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Article

Fire Resistance Performance of Reactive Powder Concrete Columns

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Abstract. This paper experimentally explores the fire resistance of reactive powder concrete (RPC) columns with varying steel and polypropylene (PP) fiber content. RPC is a concrete composition with the highest developed compressive strength and is incorporated with steel fibers that can improve the tensile strength and ductility of RPC structures. The fire resistance of RPC structures, however, has been disputed by engineers and researchers. Four columns with different weight contents of fiber were tested in fire for 30 and 60 minutes with a load applied afterwards. Then, the performance of RPC columns in elevated temperature was investigated, focusing on spalling depth, failure mechanism in fiber and residual strength. The results showed that increasing the volume fraction of steel fiber or the presence of PP fiber improves the fire resistance of the columns. However, the columns lost significant cross-sectional area and load capacity. With the knowledge that this research would provide, a better understanding for making decisions could be developed.

Keywords: Reactive powder concrete, column, fire resistance, steel fiber.

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1. Introduction

High performance concrete is now commonly used in high-rise structures and is becoming increasingly popular as a result of promising research, whereas high strength concrete is associated with compression, which is more pronounced in columns. In recent construction, the utilization of high strength concrete is increasing due to its low permeability and improved durability [1]. However, the demand for high strength structures always has a drawback in fire resistance. There have been series of studies that explain the performance of high performance concrete under fire scenarios on both the material and structural levels [2-10]. Collectively, it was revealed that the higher the strength obtained in the mixture is, the lower the fire resistance of the composition. High performance compositions of concrete tend to be denser and more prone to failure in high temperature due to their high brittleness. High performance concrete exhibits more serious deterioration, such as spalling and cracking, than normal strength concrete [11].

Reactive powder concrete (RPC), a form of ultra-high performance concrete that can reach 200 to 800 MPa of compressive strength, is one of the newer innovations in the concrete industry [12]. It is composed of a highly controlled composition of materials that include Portland cement, silica fume, sand, quartz, superplasticizers and possibly steel fibers and steel aggregates [13]. RPC has been achieved based on a micro-structural engineering concept by introducing silica components and eliminating coarse aggregate. Incorporation of steel fibers can improve the strength and ductility of high performance concrete columns. The addition of steel fibers to a high performance concrete matrix was found to be beneficial for enhancing the fire endurance of columns providing a post-cracking state in which the steel fibers form interlocking surfaces [14]. Autoclaving has beneficial effects on the RPC properties. It develops a denser microstructure that results in higher mechanical properties. However, there have been very limited studies conducted regarding RPC at elevated temperatures [15]. The fire performance of RPC would be lower than normal strength concrete (NSC) due to its dense microstructure that prevents pressure release from the core of the concrete [16]. However, incorporation of steel and polypropylene fibers yields better fire resistance based on previous research [1, 4, 17]. The effect of autoclave curing enhances the mechanical properties of RPC columns [18], which would result in improved mechanical properties but lower fire resistance. With the integration of steel and PP fibers in the mixture, the fire performance would improve [16]. In its limited research state, it is important to further study the material at its structural level for better understanding of the utilization and confidence in use. In this work, experimental assessment of RPC columns under fire exposure was conducted. In addition, steel and polypropylene (PP) fiber was used with varying amount to investigate their effects on the fire resistance.

2. Experimental Program

2.1. Material Mix-Design and Specimens

The RPC mix design used in this study was based on preliminary phase results which were conducted in order to understand the behavior of the concrete in its fresh state. The basis for the deviations of the mix proportions were made due to the differences in the materials used and workability issues. The mix design used in the study is shown in Table 1.

A number of trial mixes were cast and tested to obtain the most appropriate mixture of RPC for the criteria of strength and workability given the available materials. In this stage, parameters such as steel fiber content, water content, superplasticizer content and curing duration were varied to find the reasonable RPC mix.

The water binder ratio was w/b = 25 %, and the admixture binder ratio was ad/b = 2 %. The steel fiber volume ratios of these columns varied between values of 0.5 and 1.5 %, while the content of polypropylene (PP) fibers varied between percentages of 0 and 0.1 %. The proportion of sand in the mixture was changed relative to the corresponding steel fibers and PP fibers volume ratio. The type of steel fibers used in this study was Dramix OL 5D, with a length of 60 mm and a diameter of 0.90 mm. The fibers have a tensile strength of 2300 MPa and a modulus of elasticity of 210 GPa. PP fibers have a length of 19 mm, density of 0.9 g/cm^3 and 410 MPa in tensile strength.

Five RPC columns of dimension 200 mm^2 and 1250 mm in height were designed based on the American Concrete Institute (ACI) design [19] and the limitations of the testing equipment. Four columns (named as Col-B, Col-C, Col-E, Col-D) with adding steel and PP fibers was casted for fire test, and one control column

(Col-A) without applying fire was used to compare the load-deformation of with and without fire loading specimens. The columns comprised 4-12 mm diameter main longitudinal bars and 9 mm diameter steel ties; steel reinforcement was a constant parameter in this study. The details of the specimens and the arrangement of steel reinforcement are shown in Fig. 1. The details of properties and fiber content of all columns are presented in Table 2.

Table 1. RPC mix design ratio by weight of cement.

Compositions	RPC 200
Portland Cement	1
Silica fume	0.25
Sand	1.1
Superplasticizer	0.02
Steel fiber	Varying fiber content by volume of concrete
PP fiber (COL-E)	0.01
Water	0.25

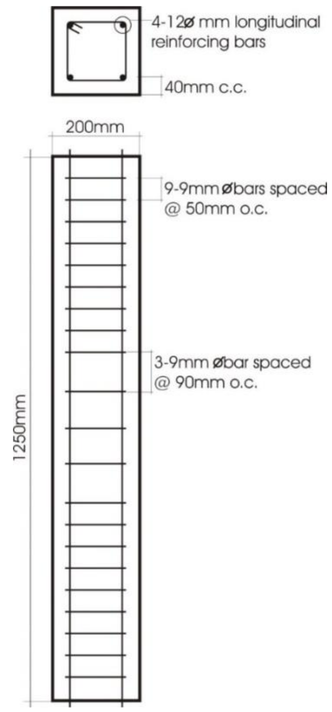

Fig. 1. Column dimension.

To obtain the material properties of RPC, such as the compressive strength and modulus of elasticity, each particular mixture proportion of the columns had a representative cylindrical specimen to test its material properties after 28 days in the curing process. The cylinders had dimensions of 150 mm in diameter and 300 mm in height. The compressive and splitting tensile test was based on the ASTM C39 [20] and ASTM C 496 [21] standard test methods, respectively. The other nineteen (19) specimens were exposed to fire for 120 minutes to evaluate the effects of fire as preliminary investigation. Due to the intense fire, all specimens spalled off (shown in Fig. 2). This resulted in the range of fire exposure used during the fire test of the column specimens in the final phase to be 30 to 60 minutes.

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(a) (b)

Fig. 2. RPC cylinders (a) before fire exposure (b) after fire exposure of 120 minutes.

The modulus of elasticity can be calculated by Eq. (1), (2), and (3) reported by Ma, et al. [22], ACI 363R [15], and Graybeal [23], respectively.

$$E = 19000\sqrt[3]{\frac{f_c^{'}}{10}} \tag{1}$$

$$E = 3320\sqrt{f_c^{'}} + 6900 \tag{2}$$

$$E = 3840\sqrt{f_c^{'}} \tag{3}$$

In this study, the stress-strain curves obtained from the cylinder tests are used to determine the chord modulus of the elasticity of the RPC columns. The compressive strength was obtained from the test following ASTM C39 while the modulus of elasticity (E) and poisson's ratio (μ) were obtained from ASTM C469 standard as the following formula. Table 2 summarizes the specifications that were integrated in each respective RPC column.

$$E_c = (S_2-S_1) / \varepsilon_{l2} - 0.00005$$

where S_1 is stress at longitudinal strain value of 0.00005, S_2 is stress at 40% of the ultimate load, and ε_{l2} is longitudinal strain at S_2.

Table 2. Specifications of the test columns.

Specimen	**Compressive strength f_c (MPa)**	**Modulus of elasticity E (MPa)**	**Steel fibers volume V_s (%)**	**PP fibers volume V_{pp} (%)**	**Fire Duration (minutes)**
COL-A	116	32.9	0	0	0
COL-B	118	34.2	0.5	0	30
COL-C	121	34.9	1.5	0	60
COL-D	112	35.1	1.5	0	30
COL-E	104	38.5	1.5	0.1	30

2.2. Mixing and Casting Procedure

To achieve good performance of RPC, the mixing and casting process must follow a certain procedure. In this research, the mixing and casting procedures were based on the mixing protocol derived from the research of Lee and Crisholm [24], and the casting procedure for all of the specimens was observed. During concrete mixing, the time was measured and noted for later studies. The times for concrete mixing used in this study were under normal laboratory conditions at room temperature, as listed in Table 3 below.

Table 3. Time procedure for mixing RPC.

Mixing Protocol	Elapsed time in minutes
Lightly grind sand to break-up agglomerates	-
Add all dry cement and silica fume	0
Start mixing	3
Add water and super-plasticizer	15
Add fiber components	20
Stop mixing and cast test specimens	25

It should be noted that the PP fibers integrated in the mixture of COL-E was not part of the preliminary investigation and was added to evaluate its effects on the RPC after fire. It was saturated with water for 24 hours prior to casting the RPC.

After 1 day of casting, the specimens were removed from the molds and then autoclaved. Autoclaved curing of RPC has been investigated to achieve better mechanical properties of the RPC mixtures (as shown in Fig. 3). From the previous research, RPC curing has significantly improved properties of high performance concretes [18, 24, 25]. Temperature and pressure increases the chemical reaction of the C-S-H gel in the mixture, thus improving the material properties of RPC. Autoclaving changes the microstructure of the concrete. Hydration of cement will be faster and will result to higher compressive strength in a shorter time. In this study, the autoclave was run for 4 hours with a maximum pressure of 4 bar and temperature of 140 °C.

Fig. 3. RPC in autoclave.

2.3. Fire Furnace Test Setup

A pilot test of specimens with steel fiber content of 1.5 % in volume was done for 60 minutes in order to assess the damage. The remainder of the columns to be fired was assessed up to 30 minutes under the ASTM fire curve due to the severe results on the pilot test. The furnace has an internal dimension of 1.8 x 0.9 x 2.6 m^3. Six gas burners were integrated within the furnace associated with a loading frame, which was installed on top for load simulation in fire. However, the columns were not loaded sue to limitation of loading equipment. The column was positioned vertically with a bottom hinge support of the furnace and a cover top support enclosed with a cover slab as shown in Fig. 4. The end supports, surface of the furnace and the cover slab were properly insulated with ceramic fiber to protect against fire.

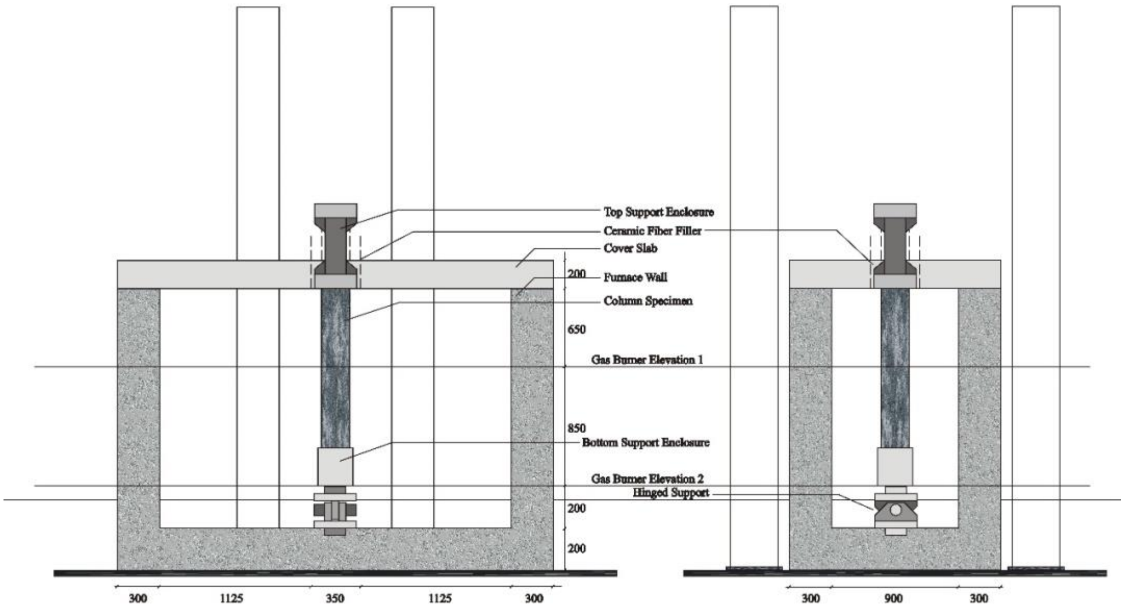

Fig. 4. Furnace specifications.

2.4. Temperature Control

The ASTM E119 standard fire curve was used to evaluate the fire-resistance performance of the RPC columns. Specimen COL-C was the pilot test and was heated for 60 minutes in the fire, and the rest of the columns were heated for 30 minutes. Figure 5 shows the average oven fire curves of the tests.

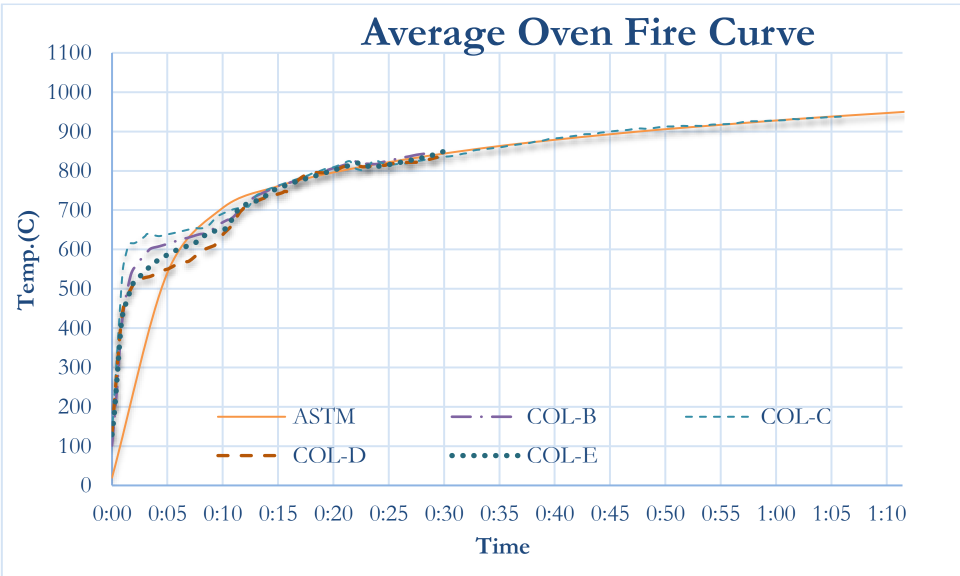

Fig. 5. Fire curve.

From this figure, it is clear that fire generation during the actual test deviates initially with a rise in temperature until reaching the range of 500 °C to 600 °C. Differences can also be observed between the span of time from 4 to 11 minutes, and a more consistent trend is apparent thereafter. All of the columns had similar trends of temperature changes according to the duration of the fire.

2.5. Spalling Depth Investigation

After exposure to fire, spalling depths were observed in the surface of the columns. Spalling depths were measured on each face of the column at five different sections to visualize the damage brought on by fire. Crack propagation and color deviations were also observed during the physical characteristic investigation of each fired RPC columns. Cracks were measured by a thin acrylic sheet that contained respective width measurements. Color deviation was analyzed based on Fig. 6 for visual evaluation.

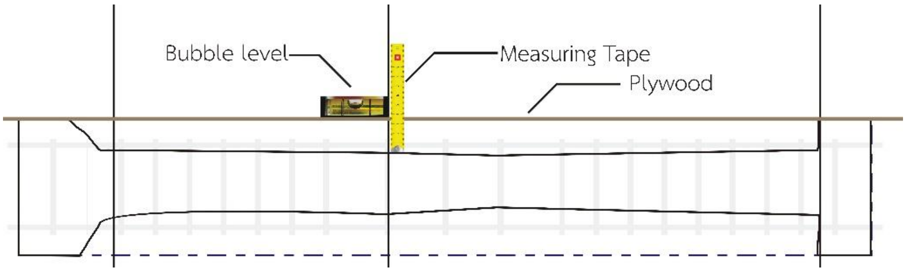

Fig. 6. Measurement of spalling depth.

2.6. Columns Test for Residual Capacity

To obtain the relationship of residual strength of RPC columns after fire, column specimens underwent axial tests. Each specimen was assessed and analyzed by the induced load, axial deformation and failure mode. As seen in Fig. 7, the load cell was positioned directly below the specimen with the LVDT measuring the deformation in the lower left corner of the bottom plate. The bottom plate of the testing equipment moves up as the applied force is resisted by the top support.

Fig. 7. Test setup of Specimen COL-B.

Strength test evaluated the performance of the RPC column based on stiffness and failure mode characteristics. Load-deflection curves of each column were determined from the actual tests. Estimates of the modulus of elasticity based on previous literature were also considered. Steel fiber volume fraction differences and polypropylene fiber inclusion were evaluated with regards to reduced concrete area due to spalling.

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3. Results and Discussions

3.1. Spalling Depth Analysis

At the conclusion of the fire test of RPC columns, severe spalling was observed for all columns. This a phenomenon is a concern in all fire-related studies. Spalling depths at 5 different sections along the length of each fired columns were analyzed to understand the spalling behavior of fire-damaged RPC columns. Sections were chosen in accordance to the position of the column in the furnace considering unfired depths on each end of the column due to support conditions.

Figure 8 shows the locations of the observed spalling depths. The designated face number and section depths that are necessary for the presentation of spalling depths are labeled in the figure. The measured spalling depth is the perpendicular distance from the surface of the original unfired column to the farthest spalling depth. The larger the value is, the deeper the spalling of concrete that was observed. It was observed that most values are greater than 40 mm, which is the depth of the concrete cover. This indicates that the spalling phenomenon exposed the main reinforcing bars of the column, which reflects the poor performance of RPC in fire. In addition, severe spalling depths were observed in sections 4 and 5, where a burner was in close contact with the sections. In this case, two parts of the columns are presented. The first part is the upper portion of the column under sections 1 to 3, and the second part is the lower portion, which involves sections 4 and 5. It should be noted that specimen COL-C was exposed to fire for 60 minutes, while the rest of the column specimens were exposed to fire for 30 minutes. Table 4 summarizes the spalling depths measured on the RPC column specimens after fire.

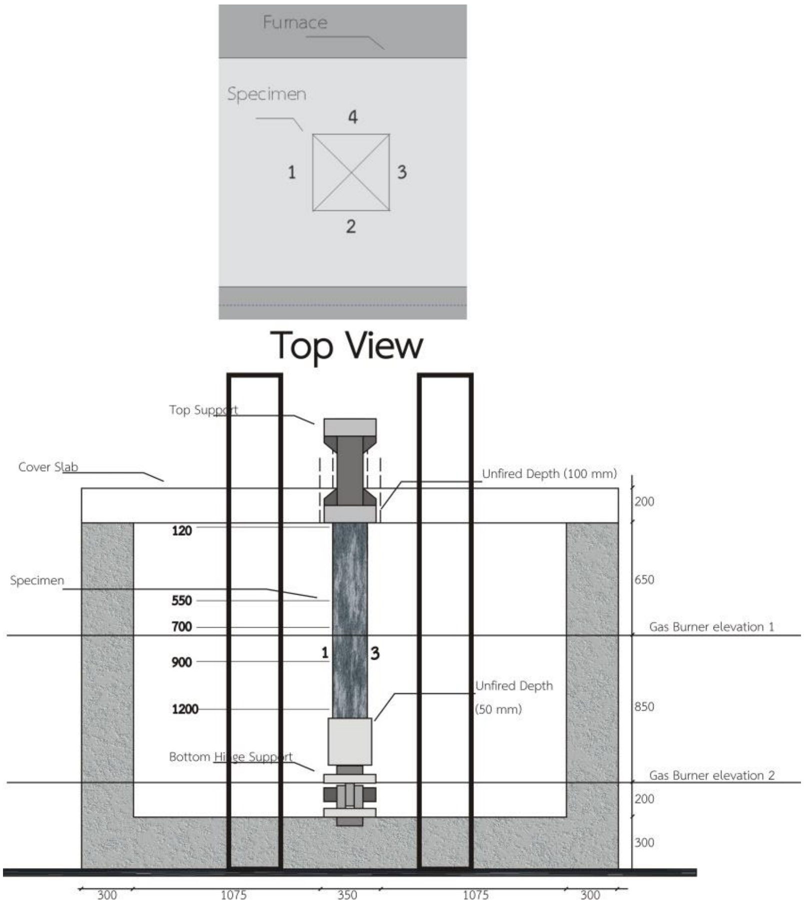

Fig. 8. Locations of spalling depth observation.

Specimen COL-B was observed to have the worst scenario of spalling compared to specimens COL-D and COL-E with the same fire exposure. A difference of 0 to 20 mm in the spalling depth was observed in each face compared to the other specimens. This difference can be attributed to a section loss of approximately 50 %. Spalling depth is more pronounced throughout the height of the specimen. This can be attributed to fewer fibers in the matrix. The mixture with less fibers tend to experience earlier spalling due to less components holding the dense microstructure of the RPC. Early pressure development caused by a large increase in temperature by the furnace has resulted in the worse spalling scenarios in the concrete. The early preheating stage trapped the free water that was not eliminated in the concrete and thus increased the pressure. Comparing the fire generation to the fire curve, COL-B also had an early acceleration of heat compared to the specimen D and E. Faster acceleration of heat can be attributed to this phenomenon. Figures 9 and 10 show the spalling depth of columns COL-B, COL-D and COL-E at each section and the spalling depth of the sections of each column, respectively. An uneven distribution of fire along the height of the column was shown. As can be observed in the figures and Table 4, the spalling in COL-E was less pronounced in comparison to COL-B and COL-D, which was true for all faces.

Table 4. Column spalling depth per section.

SECTION	FACE	Specimen Name			
		COL-B	COL-C	COL-D	COL-E
		Spalling Depths (mm)			
1 = 120 mm	1	45	42	50	45
	2	52	38	40	45
	3	52	56	45	45
	4	42	70	40	30
2 = 550 mm	1	63	43	50	60
	2	57	82	65	35
	3	66	92	55	50
	4	57	75	50	40
3 = 700 mm	1	52	65	50	70
	2	64	95	50	55
	3	72	90	70	55
	4	63	85	60	60
4 = 900 mm	1	64	57	70	100
	2	58	50	70	100
	3	70	65	45	100
	4	76	60	60	100
5 = 1200 mm	1	65	45	40	100
	2	64	45	75	100
	3	68	65	75	100
	4	78	70	40	100

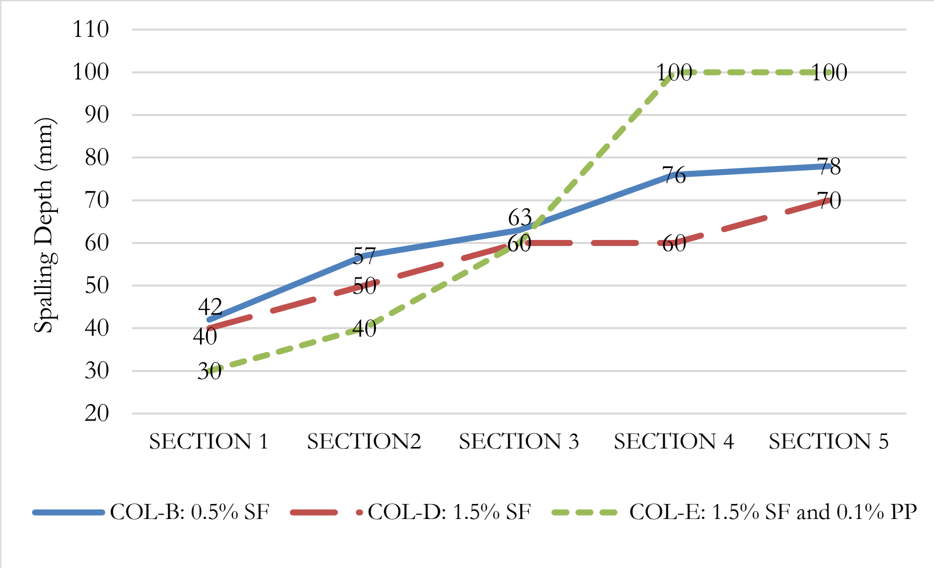

Fig. 9. Spalling depth of columns COL-B, COL-D and COL-E at different sections in face 4.

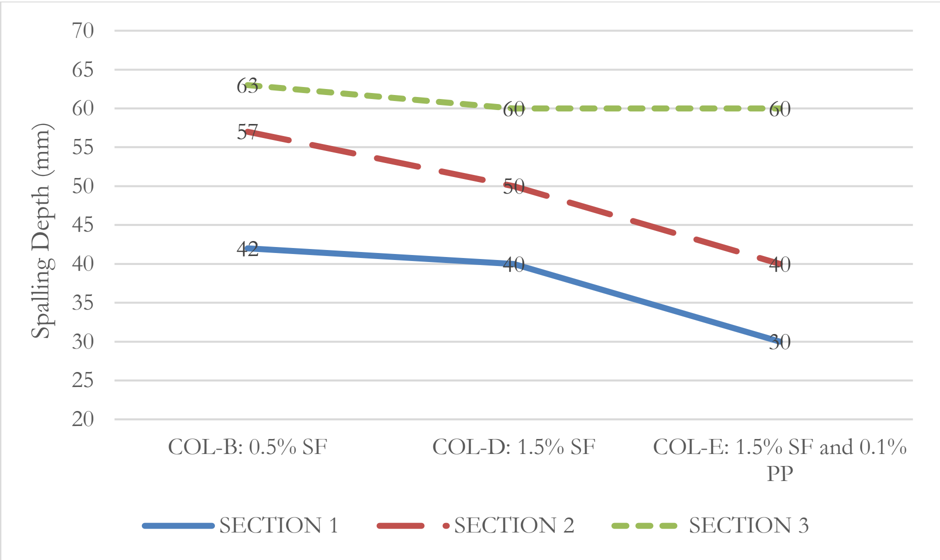

Fig. 10. Spalling depth of different sections of columns in face 4.

Specimen COL-D and COL-E both had a steel fiber content of 1.5 %. COL-E was introduced with 0.1 % polypropylene fibers to evaluate the benefit of PP fibers to the RPC. Based on previous research, PP fibers improve the fire resisting performance of concrete and limit the effect of spalling. This is due to the melting characteristics of PP fibers at 170 °C that builds interconnected capillary networks and helps release the internal pressure in concrete caused by high temperature in the presence of fire [26, 27]. In the upper portion of the two columns, sections 1-3, the advantage of PP-fiber infused specimen was observed. Difference of 0 to 15 mm spalling depth was obtained from measurements. Fire generation during the test was similar. This difference can be attributed to the inclusion of PP fibers in the matrix. In the upper sections, concrete cover in specimen COL-D had greater exposure than COL-E.

COL-C experienced the worst case after fire in terms of spalling depths, texture and color difference, which is evidently caused by the longer duration of fire exposure. It should be noted that COL-C and COL-D have the same mix design. Comparing the two specimens with their difference in fire exposure, spalling depth differences of 10 to 30 mm were observed, giving the advantage to the latter. This difference equates to a 75 % section loss, which is a very dangerous fire scenario for a building. It has to be noted that in this experiment scheme, the spalling of all columns reaches to level of the concrete cover depth, therefore, the expansion of steel may affect to the spalling of the concrete.

Table 5. Least and average remaining areas.

SECTION	COLUMN			
	B	C	D	E
1	10918	9384	12600	13750
2	6106	2795	8075	11250
3	5548	900	7200	6375
4	4356	7020	5950	N/A
5	3886	7650	7225	N/A
Least Remaining Area (mm^2)	3886	900	5950	6375
Average Remaining Area (mm^2)	6163	5550	8210	10458

The smallest remaining area of a column was evaluated to understand the worst case in terms of the performance of the RPC columns exposed to fire. The least area is a measure of how much concrete area can still resist the load after fire exposure. The results were more favorable for columns incorporated with PP fibers and the 1.5 % SF case. It can be observed in Table 5 that there is a slight discrepancy between the results for columns D and E wherein the steel fiber volume fraction is high. The section of the least area is located on the lower sections from 4 to 5 which was a result of the burner exposing the columns in direct fire. The values of the average remaining area will be used in the evaluation of the failure mode in the succeeding chapters. Furthermore, Fig. 11 shows the difference in the remaining area in the upper sections of the columns.

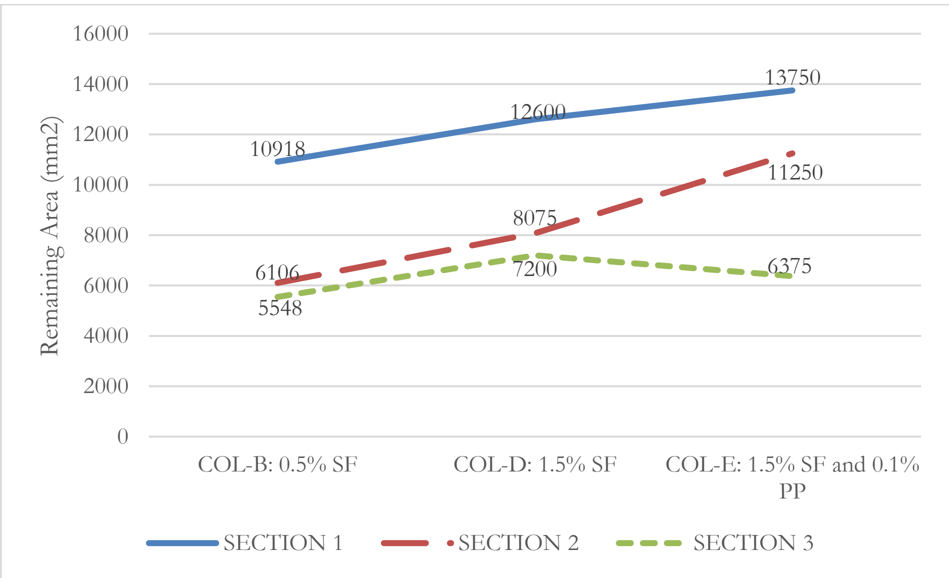

Fig. 11. Remaining area in three sections.

3.2. Color and Texture Characteristics

In recent literature, the color and texture difference of RPC exposed to different temperatures has been analyzed [28]. The aforementioned study ranks the appearance and characteristics of RPC in different ranges of temperature. This study also summarized the characterization of RPC appearance after high temperature tests.

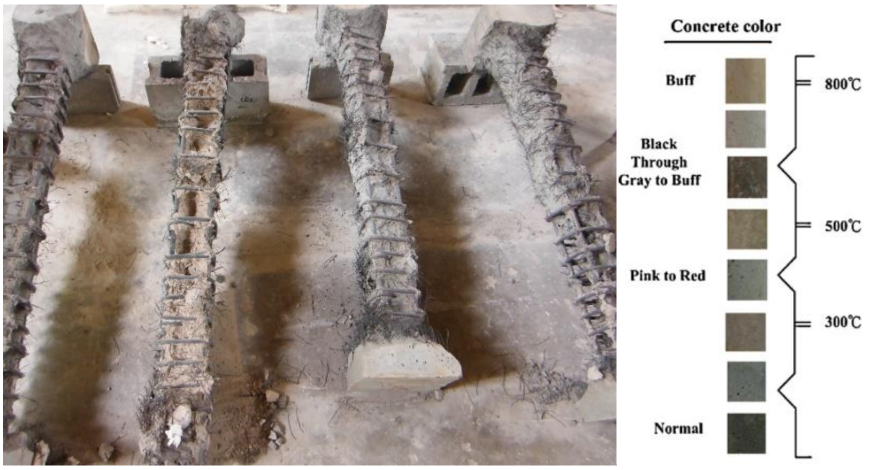

Fig. 12. Color difference from different fire exposure of RPC columns.

Figure 12 shows the variation in color of the RPC column specimens of COL-B to COL-E positioned from left to right, respectively. It was observed that the change in appearance of the specimens was caused by chemical reactions brought on by increased temperature. It can be noted that following the ASTM E119 fire curve assures that each specimen reached 800 °C. Specimen COL-C underwent 60 minutes of fire exposure and was observed to exhibit the characteristics of brittle, powdered and light brown colored appearance. Time exposure of specimens provides significant difference in color and texture.

Specimens that were exposed to fire for 30 minutes were observed to have a light gray color on the remaining core of the concrete. This means that the fire did not penetrate significantly to cause a chemical reaction in the remaining core concrete. However, changes in color can be seen as the depth of spalling increases. Concrete fragments that remained intact with the steel bars were observed to have a light brown color and a more brittle texture compared to the concrete on the core. This can be attributed to longer fire exposure on the surface concrete as the depth reaches the core. Together with color variation, texture also differs as the spalling depth deepens. The light brown color was observed to have a more brittle, powdery configuration, which is pronounced on the concrete nearer the surface, while gray to normal color of concrete with spalling and cracking phenomena was observed in the remaining core surface. This criterion can be used to estimate the severity of fire that the concrete experienced. This could also be a measure to predict the material properties of the fire exposed concrete based on the equations presented in study of Tai et al [28].

3.3. Mechanism of Fibers

Steel fiber impacts the post-cracking behavior of fiber reinforced RPC. The interlocking mechanism of fibers is expected to bridge gaps and provide additional resistance compared to non-fibered mixtures. Hooks at the end of the fibers add additional locking resistance in the possibility of fiber pullout. In the fire cases of RPC columns, microcracks have been observed, however, steel fiber functions more in holding the spalling of concrete with its interlocking mechanism.

COL-C specimen that underwent fire for 60 minutes experienced the worst spalling and loss of mass. Steel fibers on the spalled off surface have been observed to have a change of color from gray to dark gray as shown in Fig. 13. The color transformation was due to the heat induced by the steel, thus making the fibers more brittle than ductile. Fiber melting was not observed. Fibers were also bent in the case that spalling of concrete was prevented during fire. As observed in Fig. 13, hook ends were observed to be embedded onto the concrete even after spalling occurs. Crack widths of 0.1 to 0.5 cm were detected to run along the fiber embedment to small honeycombs.

(a) (b) (c)

Fig. 13. COL-C: (a) Color change and bending of fibers; (b) Cracks running along fiber; and (c) Hook ends embedment in spalled-off concrete.

Color change for the steel fibers of specimens COL-B, COL-D and COL-E exposed to 30 minutes were not significant compared to the drastic change of color for COL-C. Microcracks were observed smaller than the ones noted from COL-C. Steel fibers interlocking mechanism that prevents the spalling of concrete and bridging cracks were not prevalent.

Fig. 14. COL-B: Hook end embedment in spalled-off concrete.

The five-bend hooks of the steel fibers exemplify the good bond between fibers and concrete in prevention of spalling. Hooks are tightly locked in the concrete mixture while the concrete expands and spalls off in the region between the hooks. Figure 14 shows the effectiveness of hook bonding in the concrete to prevent spalling. Bends in the steel fibers were also observed as a reaction to the expansion of concrete.

3.4. Load-Deformation Behavior

The material properties, as presented in the previous sections, have shown the differences of each RPC material casted. The modulus of elasticity in different volume fraction of steel fiber have related values wherein it is assumed that behavior of RPC will be the same in the elastic region of the stress strain curve.

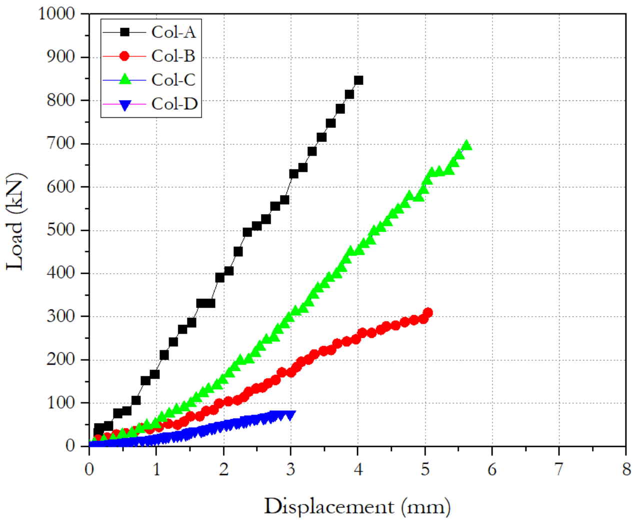

Fig. 15. Load-deformation curves of RPC columns.

It can be observed in Fig. 15 that the ideal slope projection of the unfired column (Col-A) is straight. Due to fire induced phenomenon, the behavior of columns relatively changed with lesser slope that indicates the loss in the modulus of elasticity of the material. The residual strength of columns decreased significantly with the loss of cross-sectional area and shift of failure mode from crushing of concrete to buckling. Based on the prediction from ACI 216.1-1997 with the fire resistance varying from 1 to 4 hours, this result showed that applying fire to 60 minutes without loading, the columns almost lost the capacity of resisting loading.

4. Conclusion

In the series of fire tests, RPC columns were subjected to fire for 30 to 60 minutes without loading. Specimen COL-C exhibited severe spalling after exposure to fire for 60 minutes, and its color was different from that of the rest of the fired specimens. Its residual strength characteristics were also not obtained due to the loss of core concrete from spalling. This indicates that RPC specimens with the designed dimension fired for 1 hour would not have any chance of survival. Only the steel bars would be able to resist the loading, and buckling failure may occur. The further research should test for different column sizes to better understand size effect of their fire resistance.

The rest of the fired column specimens were exposed to only 30 minutes of fire. The steel fiber amount was observed, and it was concluded that better fire performance is expected with increasing steel fiber volume. Spalling depths decreased for specimens with fewer fibers. The inclusion of polypropylene fibers in the matrix enhances the spalling criteria of the column. The load-deformation relationships of each column were also observed. It was found that the loss of material property in the column was more pronounced with fewer fibers in the matrix. Based on the result from the experiment and also previous research, adding steel fiber with volume fraction up to 2% was proven to increase physical and mechanical implications of the concrete. However, by deeply examining the macrostructure of the spalled surfaces, increasing fiber volume does not necessarily lead to improved RPC fire resistance. It was observed that hook ends were bonded deeply in the concrete; however, spalling still occurred in the area between the hooks. Improvement of the concrete mixture is important for fire resistance. It is recommended that the effect of steel bar expansion on spalling should be investigated in future study.

While ACI 216.1-1997 predicted that the fire resistance varies from 1 to 4 hours, the results showed that after applying fire for 60 minutes combined with applying loading, the columns lost the capacity to resist loading. Therefore, it is necessary to conduct more experiments to increase the reliability of design standards.

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