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Combining Polypropylene and Steel Fiber to Reduce Spalling of Reactive Powder Concrete Subjected to Fire Flame

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Abstract. The objective of the study was to investigate the spalling phenomenon rendering to standard curve ASTM E119 in matrix fiber reinforcement Reactive Powder Concrete (RPC) subjected to fire. Polypropylene fiber (PPF) and Steel fiber (SF) volumetric dosage are (0%, 1%), (0.5%, 0.75%), (1%, 0.5%), (1.5%, 0.25%) and (2%, 0%) respectively. The influence of fiber content with three different times of exposure (1, 1.5, 2) h on the mechanical properties were analyzed. The result for the investigational research is estimated to response the essential request whether if one of mixture type is susceptible to fire and avoid terrible failure of the full structure. The degradation of compressive strength, split-tensile strength, and flexural strength, ultrasonic testing analysis (UPV) were observed gradual with increasing duration of fire exposure despite the effect of different fibers. Hybrid fiber reinforced RPC (HBRPC) with volume dosage (1.5%, 0.25%), (1%, 0.5%), (0.5%, 0.75%) and steel fiber reinforced RPC (SFRPC) showed a ductile behavior. However, Polypropylenes fiber reinforced RPC (PFRPC) showed a quite brittle behavior particularly up to 1.5 hours. Hybrid fiber reinforced RPC was found to have better fire resistance than (SFRPC) and (PFRPC) and reduce the possibility of growth spalling.

INTRODUCTION

RPC is a new generation of cementitious material with excellent durability, high toughness and low porosity . Lafarge in France has been produced with compressive strength of 100-200 MPa [1,2]. High silica fume content and very tiny water cement ratio characterize RPC mixes. Coarse aggregate is eliminated and the maximum aggregate particle size is 0.3mm, which make the microstructure of RPC more dense and minor permeability, compared with conventional concrete (CC) and high strength concrete (HSC) [3,4]. RPC can be three times lighter than equivalent structures fabricated with (CC), which results in increasing usable spaces and saving in materials and cost [5]. One of the most important problems of RPC is that when subjected to fire at high temperatures, Degradations such as loss of strength and elastic module, cracking which led to concrete spalling and collapse [6, 7]. Compared with CC and HSC, RPC have dense microstructure, which make more vulnerable to spalling due to prevent water vapor from escaping and lead to high pore pressure [8,9]. Previous literature suggested that the use of fibers such as (PPF) improved concrete resistance to fires [10]. Compared with glass fiber and carbon fiber (PPF) have low melting point ,which melt at a relatively low temperature of approximately 160-170 C^0 in the RPC mix and produce selectively tiny pores throw the RPC matrix. This pores allow diffusion of the high vapor pressure generated in an RPC structure [11].

Steel fiber improve tensile cracking resistance, post cracking strength, ductility and energy absorption. (SF) have good thermal conductivity which can decrease the temperature gradient and spalling can be eliminated [12-14]. In order to achieve high performance, hybrid fibers reinforced cracking resistance and improved tensile strength of concrete matrixes. Several research work on fiber cement reinforced concrete has been carried out; the integration of

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fibers into cement materials has significantly improved their strength and ability to resist cracking [15-17]. The effect of fire duration with standard ASTM E119 curve for different volumetric dosage of fibers on mechanical properties of RPC has been neglected by most research. The object of this study is to estimation the mechanical properties of SF reinforced RPC (SFRPC), PPF reinforced RPC (PFRPC) and hybrid fiber reinforced RPC (HBRPC) with distinct volume dosage, to select the ideal mix which avoids the fire-induced spalling of the reinforced RPC with minimum strength sacrificing.

EXPERIMENTATION

Materials and Mix Proportion

The primary components in these research areas follow:

Cement

According to the specification of (IQS NO.5/1984) [18] ordinary portland cement (OPC) Type I was used. Table 1 shows the chemical compositions provided by the manufacturer.

Silica Fume

Silica fume is an ultra-fine dark gray powder that is pozzolanic material consisting of round granules with a rate size of 0.15 micrometer, which conform to requirements of (**ASTM C1240/2005**). The manufacturer's chemical composition is shown in Table 1.

Table 1. Chemical compositions of cement, silica fume.

Cementitious Materials	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO
Cement	4.8	20.1	2.7	61.9	2.5
Silica fume	0.03	90.55	0.01	1.22	0.01

Fine Aggregate

Very fine sand with a maximum size 600µm complies with IQS No.45/1984 criteria for Iraqi specification [19].

Polycarboxylate Superplasticizer

Hyperplast PC 200 is high performance super plasticizing admixture based on polycarboxylic polymer with long chain particularly intended to permit the water contented of the concrete to make more efficiently. Satisfied with ASTM C494[20], type A and G, depending on dosage used.

Steel Fiber (SF)

Ultra-Fine Steel Fibers or Micro steel fiber (SF) produced by Sika Fiber Company. The standard length was 13 mm with 0.22 mm diameter, the elastic module was 200 GPa and the tensile strength was 2850 MPa.

Polypropylene Fiber (PPF)

Micro polypropylene fibers (PPF) produced by Sika Fiber Company. The average length was 12 mm, melt point 160 C^0, diameter was 18 microns-nominal with the elastic modulus was 3.5 GPa and the tensile strength was 360 MPa .as shown in Figure.(1)

Macro (SF) and macro (PPF) were the hybrid fibers used in this research. Hybrid fiber means combining two or more concrete fibers to create a mixture that takes advantage of each individual fiber kind. Table 2 summarized the mix proportions used in this research.

Specimens Fabrication and Curing

The split-tensile strength tests was done with the cylinder of size 100 mm × 200 mm , the cubic compressive strength was completed on the cubic samples of size 50 mm ×50 mm ×50 mm. While, flexural strength the prism specimens of size 50 mm × 50 mm × 300 mm were used. The mechanical properties for each RPC were tested at three times duration of fire according to standard fire curve ASTM E119 [21].

For each exposure, time three samples were utilized. However, for each time, the average of them was recorded. At the beginning of mixing, it has been put all cementitious materials (cement + silica) and mixed in dry state for a period of (2 min). After that the addition of sand to a mixture of cementitious materials and mixing process was continuing for another (3min) to spread cementitious granules uniformly between the sand particles after that superplasticizer was dissolved in water and (80-85)% of the solution (superplasticizer + water) was added gradually to the dry mix for (3min) . In the final stage, fibers were spread over the sequence of (2 min) in rotating wet concrete and mixed for extra (5 min). Finally, add the remaining (superplasticizer + water) solution (20-15%). The RPC was relatively flowable and checked according (ASTM C1437, 2015) [22] for each mix's functionality.

(a) **(b)**

Figure 1. Fiber used in the experimental work (a) micro steel fiber (b) micro polypropylene.

Table 2. Mix proportions for reactive powder concrete (RPC) for this study.

Constituents	SFRPC	PFRPC	HB_1RPC	HB_2RPC	HB_3RPC
Ordinary Portland cement(kg/m3)	950	950	950	950	950
Silica fume (kg/m3)	235	235	235	235	235
fine sand (kg/m3)	1050	1050	1050	1050	1050
Water reducer (kg/m3)	82.95	82.95	82.95	82.95	82.95
PP fiber (PPF) 1% (9.1kg/m3)	-------	100%[a]	25%	50%	75%
Steel fiber (SF) 2% (157 kg/m3)	100%[a]	-------	75%	50%	25%
w/ cementitious	17.5%	17.5%	17.5%	17.5%	17.5%
Water (kg/m3)	207.375	207.375	207.375	207.375	207.375

(a) Fibers of SF and PPF are evaluated as % of RPC volume.

At (25) C^0 and relative humidity (70%) the molded samples were stored. after 24 hour the samples were cured in a water tank with temperature (25±2 C°) for 56 days.

Fire test

At Babylon University, The fire exposure research was conducted at the Faculty of Engineering in the test site of concrete investigation and material characteristics. The furnace wall thickness is 250 mm, with dimension (11250/1500/1500 mm) (height / width / length respectively). The inner surface of the walls was built of refractory brick with a thickness of 65 mm, refractory mortar used as linking materials to get a good heat isolation .The furnace has a tiny opening to provide the burners with adequate oxygen, the furnace cover is produced of 8 mm thick insulator sheet to maintain the temperature constant. The burners set consists of 12 liquefied petroleum gas burners set in three horizontal rows (4 burners per row) and dispersed along the iron net which place all the sample on it. As shown in Figure (2), all burners were linked in one pipeline. A digital gauge were linked together with the thermocouples and electric gas organizer to switch the liquefied petroleum gas release and reach at the target temperature.

The furnace compartment's primary aim is to raise the temperature of the fire exposure according standard curve ASTM E 119, as shown in Figure (3). To prevent thermal shock of specimen, the sample was left for two day before test. To take out the surface of the sample from fully saturated to dry surface after the curing method was completed. Figure (4) shown the time-temperature curve of the present study which compared with the standard curve suggested by ASTM E119. The heating rate of the investigational curve is a little less than that recommended by the ASTM that is a restriction of the equipment available. Conversely, it appears likely that the result on the ultimate results would be comparatively small, meanwhile the duration of exposure at the temperature was preserved for (1, 1.5 and 2) h. The gate valve will then be closed and the specimen will be left to calm down to room temperature.

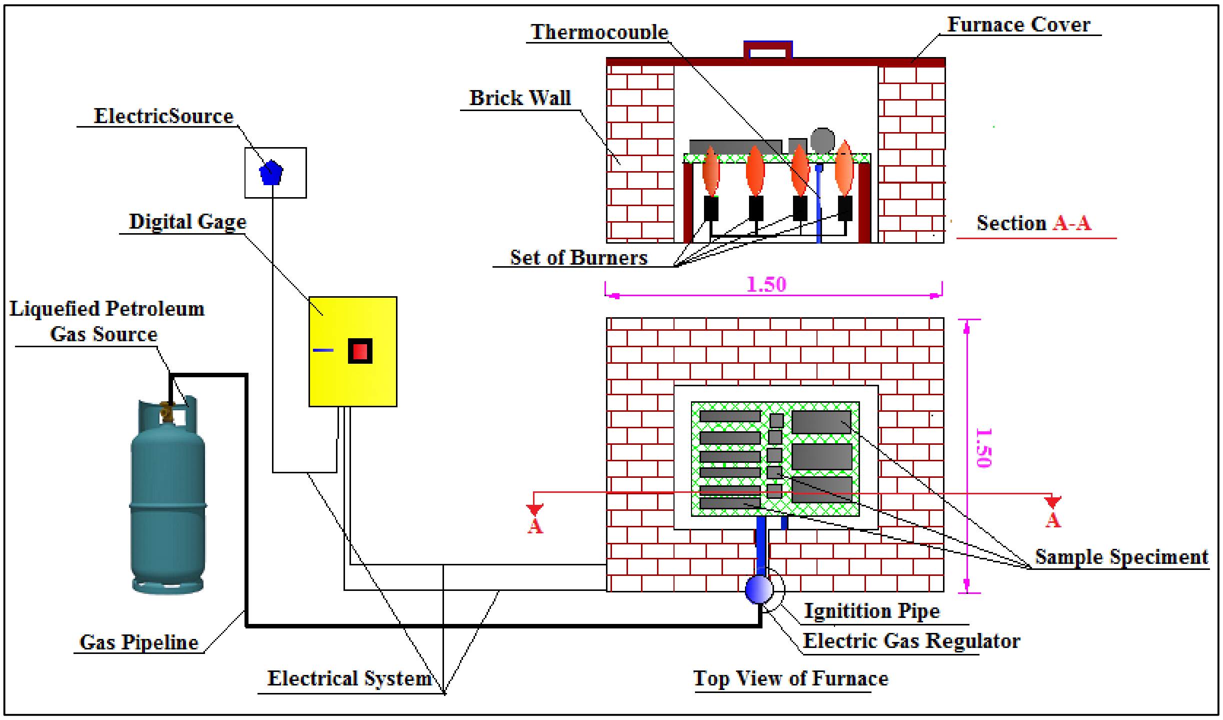


FIGURE 2. Section and top view of the furnace and equipment.

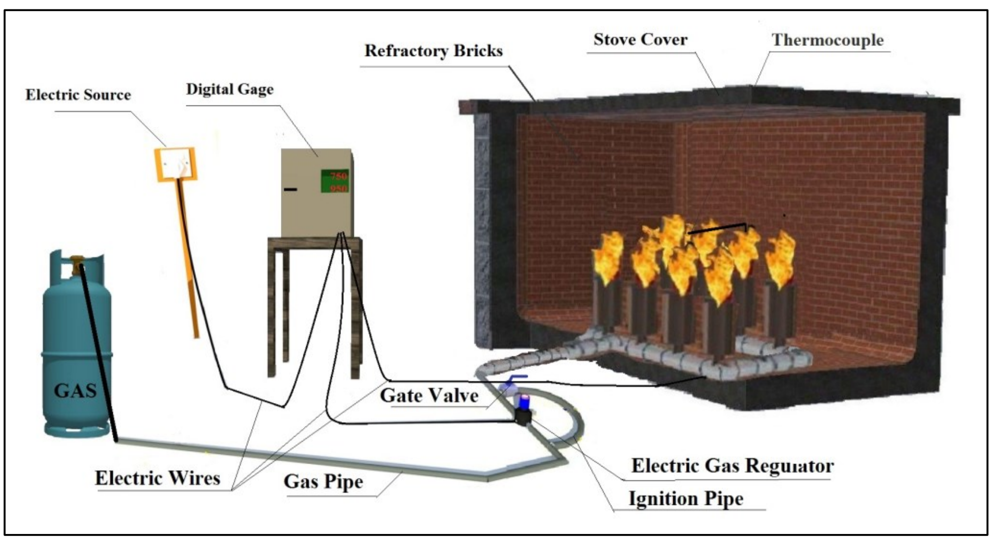


FIGURE 3. Illustrates the stove and equipment.

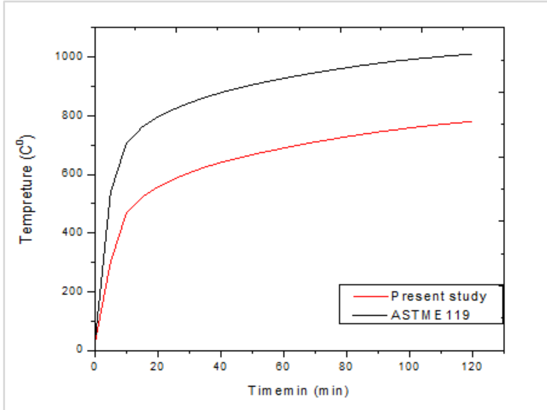


FIGURE 4.Experimental and ASTM E119 standard recommended temperature-time curves [14].

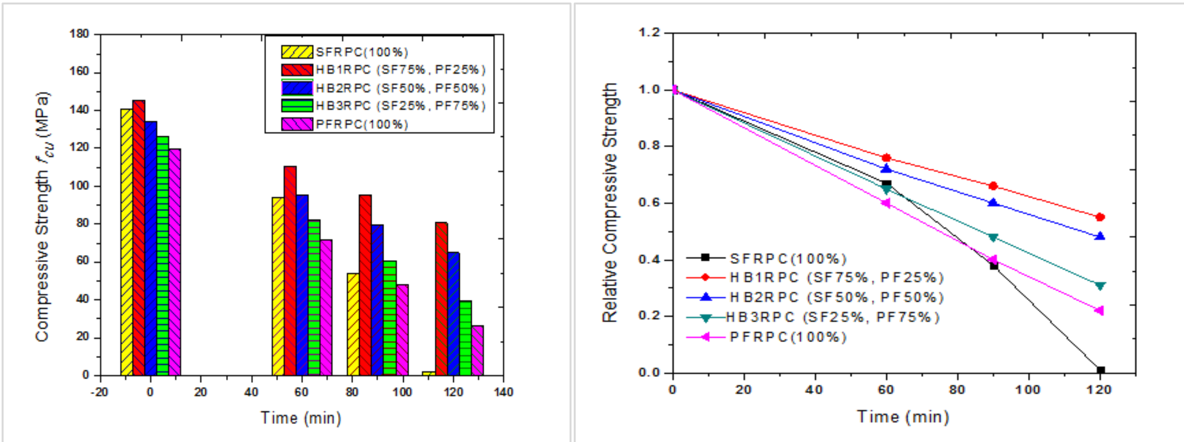
TEST RESULTS AND DISCUSSION

Compressive Strength (f_{cu})

Cubes failure loads were utilized to measure ***(f_{cu})*** of various RPC mixes as shown in Fig.5. To minimize the probable error in any result the average value of (3) cubes were measured. Before and after fire ***(f_{cu})*** of RPC mixing were recorded. The compressive strength before fire were (HB$_1$RPC > SFRPC > HB$_2$RPC > HB$_3$RPC > PFRPC). That's because of the combined effect of hybrid fiber at the concrete matrix. Early concrete age PPF works to reduce plastic shrinkage cracking that created Moreover, steel fiber catches cracks that start growing when the RPC sample was subjected to uniaxial compressive stress [23,24]. Upon exposure to fire with period (1,1.5 and 2) hours, the physical, chemical structure of the sample significantly changed and the effects were observed in ***(f_{cu})*** which decreases with increased time duration of fire [24].

After exposed to fire with period one hour the temperature will rise above 350 C^0. A gradual reduction in cubic strength was recorded. At temperature (400-600) C^0 calcium-silicate-hydrate (C-S-H) decomposed and calcium hydroxide (CH) hydrates which cause reduction in the strength of RPC matrix. Moreover, at 575C^0 the quartz aggregate transformed from α to β phase caused reduction in compressive cube [25]. Above (1.5) hour ***(f_{cu})*** for steel fiber reinforced RPC reductions more than other mixture, this is due to all mixture have a ratio of PPF. Polypropylenes dissolves with temperature (160) C^0 generated networks channel in the matrixes of RPC that discharge the interior vapor pressure, which meaningfully diminishes the spalling tendency of RPC at high temperature [26].

Moreover, when the exposed fire time reached two hours of severe deterioration, bonds between cement paste, sand and fibers occur due to expansion with increasing temperature. also samples (SFRPC) with a percentage of SF (2%) were spalling, resulted in extreme cracking generated through the matrix . Certain mixtures including percentages of PPF spalling were not recorded and the reduction in ***(f_{cu})*** was lees. Because of the scanning electronic microscopy (SEM) investigations, it is shown that the melted PPF generates a sufficient number of cavities in the heated RPC that cause the vapor pressure to escape, while PFRPC filled with gaps and weaker due to the high amount of cavity produced by dissolving PPF. As shown in Figures (6) and (7) [25-28]. From Figure.5 it clearly that (HB$_1$RPC) and (HB$_2$RPC) were considered as the optimum mixtures, which avoids the fire-induced spalling of the reinforced RPC with minimum strength sacrificing. The use of the hybrid system provided sufficient channels for esxape the internal vapor pressure and improved the tensile strength of the RPC due to higher young's modulus and high fiber stiffness.



(a) (b)

Figure 5. Compressive Strength of RPC for (a) Absolute Value (b) Relative Value.

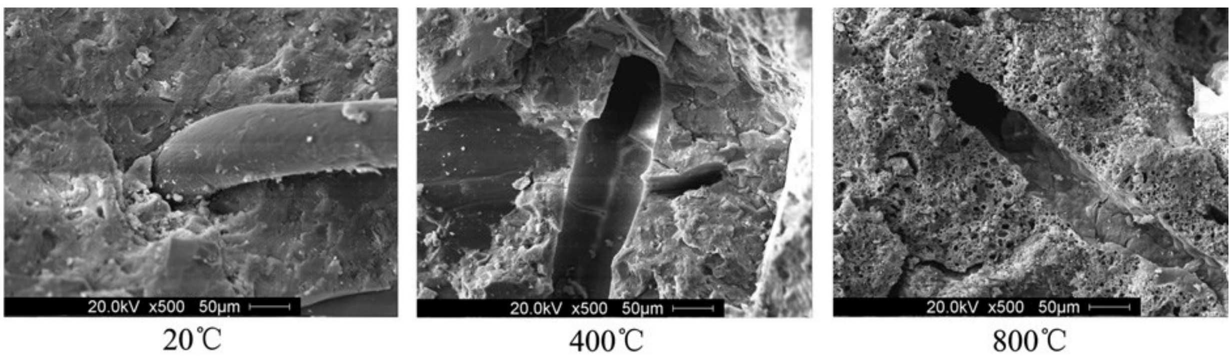


FIGURE 6. SEM for PPF melt channel with temperature [25].

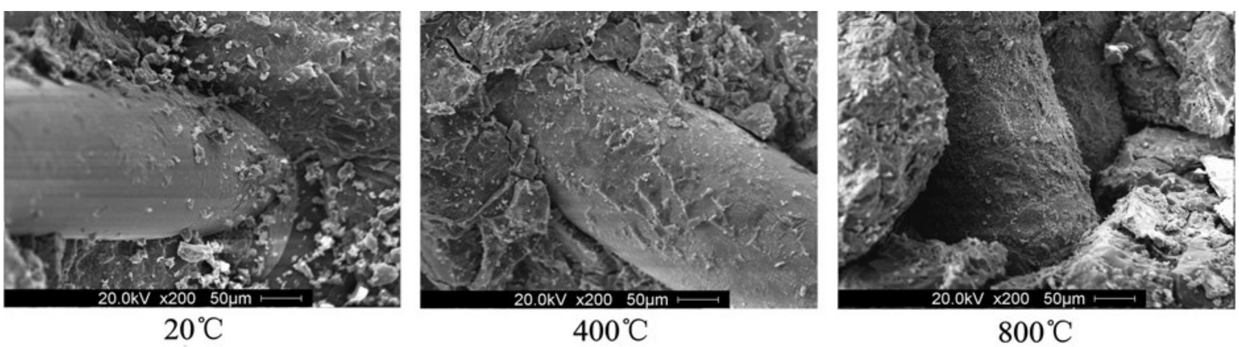
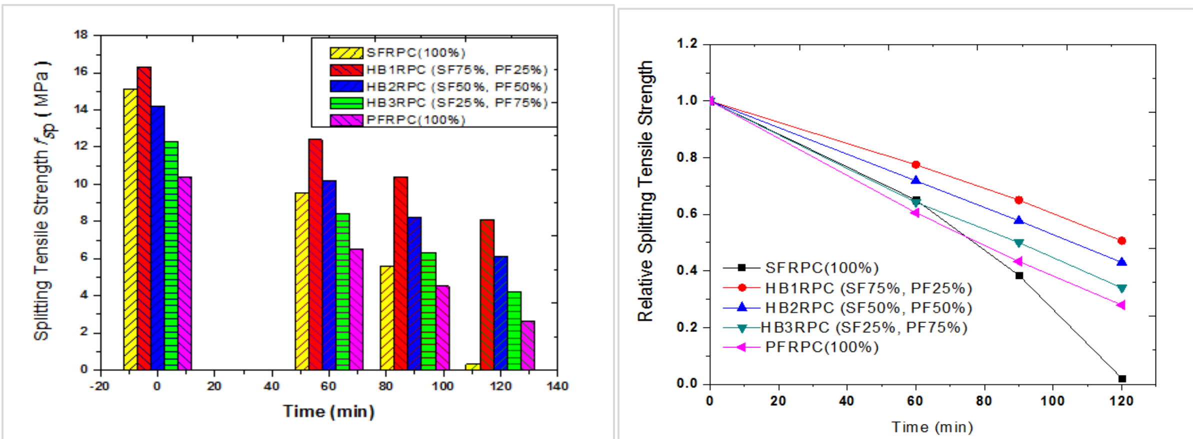


FIGURE 7. SEM of the steel fiber-matrix bonding interface with temperature [25].

Cylinder Splitting-Tensile Strength (f_{sp})

(f_{sp}) controls the cracking performance and affects other property such as RPC toughness and stiffness. Hence it is important to examine at high temperatures condition [13].Figure 8 (a) shows the evolution of ***(f_{sp})*** of different RPC mixes. Before fire the results showed (HB1RPC) tensile behavior was higher than other mixtures, which can be explained by the fact that **PPF** regulating the spreading of microcracks in the plastic stage also **SF** enhances the post-cracking behavior by "bridging" opening cracks between cement-based matrixes.[29,30] . The adding of PPF for 9.1 kg/m^3 produced a rise in strength of RPC by 14% than mixture without fiber. Hybrid fiber systems have a positive impact on the hardening of the RPC strain Reduced interial stress by bridging crack and delayed their propagation. [31,32]. For all mixes, the split-tensile strength was gradual degradation with increasing time – temperature curve. Except the mix with 2% SF, it was collapsed after two-hour fire. This is due to the same reasons as explained in Section 3.1. In Figure 8(b), shows the relative ratio of the split-tensile strength of RPC at fire duration different time and show that at 2h the SFRPC spalling while there cannot be seen for other mixes. The reduction of tensile for PFRPC, HB_3RPC ,HB_2RPC and HB_1RPC at 2h duration of fire exposed were (75% , 66% , 57% , 49.4%) respectively.



(a) (b)

Figure 8. Results Cylinder Splitting Tensile Strength of RPC for (**a**) Absolute Value (**b**) Relative Value.

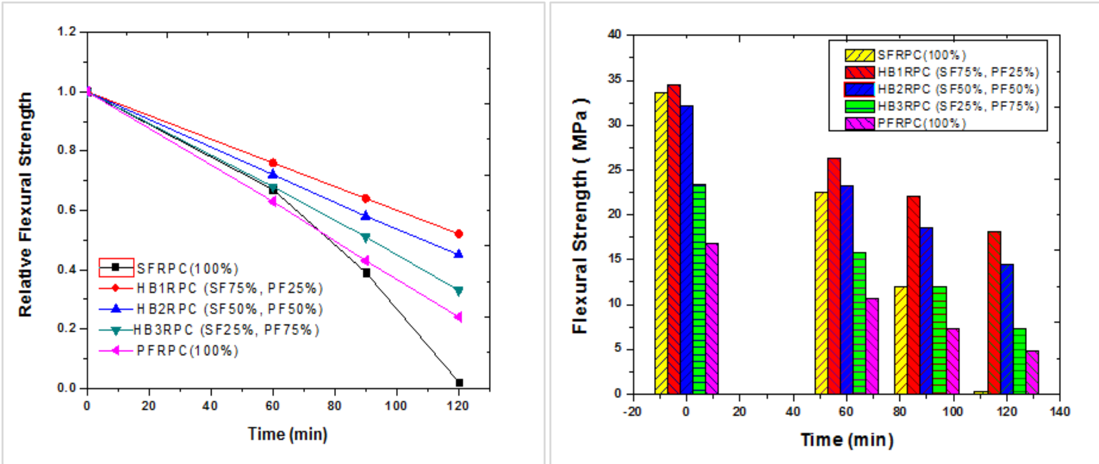
Prism Flexural Strength (f_r)

Modulus of rupture (f_r) test can be expressed as material's capability to withstand deformation below load. Each prism was tested as simply supported and subjected to two-point loading. Figure (9) presents the tested results absolute and relative values. The flexural strength (f_r) of SFRPC, PFRPC, HB_1RPC, HB_2RPC and HB_3RPC at room temperature was (34.6, 17.8, 35.5, 33.3 and 25.4) MPa respectively. In the same manner as in the compressive strength for this investigation. The prismatic flexural strength increased with rose a percentage of steel fiber in mixture. As well as (f_r) for (HB_1RPC) before fire is larger than other mixes that can be explain by adding PPF provided cracks spread also increased the porosity and permeability of RPC mixture [33-35]. SF is stronger and more rigid providing sufficient first crack strength and ultimate strength, whereas PPF is highly flexible, resulting in increased toughness and tension capacity in the post-crack area [36, 37].

The performance of PFRPC was very brittle after fire because of melting PPF, which make the RPC filled with cavities .whereas the SFRPC and HBRPC showed ductile behavior [38]. Under fire, the flexural strength reduced due to the same reasons that explain in compressive strength which included the loss of water from the hydrated cement paste and the bonds between fibers, fine sand and cement past were sternly declined due to mixed expansion with the temperature increased. At 120 min fire, SFRPC samples were collapsed by interior stresses, sloughing off and corner spalling happen due to the internal vapour pressure as shown in Figure (10).

Ultrasonic testing analysis (UPV)

Figure 11. Described the relationship between fire duration and the RPC ultrasonic pulse velocity. So as to study the effect of the difference dosage from SF and PPF on the RPC ultrasonic pulse velocity after subjected to fire. The UPV measurement were taken for samples at 25 C^0 and after fire for (60,90 and 120 min) using direct transmission method. This test was carried out according to (ASTM C597-71, 1977).[39]



(a) (b)

FIGURE 9. Flexural Strength of RPC for (**a**) Absolute Value (**b**) Relative Value.

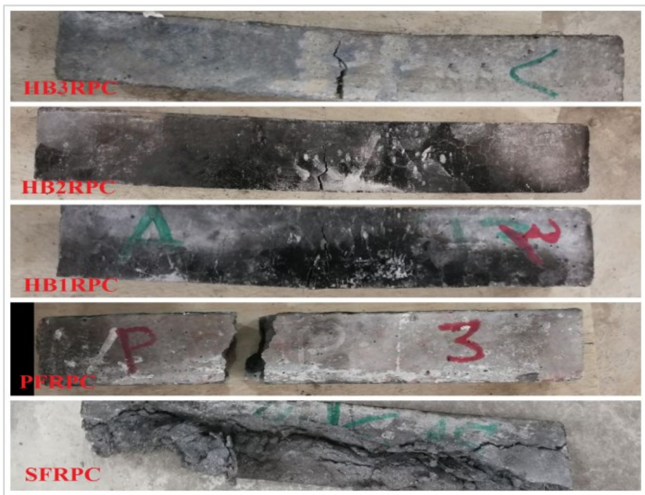


Figure 10. Prism Samples after Subjected to Fire Flame by 2 hour and Tested.

Portable ultrasonic concrete tester (PUNDIT) worked with 25 to 60 kHz frequency range which used in this study Figure (12) show theequepment. From the results it is clear that the reductions in the UPV after exposure to fire flame were as follows:

- After fire burning at 1 hour the velocity decreases. The decreasing ratio for **(PFRPC, HB3RPC, HB2RPC, HB1RPC and SFRPC)** were (29.2%, 25.8%, 24.9%, 17.9% and 21.3 %), respectively.
- At 1.5 hour the **UPV** decrease ratios for **(SFRPC, HB1RPC, HB2RPC, HB3RPC and PFRPC)** were (46.4%, 24.9%, 29.5%, 37.7% and 43.3%), respectively.

The main purpose can be described downward trend of the UPV fpr RPC samples with rise duration of fire due to evaporating water and decomposing the chemical components (C-S-H) which led to gradual growth of micro-cracks and pores in the structure RPC , These variations lead in more air voids, which reduce the velocity of sound waves [39-41]

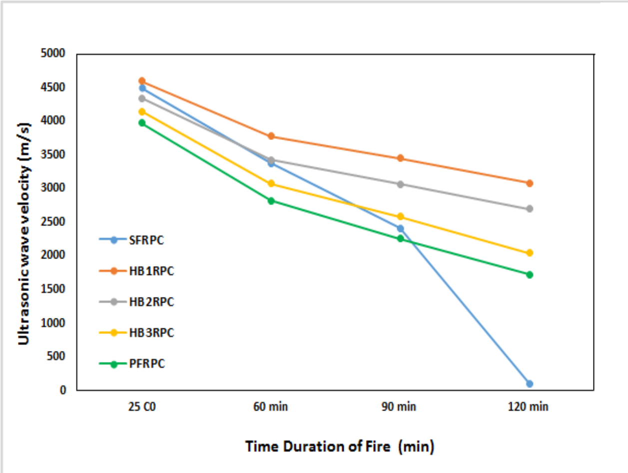


FIGURE 11. Relation between UPV and duration of fire.

FIGURE 12. Ultrasonic testing of concrete sample.

CONCLUSIONS

1. Adding PPF with percentage (0.25%) to (1%) from total volume of mixture, enough to reduce the risk of internal stresses and diminish spalling of RPC.
2. Steel fiber with percentage (157 kg / m^3) will not avoid explosive spalling effectively and collapse failure will occur at duration fire 2 hour.
3. As soon as RPC exposure to fire the mechanical properties such as splitting tensile strength, compressive strength, and flexural strength started to reduction with rise time-temperature curve. After fire it can be said that hybrid fiber mixtures (HB1RPC and HB2RPC) significantly lose lower strength compared with hybrid (HB3RPC) and polypropylene (PFRPC) mixtures, that can be expressed as with increases percentage of PPF in matrixes, RPC samples filled with many internal cavities making them weaker.
4. UPV for RPC mixtures decreases with rise duration of fire, whereas the mixture (PFRPC) with dosage (9.1 kg/m^3) of polypropylene fiber reduced more than hybrid mixes. In order to dispersion UPV with rises air void in mixtures.
5. HB_1RPC with steel fiber (1.5%) and (0.25%) polypropylene fiber consider as optimum percentage which enhance the mechanical properties of RPC before and after fire.

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