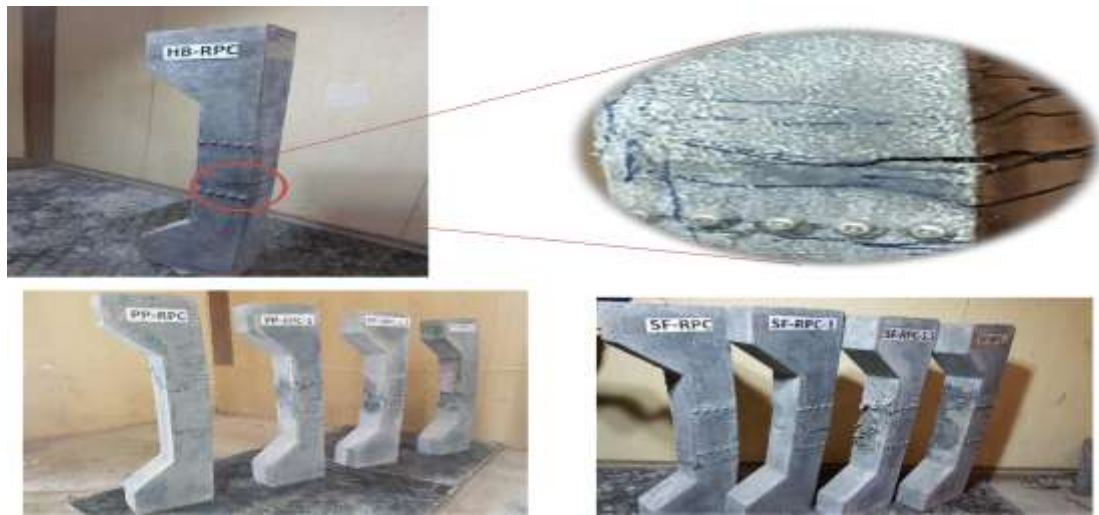**Figure 8. Load –deflection of Columns for each group**

Figure 9. Failure modes of (HB-RPC), (PPC-SFRPC), (SF-RPC) and (PP-RPC) columns after the burning and testing

VI. CONCLUSIONS

☐ For the reference RPC columns of each group, the load carrying capacity was higher when using steel fiber, hybrid fiber and hybrid cross section compared to using polypropylene fiber.

☐ The effect of the increased duration of fire exposure on the load carrying capacity was less for (HB-RPC, PPC-SFRPC) column specimens than (SF-RPC, PP-RPC) column specimens. For 2 hours fire duration the best residual load carrying capacity is obtained by using (HB-RPC and PPC-SFRPC).

☐ From the test results, it has been concluded that the cover of concrete contributed to improving the fire resistance of (PPC-SFRPC) columns after burning for different burning durations.

☐ For the reference columns, it is observed that SF-RPC columns have much greater ductility compared to other references in each group. Also, it is discovered that using polypropylene fiber in RPC such (PP-RPC) columns gives lower ductility compared to other groups.

☐ The experimental findings show that the absorption energy capacity of RPC columns clearly decreases with increment the duration of fire exposure.

☐ The first crack load of RPC columns with steel and hybrid fibres, compared to RPC columns with polypropylene fibers was improved to (3-2.5) times. The first crack load of RPC columns decrease with increasing the duration of fire exposure.

☐ Hybrid, polypropylene and Steel fibers influence the prevention of explosion and spalling concrete cover even after column failure. However, columns (HB-RPC) have no explosive spalling occurred before testing the columns due to elevated temperature and after testing columns.

Conflicts of Interest
The authors declare no conflict of interest.

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