Effects Of Different Fibers On Mechanical Properties Of Reactive Powder Concrete (RPC)

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ABSTRACT:
An example of an ultra-high-performance cement-based composite is reactive powder concrete (RPC). Its engineering characteristics are achieved due to a dense and homogenous microstructure. Usually, RPC is reinforced with steel fibers (SF) to improve ductility and fire-resistance. In the case of RPC, studies must be conducted using lightweight and durable fibers because of the concerns regarding high density, low durability, and high conductivity. This study focuses on the RPC's mechanical properties that use a single and hybrid fiber mixture of carbon fiber (CF) and conventional SF. The effects of performing high temperatures of 200°C, 400°C, 600°C, and 800°C for two hours, on the mechanical properties of plain RPC and fiber reinforced RPC were evaluated. It was observed that CFRPC performs mechanically up to 85-90% of SFRPC's conventional value. Mechanical property hybridization of SF 1.5% and CF 0.5% synergized at higher and normal temperatures. Compared to plain RPC, CFRPC showed, after 800ºC exposure, around two, four, and five times more residual compressive, tensile, and flexural strengths, respectively. Moreover, valued less than SFRPC, the compressive strength-per-unit weight of CFRPC was significantly improved.

Keywords:*Reactive Powder Concrete (RPC), Steel fibers, Polypropylene fibers, Carbon fibers, Glass fibers, Mechanical properties, Flexural strength, Tensile strength, Ductility, Fiber-reinforced concrete*

1. INTRODUCTION

Reactive Powder Concrete, first developed as an innovative form of ultra-high-performance concrete (UHPC), packs cement, silica fume, quartz flour, and fine aggregates into a highly compact microstructure with the value of water to binder lower than normal coupled with the aid of the super-plasticizer [1]. The compressive strength of these ultra-high-strength concretes is beyond 150 MPa, and they also present adequate durability while resisting aggressive environments [2]. The great ability of concrete, therefore, has ranged from the applications being used in infrastructure works where structural performance and durability are of prime consideration.

As remarkable as its mechanical properties are, RPC suffers from the inherent brittleness and weakness in tension, leading to a sudden failure on tension or flexural loading [3]. To overcome this shortcoming, the fiber reinforcement has been incorporated into the RPC matrix to increase ductility, energy absorption capacity, and behavior after cracking [4]. Different forms of fibers that have been considered to alter various mechanical properties of RPC include steel, polypropylene, carbon, and glass. Steel fibers are generally recognized for improving flexural and tensile strength considerably, given their high modulus and bond characteristics [5]. Polypropylene fibers, although low in stiffness, improve impact resistance and reduce spalling under high temperatures [6]. Carbon fibers improve electrical conductivity and flexural toughness [7], whereas glass fibers assist in knitting early-age cracks but may degrade from alkali-silica reaction after some time [8].

Many researches have proven that fiber reinforcement greatly enhances the performance of RPC. Richard and Cheyrezy [9] were among the first developers of RPC and emphasized the need for dense packing and pozzolanic reaction to obtain ultra-high strength. Later on, the research of Behfarnia and Salemi [10] was directed toward investigating the effects of nano-additives on the properties of RPC. Banthia and Gupta [11] brought out that fiber geometry plays a role in crack control in cementitious materials. The fracture behavior changes in the presence of fibers, improving the service life of structural elements. This enhancement in fracture control qualifies RPC for use in advanced engineering applications like bridge decks, tunnel linings, precast elements, and offshore structures [12]. Nevertheless, utmost importance should be given to the selection of the most appropriate fiber type and dosage to get the best performance [13].

This research aims to account for different kinds of fibers-they are steel, polypropylene, carbon, and glass-on the mechanical properties of the RPC:

compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and post-crack behavior. The results will offer practical guiding principles for engineers and consultants selecting fiber-reinforced RPC mixtures according to particular structural requirements [14].

2. MATERIALS & METHODOLOGY

2.1 Materials

a) Cement

53 Grade Portland cement was used as a primary binder in manufacturing of RPC. Its physical and chemical characteristics are provided in Table 1. This cement is Type-I general-purpose Portland cement.

Table 1: Properties of Materials

Typeof cementitious material	Oxidecomposition(%)						Physicalcharacteristics			
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	Surfaceareaof particles (m^2/kg)	Particle density (kg/m^3)	Bulk density (kg/m^3)	Lossin ignition (%)
Cement	62.55	21.75	11.51	2.04	2.88	0.21	365	3.09	1,440	1.22
Silicafume	0.06	95.12	0.22	0.17	0.02	—	25,000	2.12	305	0.69

b) Silica Fume

Silica Fume is a fine dust composed of ultrafine spherical particles containing a large amount of amorphous silica and is produced as a by-product of silicon and/or ferrosilicon alloy production. Characteristically, it improves cementitious materials by way of imparting compressive strength, durability, and reducing permeability. Essentially, because of its pozzolanic nature, silica fume combines with calcium hydroxide inside concrete to produce more calcium silicate hydrate (CS-H) and densify the matrix [1]. In Fiber Reinforced Reactive Powder Concrete, silica fume is most essential to producing an ultra-high strength RPC while maintaining compactness [2].

c) Quartz mineral

In comparison to natural sand and various other minerals, quartz exhibits exceptional strength and durability. This study employed both quartz powder and sand as mineral aggregates within the binder matrix of Reactive Powder Concrete (RPC). The primary component of quartz is silica (SiO2), which constitutes over 98% of its overall weight. The outcomes of the granulometry analysis for both quartz sand and powders are illustrated in Figure 1.

d) Fibers

Two types of fibers, namely hooked SF and CF, were used as reinforcement in RPC. The main characteristics of fibers are given in Table 2.

Table 2: Properties of SF & CF

Characteristic	SF	CF
Length-(mm)	35	35
Filamentdiameter-(μm)	900	18
Directtensilestrength(MPa)	1250	3000
Elastic-modulus(GPa)	210	380
Specificgravity (kg/m^3)	7.75	1.82

2.2Manufacturing details of RPC mixes

A total of five different RPC mixes were investigated in this research. These five mixes include one control plain mix serving as a reference and four fiber-reinforced RPC mixes. Four types of fiber-reinforced RPCs were manufactured by using 2%SF, 1.5% SF-0.5% CF, 1% SF-1% CF, and 2%CF, respectively. Fiber volume was maintained at 2% by volume of RPC in all mixes. The details about RPCs are provided in Table 2. The mix design of these mixes was adopted after a rigorous hit-and-trial basis such that plain RPC achieves a compressive strength of 140 MPa after 3 days of curing in hot water (at a temperature of 90 °C). The RPC mixes were manufactured in rapid speed mixer and the proce- dure is explained as follows:

(I) In the 1st step, cement, silica fume and quartz aggregate were mixed at 4 min @40 rpm; (II) In the 2nd step, half quantity of water and plasticizer (Viscocrete 3110) was added to the mixer, and mixing speed was increased to 80 rpm and sustained for 4 min; (III) in the 3rd step, fiber (CF, SF or hybrid CF + SF) was added to the mixer with the remaining half of the water and plasticizer, and the third stage sustained for 4 min@120 rpm. For the preparation of plain RPC, only water and plasticizer were added to the machine in the 3rd step but without fibers. After that, the machine was turned off for 2 min and then it continued to run @40 rpm until the casting of specimens was completed. During the casting stage, fresh mix was poured into the molds that were vibrated on a high-frequency vibrating table.

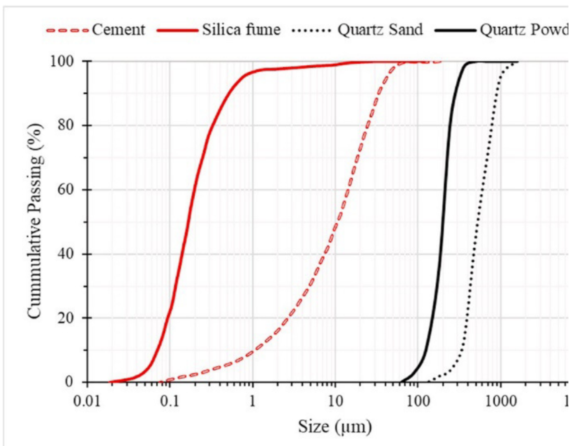


Fig. 1. Particle size gradation of binders (cement and silica-fume) and mineral components (quartz powder and sand) of RPC.

MixtureID	Cementitiousmaterials(kg/m^3)		QuartzFiller (kg/m^3)		Volumeoffractionoffibers		Waterreducer(kg/m^3)	TapWater
	Type Icement	Silica fume	Powder	Sand	SF	CF	Viscocrete-3110	
Plain-RPC	845	240	355	780	–	–	45	152
2SF-RPC	845	240	355	780	2	0	45	152
1.5SF-0.5CF-RPC	845	240	355	780	1.5	0.5	45	152
1SF-1CF-RPC	845	240	355	780	1	1	45	152
2CF-RPC	845	240	355	780	0	2	45	152

Table 2: Ingredients of RPC mixes.

2.3 Preparation and testing of specimens

All specimens were cast using standard steel molds. The specimens were enclosed in waterproof thin plastic to prevent them from drying out. After casting, the specimens were retained in the molds for a duration of 24 hours to allow for setting. Following this 24-hour period, the specimens were demolded and placed in a temperature-controlled curing tank for four days. The temperature of the curing tank was gradually raised to 90°C over a span of 24 hours, after which the specimens were cured at a constant temperature for the remaining three days. This high-temperature curing process accelerates pozzolanic reactions and reduces the time required for strength development. After conditioning in the water tank, the specimens were taken out and air-cooled for 24 hours at room temperature prior to the heating and testing procedures.

The influence of single carbon fibers (CF) and hybrid carbon-silica fume (CF-SF) fibers was examined concerning three primary mechanical properties of reactive powder concrete (RPC), specifically compressive strength (CS), splitting tensile strength (STS), and modulus of rupture (MOR). To assess CS and STS, specimens with a diameter of 100 mm and a height of 200 mm were tested in accordance with ASTM C39 and ASTM C496 respectively. The MOR test was performed on prismatic specimens measuring 100 mm × 100 mm × 350 mm under third-point loading. The specifics of the specimen testing are detailed in Table 3. An overview of the mechanical testing is illustrated in Fig. 2. Additionally, the density of all RPC mixes was evaluated. The density test was conducted on RPC cylinders with a diameter of 100 mm and a height of 100 mm.

Table3:DetailsoftestsconductedonspecimensofdifferentRPCmixes.

Properties	Standardmethod	Specimensize	Specimenstestedpermixateachtemperature	Temperatures(°C)
Compressivestrength(MPa)	ASTM C39	100mm x 200mmcylinder	5	25,200,400, 600and800
Splitting-tensile strength(MPa)	ASTM C496	100mm x200mm Cylinder	3	25,200,400, 600and800
Flexuralstrength/Modulusof Rupture(MPa)	ASTMC1609	100mm x100mm x 350 mm prisms	5	25,200,400, 600and800
Density(kg/m^3)	ASTM C948	100mm x100mm cylinders	3	25

2.4 Heating of RPC specimens

After the curing process, specimens were conditioned in ambient air for a duration of 2 months to replicate natural conditions within the specimens. Three specimens from each mix were subjected to testing at normal temperature to examine the performance variations of RPC with different fiber types and combinations. Subsequently, specimens from each mix were subjected to four distinct temperatures: 200, 400, 600, and 800 °C. The temperature-time curve of the furnace for the various exposure temperatures is illustrated in Fig. 3. The temperature gradient was set at 4 °C/min. Once a specific temperature was reached, the specimens were maintained at that constant temperature for 2 hours. Before conducting compression, split tensile, and flexural tests, all specimens were allowed to cool at room temperature for 2 days.

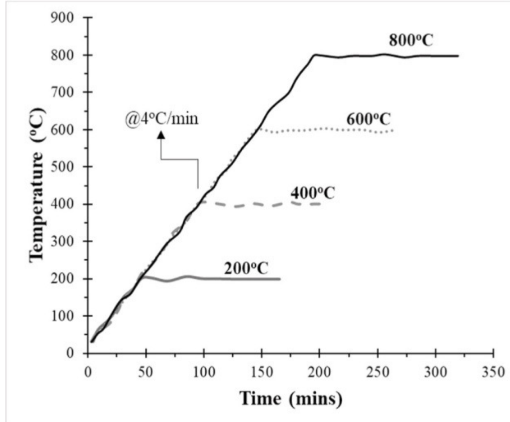


Fig. 3. Temperature-time curve for the different target temperatures in electric- furnace.

3. RESULTS AND DISCUSSION

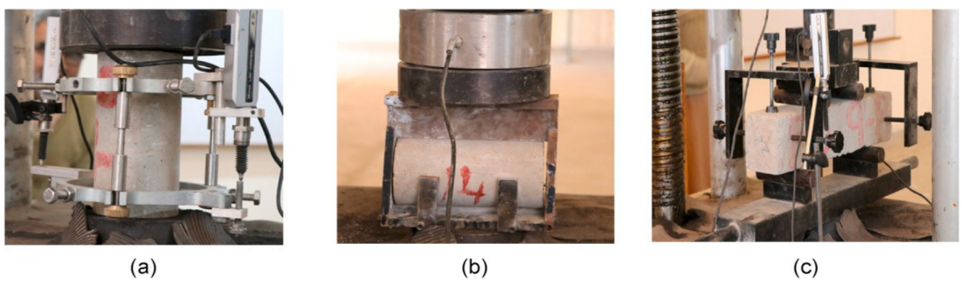


Fig. 2. Overview of testing of samples a) compression-testing (b) 202 splitting-tensile test (c) bendingtest.

3.1 Compressive Strength

The compressive strength (CS) of each RPC mix at normal tempera- ture is shown in Fig. 4. The net change in CS of RPC due to the addition of fiber is illustrated in Fig. 4(a). A net increase of 8–13.5% was ob- served in CS of RPC due to the addition of fibers. The single 2%SF incor- poration shows more net gain in CS than the single 2% CF. Moreover, hybridization of 1.5% SF and 0.5%CF shows 13% higher CS than plain RPC. Hybrid 1.5% SF and 0.5CF fiber-system produce optimum CS. The net gain in CS due to fiber addition is credited to the increase in stiffness and toughness of concrete [34]. Fibers prevent premature cracking of RPC matrix that leads to efficient utilization of material's strength in re- sisting compressive stress. The superior performance of SFRPC com- pared to CFRPC is credited to the higher stiffness and better bond strength of SF-filaments [9] compared to CF. Moreover, the superior performance of hybrid fiber mix (1.5SF-0.5CF-RPC) compared to single fiber mixes (SFRPC and CFRPC), is credited to the synergistic effects of SF and CF in restraining crack-growth due to a significant difference in the lengths and diameters of these fibers.

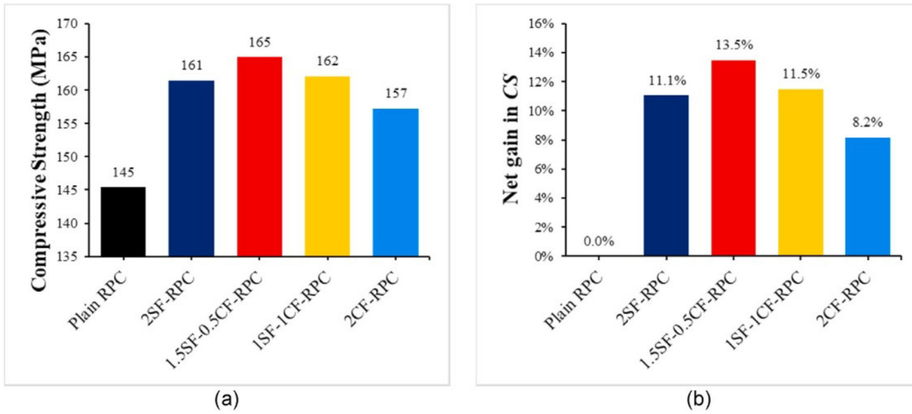


Fig. 4. Compressive strength (CS) at normal temperature (a) CS for different types of fiber-reinforcements (b) the net gain in CS due to addition of fibers.

Experimentation confirmed that the incorporation of fibers enhances the compressive strength significantly for RPC. Highest improvements were noticed in hybrid fiber-reinforced RPC mixtures among the fiber types and combinations applied. The mixture of 1.5% steel+0.5% carbon fiber obtained a maximum compressive strength of 165 MPa, which was 13.5% higher than that of plain RPC. Steel fiber-reinforced (2%) RPC had also shown a considerable increase of 11.1%, while carbon fiber-reinforced (2%) RPC increased by 8.2%. This is an indication that while steel and carbon fibers independently contribute to compressive strength, in the right balance, their combination can give the best mechanical performance, hence making hybrid fiber systems worth looking into for future development of the structural behavior of RPC in real applications.

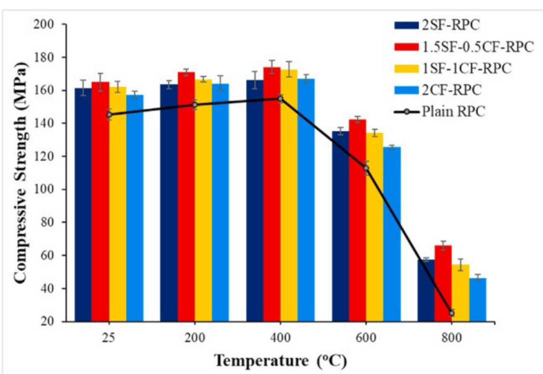


Fig. 5. Residual CS of all RPC mixes after exposure to different temperatures.

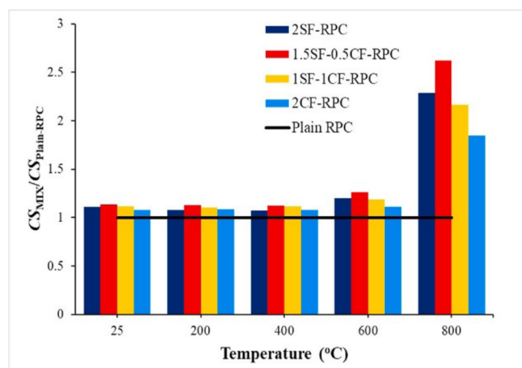
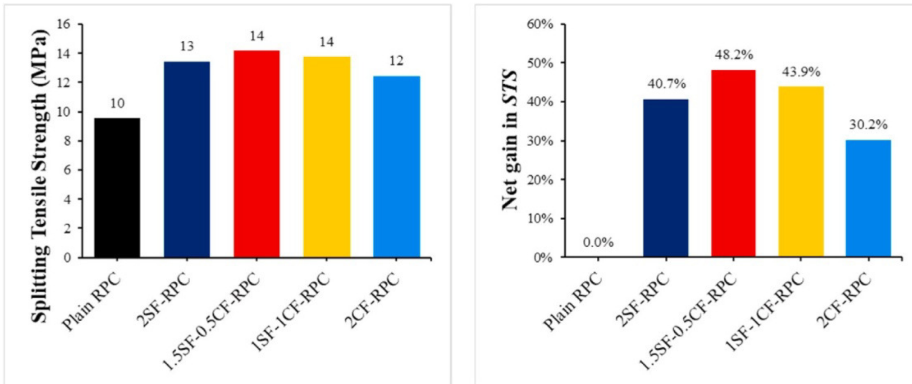


Fig. 6. Normalized CS of each RPC mixture after exposure to different tempera- tures.

3.2 Splitting tensile strength

Splitting-tensile strength (STS) is an indirect estimation of the true tensile strength of cement-based materials. Fig. 7 shows the STS of RPC with the varying fiber content and combination. It is apparent that the single fiber SFRPC has notably higher STS than the single fiber CFRPC. CFRPC and SFRPC show 82% and 60% higher STS than the plain-RPC (0% fiber), see Fig. 7(b). Hybridization of 0.5%CF and 1.5%SF shows the synergistic effect on STS. Hybrid fiber 1.5 SF-0.5CF-RPC shows 10% higher STS than single fiber SFRPC. These results show that fiberaddi- tion is more useful to boost STS than they are in CS. This is because the activation of fibers starts earlier under the pulling action of splitting- tensile loads. It can be concluded from the results of STS and CS that fibers attribute 5–7 times more to STS than CS. Higher efficiency of SF compared to CF can be ascribed to difference in the bond strength of fil- aments of SF and CF. SF has a large diameter than CF, which means the bond strength of SF is very much higher than CF. High bond strength helps increasing the utilization of tensile strength of fibers in tensile strength. Furthermore, hook-ends also provide extra bond resis- tance to SF against pulling action to control the cracking that ultimately contributes a huge deal to the STS of concrete.



(a) (b)

Fig. 7. Splitting-tensile strength (STS) at normal temperature (a) STS for different types of fiber-reinforcements (b) the net gain in STS due to addition of fibers.

The comparison is made between the splitting tensile strength (STS) of fibered RPC, containing different fiber types and combinations, thus showing the significant role of fibers in RPC tensile behavior. The control mix (plain RPC) would demonstrate the STS of 10 MPa; all the combinations with fibers show significant improvements. Among all mixes, those with steel fibers either alone or combined with carbon fibers show the greatest enhancements in STS. Thus, a mix with 2% steel fibers (2SF-RPC) attains an STS of 13 MPa, with a 30% increase over the control mix, showing how well steel fiber arrests cracks and transfers load. More importantly, the hybrid mixes of 1.5% steel + 0.5% carbon fiber (1.5SF-0.5CF-RPC) and 1% steel + 1% carbon fiber (1SF-1CF-RPC), both attain an STS of 14MPa, showing a 40% improvement, thereby showing how dual fibers can be combined to maximize performance with mechanical interlocking from steel fibers and crack dispersion from carbon fibers. The carbon fiber mix with 2% carbon fibers (2CF-RPC) also shows enhanced performance with an STS of 12 MPa (20% gain) but still not as much as the steel-based mixes.These findings suggest that while carbon fibers contribute positively to tensile strength, steel fibers remain superior in enhancing ductility and post-cracking resistance. Importantly, the results confirm that fiber reinforcement significantly improves the tensile performance of RPC, addressing its inherent brittleness and making it more suitable for structural applications subjected to tensile stresses.

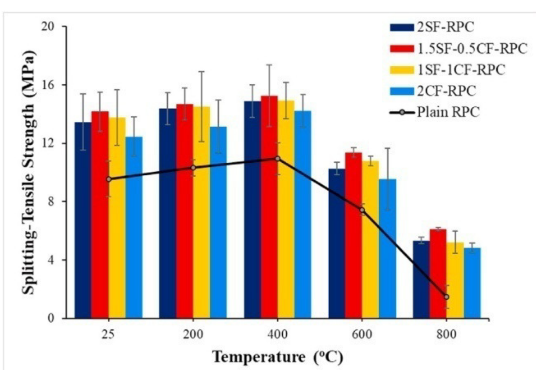


Fig. 8. Residual STS of RPC mixes after exposure to different temperatures.

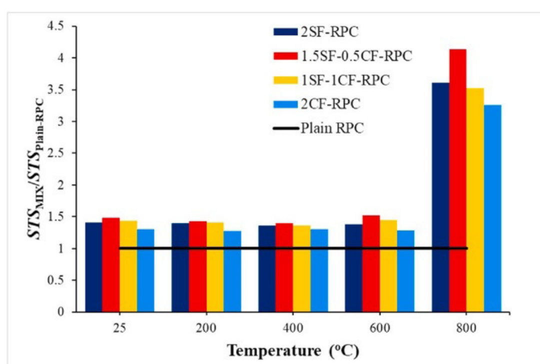
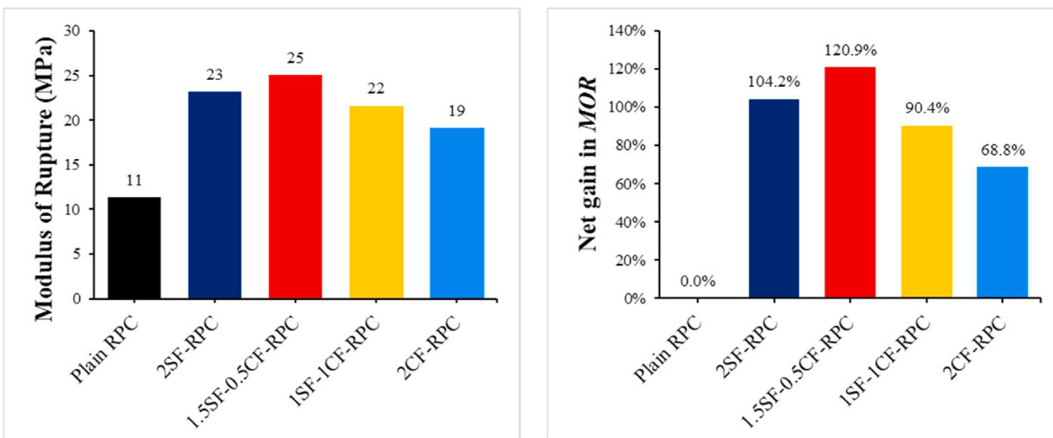


Fig. 9. Normalized STS of each RPC mixture after exposure to different temperatures.

3.3 Modulus of rupture and ductility

The modulus of rupture (MOR) serves as an indicator of the flexural strength of concrete. Additionally, it is utilized as an alternative estimation of true tensile strength, and it can be directly applied in the structural design of flexural components such as slabs, pavements, tunnels, and more. Unlike compressive strength (CS) and tensile strength (STS), MOR is a complex measure that necessitates stringent quality control, as it is significantly affected by factors such as the casting method, support conditions, specimen size, and the orientation of fibers. To establish a reliable trend with varying types and combinations of fiber, five specimens were tested for each reactive powder concrete (RPC) mix at both normal and elevated temperatures, with their average results documented in this study. The MOR of each RPC mixture at normal temperature is illustrated in Fig. 10. Similar to STS, the MOR of fibrous RPC is markedly different from that of plain RPC. The addition of fibers results in a slightly greater net gain in MOR compared to the increase observed in STS. The high efficiency of fibers in enhancing MOR, in contrast to CS and STS, has been experimentally validated in other strength classes of concrete, including normal strength, high strength, and ultra-high strength concrete. The MOR of RPC increases by 104%, 121%, 90%, and 69% with the addition of 2%SF, 1.5%SF-0.5%CF, 1%SF-1%CF, and 2%CF, respectively. These findings indicate that the incorporation of 2%SF can effectively double the MOR. Similar to the results observed with CS and STS, MOR also exhibits synergistic effects due to the inclusion of the hybrid combination of 1.5%SF and 0.5%CF.

The MOR results for each RPC mixture at various elevated temperatures are presented in Fig. 11. Initially, the MOR of all RPC mixes shows improvement after exposure to temperatures of 200 and 400°C. The variation in MOR across all RPC mixes follows a comparable trend up to 400°C. However, beyond 400°C, the RPC mixes, particularly plain RPC, experience a significant decline. Following exposure to 800°C, plain RPC loses nearly 90% of its MOR at normal temperature. These reductions are attributed to the degradation of the integrity and microstructure of the RPC matrix at temperatures of 600 and 800°C.



(a) (b)

Fig. 10. Modulus of rupture (MOR) at normal temperature (a) MOR for different types of fiber-reinforcements (b) the net gain in MOR due to addition of fibers.

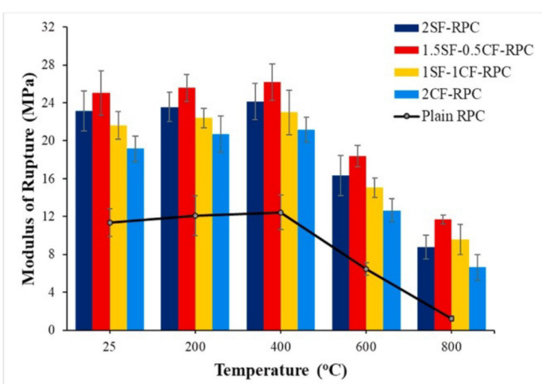


Fig. 11. Residual MOR of RPC mixes after exposure to different temperatures.

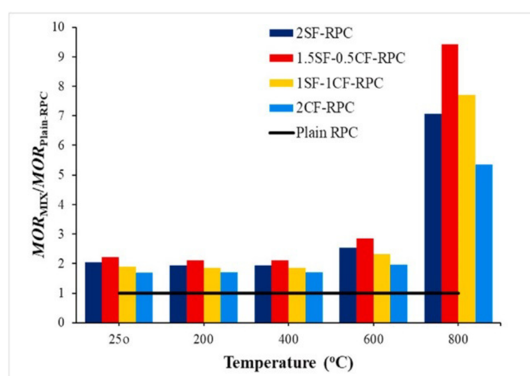


Fig. 12. Normalized MOR of each RPC mixture at different elevated temperatures.

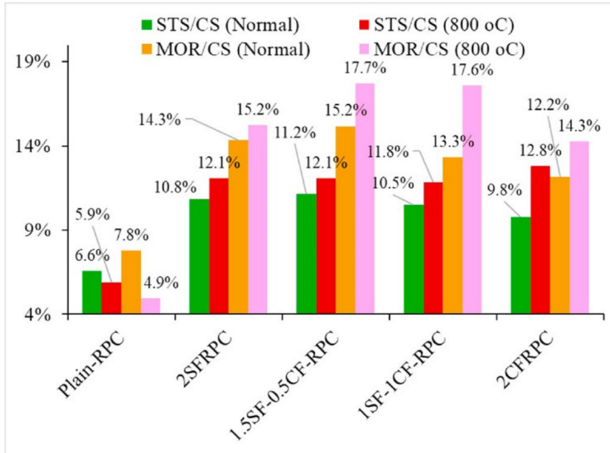


Fig. 13. Ratio of STS and MOR w.r.t corresponding CS of all RPC mixes.

3.4 Density and strength per unit density

The density of all examined RPC mixtures is illustrated in Fig. 14. Typically, RPC is reinforced with SF, which is why its unit weight generally exceeds 2500 kg/m3. As anticipated, the SFRPC mixture exhibited the highest density. Additionally, the density of RPC decreases as the CF content in the matrix increases. CF contributes to the creation of lighter RPC. The CFRPC has a density that is 200 kg/m3 less than that of the corresponding SFRPC at a 2% fiber volume. Since SF is nearly four times heavier than CF, the mass of fiber needed for SF per unit volume fraction is considerably greater than that required for CF.

Fig. 15 presents the strength per unit density of each RPC mixture. Although the mechanical properties indicate that the single 2CFRPC has lower compressive strength (CS), tensile strength (STS), and modulus of rupture (MOR) compared to the single 2SFRPC, the strength per unit density analysis reveals that CFRPC has a higher compressive strength per unit weight than SFRPC. In contrast, the hybrid 1.5SF-0.5CF-RPC mixture demonstrates the highest STS and MOR per unit density among all mixes. The hybrid 1SF-1CF-RPC exhibits a greater STS/density ratio than the single SFRPC. Furthermore, CFRPC shows a slightly lower STS and flexural strength (FS) per unit density compared to the single SFRPC.

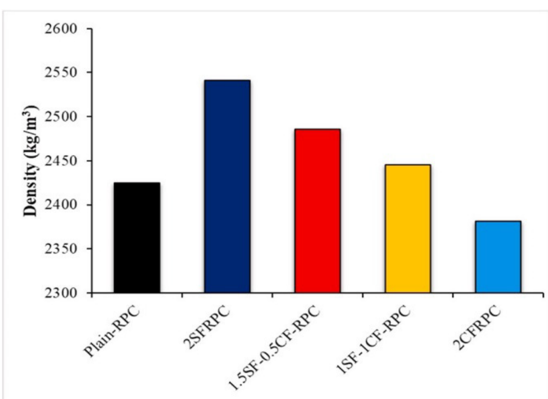


Fig. 14. Density of RPC mix with different combinations of fibers at normal temperature.

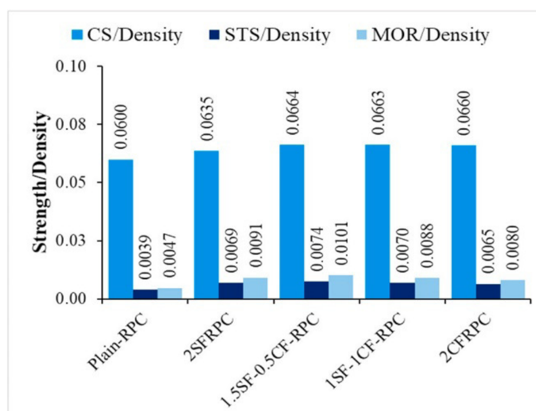


Fig. 15. Strength per unit weight of different RPC mixtures at normal temperature.

4. CONCLUSIONS

In this research, the mechanical properties of RPC at elevated temperatures were examined using various fiber combinations (single CF, hybrid CF + SF, single SF). The key conclusions drawn from this study are as follows:

- The compressive strength (CS) of RPC improved by 8–13% with the incorporation of fibers. The combination of 0.5% CF and 1.5%

SF yielded the highest CS. After exposure to 800°C, single fiber CFRPC and hybrid fiber 1.5SF-0.5CF-RPC exhibited approximately 1.85 and 2.63 times greater residual CS compared to plain-RPC, respectively.

- The splitting tensile strength (STS) increased by 60% due to the addition of 2% CF. The single fiber CFRPC demonstrated lower STS than the single fiber SFRPC. The hybrid-fiber 1.5SF-0.5CF-RPC achieved superior STS compared to other RPCs at both normal and elevated temperatures. At 800°C, the single-fiber CFRPC and hybrid-fiber 1.5SF-0.5CF-RPC maintained about 3.52 and 4.2 times higher residual STS than plain-RPC.
- The modulus of rupture (MOR) of RPC rose by over 65% with the inclusion of 2% CF. The highest MOR, approximately 120% greater than that of plain RPC, was found in the hybrid RPC containing 1.5% SF and 0.5% CF. The single-fiber CFRPC and hybrid 1.5SF-0.5SF-RPC exhibited about 5.3 and 9.4 times more residual MOR than plain-RPC at 800°C.
- The CFRPC demonstrated superior compressive strength per unit weight compared to SFRPC. Additionally, the hybrid-fiber 1.5SF-0.5CF-RPC displayed higher STS and FS per unit weight in comparison to conventional SFRPC. The CFRPC can facilitate the creation of lighter and stronger composite structures than SFRPC.

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