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The Effect of Concrete Cover Thickness for Reactive Powder Concrete on the Column Resistance Against Fire

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ABSTRACT

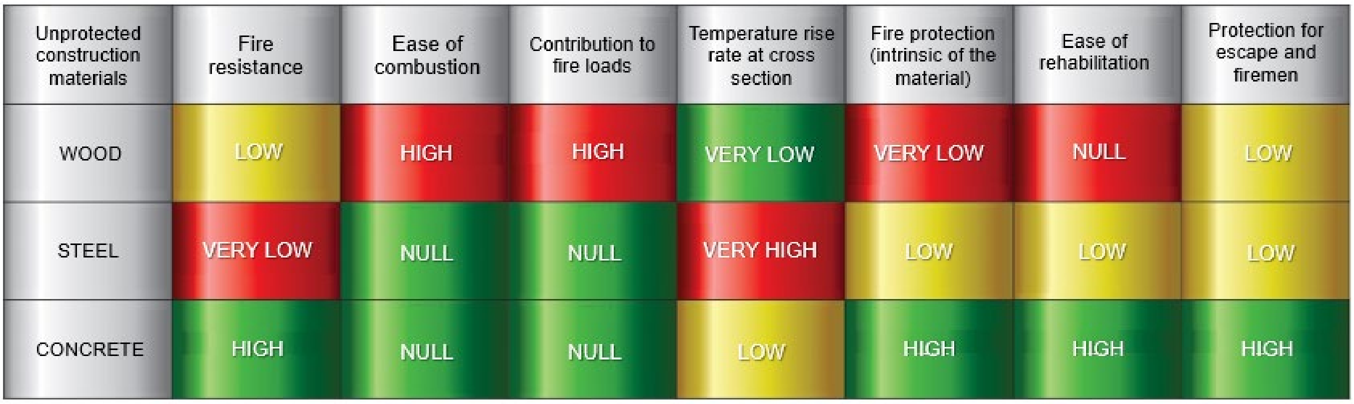
Structures made of reinforced concrete are often exposed to fire of varying intensity. If the building does not burn down, a post-fire study of the building's structural integrity is necessary before determining the building's destiny. It can forecast the remaining loading capacity of the columns after a fire by knowing the temp of the fire, the thickness of the cover of concrete, the concrete's residual strength, and the tensile strength of the embedded strengthening. Over the past few years, there has been significant progress in the construction of urban cities. This progress has led to improvements in the building process, particularly in the requirements of structural design for extremely robust building products. One important factor that has been given more attention in building design is the length of building elements. Since its exceptional strength and durability, reactive powder concrete (RPC) has gained significant attention in the field of building construction in recent times. Therefore, incorporating enhancements can greatly contribute to preserving the optimal performance of concrete in various scenarios, including fire exposure. The current study seeks to examine the variations in strength of reactive powder concrete once subjected to different burning temperatures (200, 400, and 600℃) through experimental testing. The experiment involved three sets of specimens; each set exposed to different burning temperatures for one hr. Within each set, the specimens were further split into four subgroups to observe the effects on cover of concrete at depths of 15mm and 30mm, with and without secondary strengthening. The findings gained indicate that greater burning temperatures, ranging from 200-600, lead to a decrease in the compressive, tensile, and flexural strength of reactive powder concrete. In addition, the decision for increment the cover of concrete from 15 to 30 mm has proven to be effective in enhancing the fire resistance of the concrete column. Furthermore, the utilization of secondary strengthening with a similar cover of concrete has resulted in a significant increment in the overall fire resistance of the concrete structure.

1. INTRODUCTION

Reinforced concrete columns are utilized to support compressive loads and are made of concrete with a steel frame. Since there is constant bending, axially loaded columns are unusual. The member bent since eccentricity generated by continual construction moments and inevitable structural defects. Material strength (particularly concrete compression strength) and cross-section geometry determine column strength [1-3]. High performance concrete (HPC) has gained significant traction in the construction of tall buildings due to its impressive properties. It has garnered attention from researchers and is now extensively utilized. On the other hand, HPC is primarily known for its ability to withstand compression, making it ideal for column construction. HPC is becoming more popular in modern construction because of its low permeability and great durability [4]. Nevertheless, the need for structures with exceptional strength always presents a challenge when it comes to fire resistance. Several studies were conducted to analyze the behavior of HPC when exposed to fire, considering both its material properties and structural performance [5]. It was found that as the strength of the mixture increases, the fire resistance of the composition decreases. Concrete compositions with superior performance often exhibit increased density and are more susceptible to failure under great temperatures owing to their inherent brittleness. HPC shows more severe deterioration, including cracking and spalling, compared to normal strength concrete [6].

Stronger, space-saving solutions are in demand as construction and material prices rise. Recently, Bouygues, France, created reactive powder concrete (RPC), a cement-based composite with exceptional strength and ductility [7]. RPC, a cemented material, has minimal shrinkage creep and permeability, ultra-great strength, and corrosion protection [8, 9]. The necessity for strong buildings constantly raises fire resistance concerns. Together, they revealed that the blend's strength reduces fire resistance. The brittleness of denser great-performance concrete compositions makes them more prone to break at great temperatures. Great-performance concrete spalls and cracks more than standard concrete. With the usage of new cement advancements (lately RPC) to manufacture loading -carrying members for great-rise beam and column buildings, fire safety design is vital [10-13]. Many fire mishaps have happened worldwide. If other methods fail to extinguish the fire, these members' fire resistance is the last defensive line [14]. Secure buildings must minimize risk to people and property.

Once compared concrete to other (unprotected) construction materials, concrete offers a lot of advantages in terms of the design of buildings and the extraordinary action of fire, as shown in Figure 1. In this regard, it is underlined that concrete performs well under fire circumstances since two primary factors: the first is connected to the material's inherent qualities, and the second is related to its utility once utilized as a part of the total construction.



Unprotected construction materials	Fire resistance	Ease of combustion	Contribution to fire loads	Temperature rise rate at cross section	Fire protection (intrinsic of the material)	Ease of rehabilitation	Protection for escape and firemen
WOOD	LOW	HIGH	HIGH	VERY LOW	VERY LOW	NULL	LOW
STEEL	VERY LOW	NULL	NULL	VERY HIGH	LOW	LOW	LOW
CONCRETE	HIGH	NULL	NULL	LOW	HIGH	HIGH	HIGH

Figure 1. The unprotected performance summary of building materials under flames

The durability parameters for reinforced concrete specified in technical standards, such as strength at compression, water-cement proportion, cement usage and cover thickness, influence not only how concrete behaves at room temp but also how concrete and reinforced concrete elements behave once subjected to great temps [15, 16]. It is feasible to confirm that the processes involving the behaviour of column prototypes increased environment aggression class resulted in stronger material resistance to compression, an increment in spalling, and a deterioration of concrete structures. The increment in concrete resistance and decrease in the water/cement proportion led to a great degree of durability and low permeability, as well as the control of aggressive agents within the concrete [17].

Under these conditions, the level of decrease, bonding breakage in the cement paste microstructure, and disintegration of hydrated cement products would depend on moisture loss [18]. Although having a positive impact on durability, a cover of concrete with a larger thickness may make the mechanism stronger. The project's stipulated specifications do not take into account an inverse connection between fire resistance and durability under these circumstances [19].

Guo and Shi [20] confirmed that a cover increment of 10–30 mm at the beam's max moment zone increases its fire resistance once considering the impact of the cover of concrete thickness. Nevertheless, once the cover increment is more than 20 mm, this impact decreases. In research employing reinforced concrete columns, Nazri1a et al. [21] confirmed a rise in the degree of spalling with the increment of cover of concrete thickness. Additionally, Kodur and Dwaikat [22] investigated the behaviour of beams and established that an increment in cover thickness lowers the temp in the reinforcing steel bars, which in turn lowers element deflection.

Ergün et al. [23] examined the residual mechanical behaviour of concrete samples with various cement usage (250 and 350 kg/m^3) and discovered that, despite influencing the performance at air temp, this variable has no effect on the residual strength at compression of concretes subjected to great temps. A further influencing factor is the kind of aggregate [24].

Aldea and Franssen [25] conducted six fire experiments on NSC and HSC short columns to evaluate fire-induced spalling characteristics. Strengthening, steel bar diameter, quantity, and concrete strength were considered. The research found early corner spalling in HSC columns but not in NSC columns. The investigation also found that material qualities affect fire failure modes more than structural details. But typical fire exposure impact under concentric loading hampered the investigation.

Kodur and Sultan [26] tested three concrete-reinforced columns for fire resistance. One column had conventional concrete strength and the other two had increased concrete strength. For all these columns, temperatures rise fast to roughly 100°C, then slow down. HSC columns behave differently at greater temperatures than NSC columns. HSC columns have lower fire resistance than NSC columns.

Under fire circumstances, Raut and Kodur [27] found that eccentric stress may produce biaxial bending in RC columns. HSC columns may experience biaxial bending by spalling fire flames. However, few researches have examined the effects of fire-induced biaxial bending, particularly in asymmetrically burned columns, on column strength. The fire resistance of six RC columns was evaluated utilizing the working program. These columns included one NSC, one half HSC column, and one HSC column containing polypropylene fibers (HSCP). The columns that were examined had dimensions of 203 millimeters by 203 millimeters and a length of 3350 millimeters. They are reinforced with lateral strengthening measuring Ø10@200 millimeters and main strengthening of 4 Ø20 millimeters. According to the findings of the tests, the most significant factors that influence the fire resistance of RC columns are the concrete strength (permeability), the fire scenario, the biaxial bending from one, two, or three sides, the slender proportion, the eccentricity of the loading, and the loading proportion. In some circumstances, the fire resistance of NSC columns is sixty-five percent higher than that of HSC columns. Polypropylene-fibers in the concrete mix tripled columns' HSC fire resistance, and fire exposure affects RC column fire resistance. Polypropylene-fibers in the concrete mix tripled columns' HSC fire resistance, and fire exposure affects RC column fire resistance. Utilizing a macroscopic approach to finite elements, the model calculates RC column response under fire circumstances utilizing time-dependent M-κ interactions.

RC column behavior at great temperatures was examined by Nassar [28]. RC column specimens employed polypropylene (PP) fibers. We created three concrete mixes utilizing different concentrations of Polypropylene (0.0, 0.5, and 0.75) kg/m^3. The specimens were heated at 400, 600, and 800°C for two, four, and six hours to validate strength at compression. The behavior of reinforcing steel bars was also studied and inserted into 20- and 30-mm concrete specimens for coverings. After six hrs at 800°C, these bars were evaluated for max elongation ratio and yield stress. The analysis revealed that 75×10-2 kg/m^3 of PP was optimal for reducing strength at compression by 20%, surpassing specimens without PP at 400°C for 6 hrs. Cover of concrete of roughly 3 cm helps protect concrete buildings and steel reinforcing bars from fire, while it is 5% greater than the specimen's column with 20 mm cover of concrete at six hrs and 600°C.

Bikhiet et al. [29] tested 15 columns (15*15*100) cm except one to (600) degree Celsius fire and axial stress. Evaluation of fire-induced compressive capacity loss. Main factors tested were concrete strength, weights applied, fire duration, longitudinal reinforcing %, yield strength, and bar diameter. Unexposed columns had the first fracture at 80% of column failure loading, whereas exposed columns had it at 50%. Columns with equivalent strengthening but smaller bar diameters experienced reduced lateral strain and vertical displacement. A column reinforced with great-grade steel has a 55% greater failure force than one reinforced with mild steel.

2. EXPERIMENTAL PART

2.1 Materials

i. Cement: Ordinary Portland cement (Type 1) was applied in the formwork of column models and specimens during this study that compatible with Iraqi specification for cement [30].
ii. Fine aggregate (sand) and coarse aggregate (gravel): Sand has been applied as fine aggregate in this project. It is utilized for classification and falls within the lower and upper bounds of the Iraqi Standards Area (IQ. S 45/1984) [31] (AL-Nibaai) region.
iii. Steel strengthening that utilized in this study come in two types of steel bars commercially available in local market (Φ6, Φ5) mm. Tension and compression are reinforced by reinforcing bars with a diameter of (Φ6) mm. Connecting rods with a diameter of (Φ5) mm are utilized.
iv. Silica fume utilized supply by the chemical business (CONMIX), commercially recognized as Mega Add MS (D). It is powder colored (gray) and varies from (0.1-1) μm in particle size.

The concrete mix for reactive powder concretes that utilized in the current study is as listed in Table 1.

Table 1. Mix proportions of the test specimens

Mix No.	Mix Type	Mix Proportions						
		Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silica Fume kg/m^3	Steel Fiber kg/m^3	W/cm	Super Plasticizer by wt. of Cementious (%)
1	RPC	950	1050	---	210	156.5	0.17	6.5

2.2 Description of the tested column specimens

The purpose of this study is to study RPC columns exposed to fire flame on two sides. The experiment tested 12 RPC columns. Each column received 4×6 mm longitudinal strengthening and Ø5 mm transverse strengthening (ties) with varied spacing, as illustrated in Figure 2. Every column specimen has 90 cm dimensions and 10×10 cm cross-sections. According to fire temperature, column specimens are divided into three categories. Table 2 shows that each group had four RPC columns based on transverse strengthening (ties) and cover of concrete spacing.

Table 2. Summary of RPC column specimens

Group No.	Variables				Constants	
	Fire Temp (℃)	Columns ID	Concrete Cover (C.C) (mm)	Transverse Reinforcement (Ties)	Cross Section Dimensions (mm)	Main Reinforcement
One	200	RM1	15	Without	100×100	4Ø6
		RM2		Ø5@200mm		
		RM3		Without		
		RM 4	30	Ø5@200mm		
Two	400	RM1	15	Without	100×100	4Ø6
		RM2		Ø5@200mm		
		RM3	30	Without		
		RM 4		Ø5@200mm		
Three	600	RM1	15	Without	100×100	4Ø6
		RM2		Ø5@200mm		
		RM3	30	Without		
		RM 4		Ø5@200mm		

2.2.1 Column specimens' identification

Since the large number of column specimens evaluated in this research, each RPC column has three symbols to make comparison simpler. Letters representing concrete are the first symbol. The letters RM indicate RPC. Figure 2 shows the 15mm and 30mm cover of concrete (C.C.). The third symbol is a number that indicates tie spacing, with (0) indicating no ties and (1) 200mm.

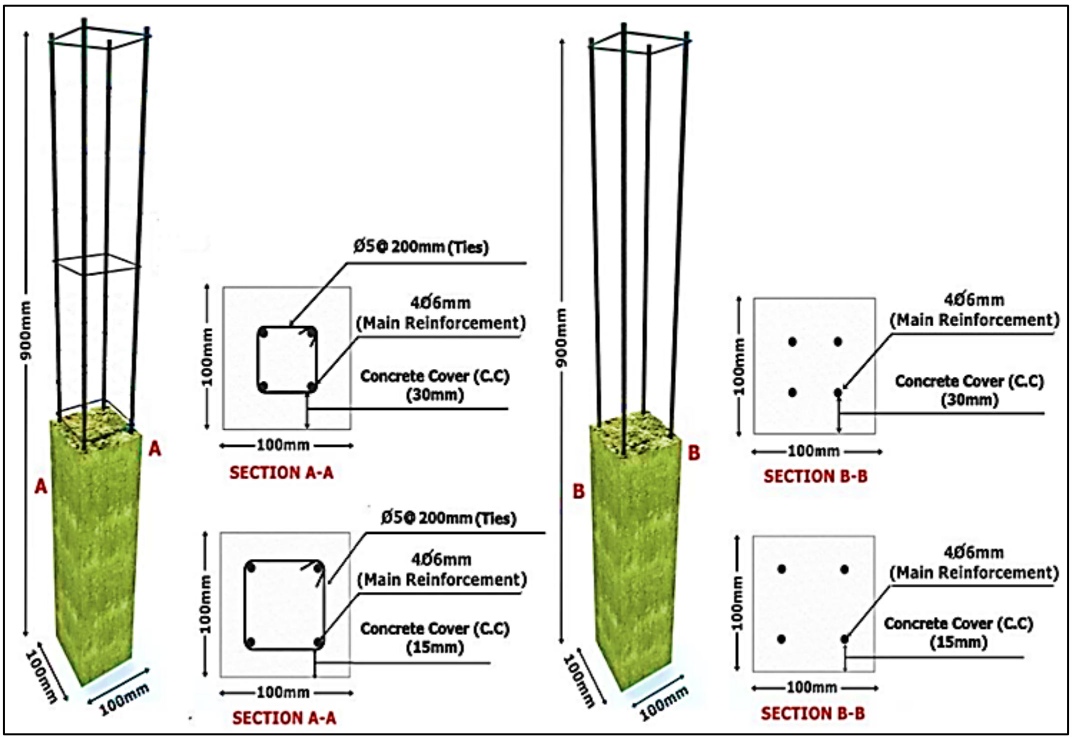


Figure 2. Strengthening details of the reinforced column specimens

2.3 Control specimens testing

After selecting RPC column specimen mixtures, cylinders, cubes, and casting prisms were inspected after 3, 7, 28, and 56 days with different fiber types at room temperature and after a one-hr flame fire utilizing the same column burning procedures and circumstances. These tests measured cube compression, rapture, and tension splitting strength. All examinations were at Babylon University.

2.3.1 Compressive strength test

Strength at compression is a key concrete engineering property that indicates concrete class. As illustrated in figure 3a, three 50×50×50 mm cubes were cast for each mix and burned in the same way as column specimens for 1 hr to determine strength at compression and average magnitude according to ASTM C109/C109M [32]. Cracking these cubes at 3, 7, 28, and 56 days utilizing a 1900 kN digital instrument at 0.3 MPa/sec tested their compression strength.

2.3.2 Splitting Tensile Strength (STS)

Concrete's STS met ASTM C496 [33]. Three cylindrical concrete specimens (100×200 mm) were cast for each mix at ages 3, 7, 28, and 56 days, and the 28-day examples were burnt like column specimens for varying durations. Figure 3b shows two bearing strips (length=20 cm, width =2.5 cm, and 3 mm plywood thickness) placed below and above the specimen in the testing machine (1900 kN capacity).

The following equation calculates specimen splitting tensile (fsp):

$$f_{sp} = \frac{2p}{\pi \mathrm{DL}} \tag{1}$$

f_{sp}: Strength under Splitting Tension MPa.
P: Max practical load in splitting test N.
D: Cylinder's Diameter mm.
L: Cylinder's Length mm.

2.3.3 Strength of flexural

To determine the concrete rupture modulus, a 50×50×300mm prism was utilized for RPC experiments, following ASTM C78 / C78M [34]. Figure 3c shows two-point loading of each prism utilizing a 1900 KN testing equipment. The average rupture modulus (flexural strength) is 3 prisms per age (3, 7, 28, and 56 days). The equation below calculates rupture's modulus (fr):

$$f_r = \frac{PL}{bh^2} \tag{2}$$

f_r: Rupture's Modulus of, MPa.
P: loading of failure, N.
L: supports spaces, mm.
b: Prisms' Width, (mm).
h: Prisms' Depth, (mm).

2.4 Instrument and test procedure

2.4.1 Instrumentations

Concrete columns were monitored during loading utilizing appropriate equipment. In addition to initial fracture loading, lateral deflection, axial deformation, and concrete strain at mid height were recorded in each loading stage. The final loading has been recorded and testing proceeded till failure. This investigation utilized the following instruments:

(1) A mechanical strain gage with 0.001mm precision recorded concrete stresses. Column was utilized to measure concrete strain at different loading levels for each column specimen at mid-height.

(2) Dial gages with 0.01mm precision identified longitudinal and horizontal deflection.

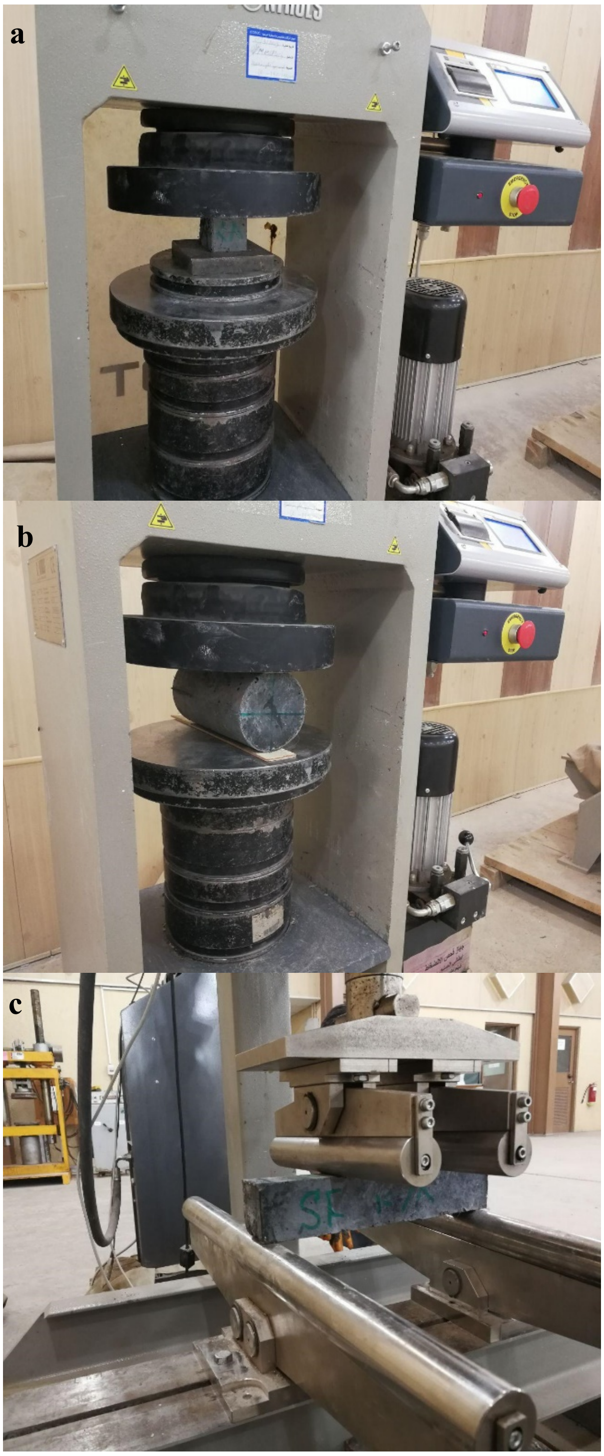


Figure 3. (a) Compression strength; (b) STS test; (c) Flexural strength compressive

2.4.2 Testing procedure

The column the specimen was thoroughly cleaned prior to testing, carefully set in an upright position, and the dial gauges were securely attached. Notable structural behavior characteristics have been noted at every stage of the testing process. Measurements are taken for each test to record the max loading, lateral displacements at mid-height, and axial deformation.

The column specimens were subjected to increasing concentrical loading s until failure utilizing calibrated electro-hydraulic testing devices with a max range of 2500 KN. The tests were conducted at the 60-day mark.

Two dial gauges were utilized to determine mid-height laterally and axially deformation. The gauges had a great level of accuracy for deviation and a max sensor length of 5 cm. The dial gauges are positioned conveniently on the electro-hydraulic testing apparatus piston and along the vertical center line of the column specimens. As depicted in Figure 4, a spirit level was utilized to assess the vertical alignment of each column at both ends prior to applying any additional loading. Minor loading adjustments were implemented, and a computer system closely monitored these specifications until damage was incurred.

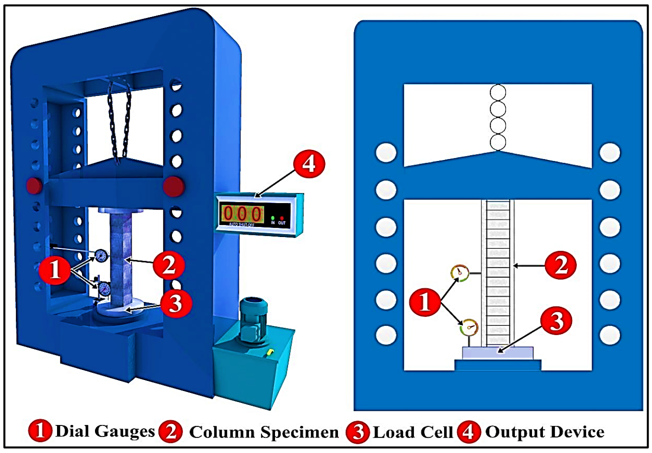


Figure 4. Electrohydraulic device for testing specimens

3. RESULTS AND DISCUSSION

3.1 Compressive strength

The compression strength test is most common for cemented concrete. Calculates concrete's potential strength. Local and international standards classify concrete by strength at compression. RPC is most known for its great strength at compression. For the strength at compression (fcu) test, 50×50×50 mm RPC cubes with 2% micro steel fiber were employed. After being burned at 200, 400, and 600°C for 3, 7, 28, and 56 days, the cubes were tested for strength at compression. The strength at compression of RPC before and after burning is given in Figure 5. Every magnitude in this Figure 5 is based on the average value of three cubes to decrease the expected error in every measured result. Figure 5 shows RPC strength at compression at 3, 7, 28, and 56 days at 200, 400, and 600°C. Strength at compression grew progressively with curing age, but burning temperature decreased from (83.1 to 24.7 MPa) during 3 curing ages while temperatures rose from 200-600°C.

3.2 STS test

This study's specimens' tensile strength (fsp) results are in Figure 6. Tensile strength affects RPC cracking, durability, stiffness, and other properties. The STS of a 100×200 mm cylinder was tested at 3, 7, 28, and 56 days. Cylinders were cast utilizing RPC with 2% micro steel fiber. Strength was calculated by three specimens for each test.

Figure 6 shows RPC tensile strength at 3, 7, 28, and 56 days at 200, 400, and 600℃. Tensile strength improved steadily with curing ages as strength at compression, but rising burning temp reduced strength from 10.4 MPa to 3.6 MPa at 3 curing ages with raise temperatures from 200-600℃.

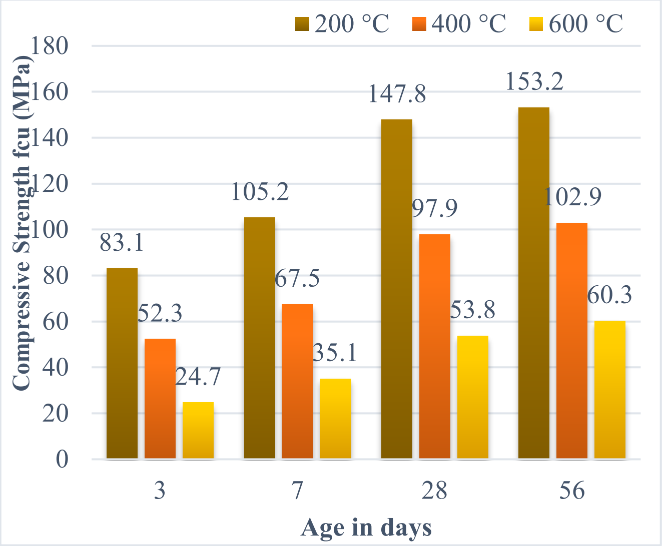


Figure 5. The strength of compression for RPC post-subjecting to different temperatures

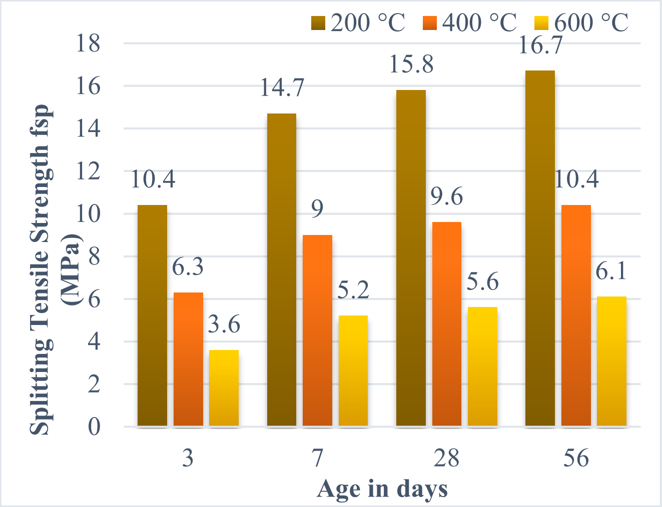


Figure 6. The STS for RPC post-subjecting to different temperatures

3.3 Modulus of rupture

The modulus of rupture test measured flexural strength. Prisms were simply supported and tested for two-point loading. Figure 7 provides test results. This Figure shows the mean value of three prismatic specimens to decrease expected error in each measured result. Figure 7 shows RPC flexural strength at 3, 7, 28, and 56 days at 200, 400, and 600℃ that flexural strength grew progressively with curing ages as strength at compression increased, but burning temperature decreased the strength value from (35.7-24.8 MPa) at 56 curing ages once temperatures rose from 200-600℃. Nevertheless, the majority of flexural strength measurements at 400℃ are greater than at 200 and 600℃.

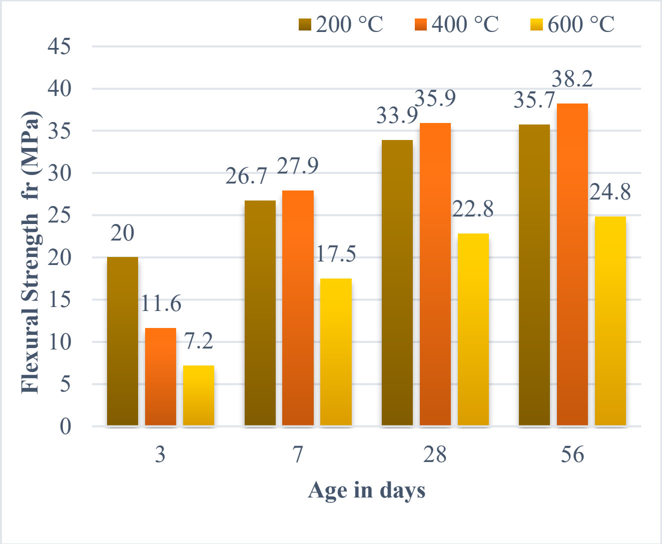


Figure 7. The modulus of rapture strength for RPC post-subject to different temperatures

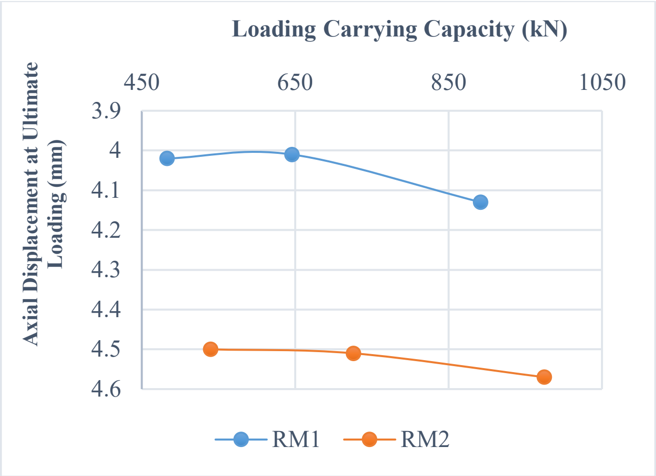


Figure 8. RPC column with 15 mm cover

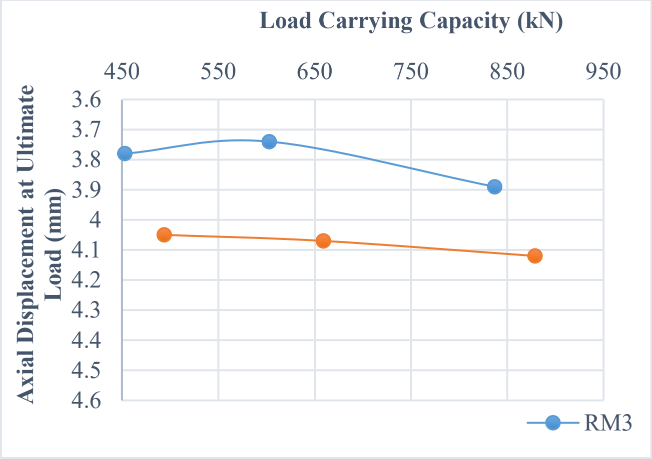


Figure 9. RPC with 30 mm cover

3.4 Column under different flaming temperatures

Figures 8-11 illustrate the behavior of columns once exposed to different temperatures (200, 400, and 600℃). Figures 8 and 9 illustrate the correlation between axial forces displacing at the max loading (mm) and loading carrying capacity (kN) for different specimens. The first set of specimens, RM1 and RM2, had a cover of concrete of 15 mm, while the second set, RM3 and RM4, had a cover of concrete of 30 mm. To assess the impact of incorporating secondary strengthening, we conducted tests on four specimens. Two of the specimens (RM1 and RM3) were left without any strengthening, while the other two specimens (RM2 and RM4) were reinforced with Ø5@20cm as secondary strengthening. Figures 8 and 9 clearly illustrate a significant decrease in axial displacements once employing Ø5@20cm for comparable flaming temperatures as illustrated in Table 3.

Table 3. Empirical test findings of RPC column samples

Columns Symbol		Fire Temperature (℃)	Loading Carrying Capacity (kN)	Axial Displacement at Ultimate Loading (mm)	Mid-Height Lateral Deformation at Ultimate Loading (mm)
One	RM1	200	892	4.13	0.702
	RM2		975	4.57	0.777
	RM3		837	3.89	0.661
	RM 4		879	4.12	0.700
Two	RM1	400	646	4.01	0.681
	RM2		726	4.51	0.766
	RM3		603	3.74	0.635
	RM 4		659	4.07	0.692
Three	RM1	600	483	4.02	0.683
	RM2		675	6.14	1.041
	RM3		453	3.78	0.643
	RM 4		494	4.05	0.688

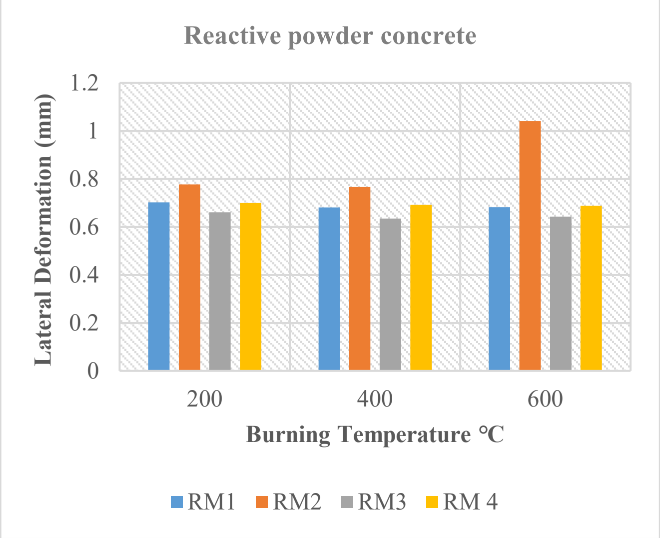


Figure 10. Mid –height deflection at ultimate loading for concrete

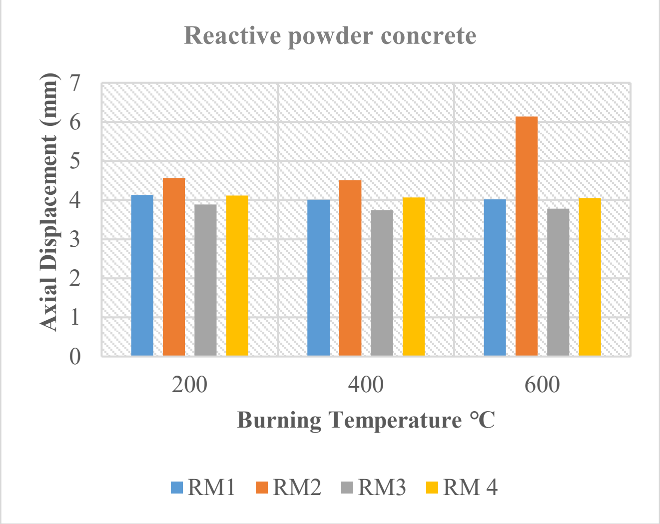


Figure 11. Axial displacement at ultimate loading for concrete

4. CONCLUSIONS

Using the characteristics analyzed in this research, several inferences about column specimens' (structural performance) subjected to real fire may be drawn:

i. Findings indicate that increasing flaming temperatures from 200 to 600 decreases flexural, tensile, and strength at compression in reactive powder concrete.
ii. Increasing cover of concrete from 15-30mm to strengthen columns against fire and use secondary strengthening for equivalent coverage to boost fire resistance.
iii. Tensile strength improved somewhat with curing ages; however, strength at compression decreased dramatically with higher flaming temperatures (from 10.4-3.6 MPa) at 3 curing ages (200-600°C).

Overall, flexural strength findings are greater at 400°C than at 200 and 600°C.

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