BILINGUAL PUBLISHING GROUP

Journal of Building Material Science

https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Spalling Resistance and Residual Strength of Hybrid Fibre-Reinforced Reactive Powder Concrete at Elevated Temperatures

Widodo Kushartomo * , *Andy Prabowo* , *Daniel Christianto* , *Arianti Sutandi*

Department of Civil Engineering, Universitas Tarumanagara, Jakarta 11440, Indonesia

ABSTRACT

Reactive Powder Concrete (RPC) is an advanced construction material prized for its superior strength and durability. However, its dense, ultra-low porosity microstructure, while beneficial for mechanical properties, renders it highly susceptible to explosive spalling when exposed to temperatures between 200 °C and 400 °C. This dangerous phenomenon occurs as trapped moisture and air within the RPC's pores rapidly expand upon heating, generating immense internal vapour pressure that causes sudden surface bursting. This study investigates a synergistic approach by combining steel fibres with low-melting-point polypropylene fibres within fibre-reinforced RPC (FRPC). The principle is that polypropylene fibres melt at approximately 170 °C, creating a network of micro-channels that provide pathways for the release of trapped vapour and air, thereby relieving the internal pressure that causes spalling. To evaluate this, cylindrical specimens (10 cm × 20 cm) were prepared, water-cured for 26 days, and then subjected to steam curing at 95 °C for 4 h. Subsequently, they were exposed to elevated temperatures of 200, 300, and 400 °C for 2 h to simulate fire exposure. The results conclusively show that the hybrid fibre combination effectively prevents explosive spalling. Furthermore, the hybrid FRPC maintained an impressive 80–90% of its original compressive strength post-heating. In stark contrast, FRPC specimens containing only steel fibres suffered severe damage and retained a mere 20–40% of their room-temperature strength. These findings demonstrate that hybrid fibre reinforcement is a highly effective strategy for enhancing the fire resistance of RPC, thereby enabling its safer application for structures prone to elevated temperatures.

Keywords: Reactive Powder Concrete; Explosive Spalling; Hybrid Fibres; Fire Resistance; Residual Compressive Strength

*CORRESPONDING AUTHOR:

Widodo Kushartomo, Department of Civil Engineering, Universitas Tarumanagara, Jakarta 11440, Indonesia; Email: widodo@untar.ac.id

ARTICLE INFO

Received: 12 August 2025 | Revised: 23 October 2025 | Accepted: 25 November 2025 | Published Online: 1 December 2025

DOI: https://doi.org/10.30564/jbms.v7i4.11597

CITATION

Kushartomo, W., Prabowo, A., Christianto, D., et al., 2025. Spalling Resistance and Residual Strength of Hybrid Fibre-Reinforced Reactive Powder Concrete at Elevated Temperatures. Journal of Building Material Science. 7(4): 128–141. DOI: https://doi.org/10.30564/jbms.v7i4.11597

1. Introduction

The relentless pursuit of advanced construction materials with superior mechanical properties and enhanced durability has been a cornerstone of modern civil engineering. In this context, Ultra-High-Performance Concrete (UHPC) and its specific variant, Reactive Powder Concrete (RPC), represent a paradigm shift from traditional concrete technology. Reactive Powder Concrete (RPC) is an advanced cementitious composite characterized by its unique composition of ultra-fine particle materials, including cement, silica fume, quartz sand, quartz powder, superplasticizer, and typically, steel fibres [1,2]. The fundamental philosophy behind RPC is the elimination of coarse aggregates to enhance homogeneity and the optimization of the particle packing density of the remaining constituents. This results in a material with an exceptionally dense and compact microstructure, which translates into exceptional mechanical properties, with compressive strengths ranging from 200 to 800 MPa and flexural strengths between 30 and 50 MPa [3]. The high performance of RPC is further attributed to its high cement content, very low water-to-cement ratio (often below 0.25), and the incorporation of steel fibres for ductility [1,2,4,5].

The development of RPC can be traced back to the pioneering work in the early 1990s by researchers at the Bouygues laboratory in France [1–6]. This breakthrough was not merely a single innovation but a systematic approach involving the careful selection of material types, optimized mix designs based on particle packing models, and specialized curing methods, most notably pressurized steam curing [1,2]. This thermal treatment accelerates the pozzolanic reactions between cement hydration products and silica fume, leading to a further refinement of the microstructure, a reduction in pore volume and size, and a consequent significant boost in compressive strength [7–10]. The exceptional strength, durability, and toughness of RPC have positioned it as a premier material for specialized applications, including long-span bridges, seismic-resistant structures, high-rise buildings, and critical infrastructures like nuclear containment facilities and military shelters where superior performance is non-negotiable [11,12].

However, the very properties that confer RPC its outstanding performance—its high density and extremely low permeability—also constitute its shortcomings when subjected to fire. The dense, nearly impermeable microstructure means that free and chemically bound water within the cement paste, along with trapped air in the minimal pore space, have limited pathways to escape when heated rapidly. As the temperature rises during a fire event, this trapped moisture vaporizes and the trapped air expands, generating immense internal pore pressure. When this pressure exceeds the tensile strength of the concrete matrix, it leads to a violent, explosive failure known as spalling. This phenomenon is particularly severe in RPC, with studies indicating that explosive spalling can occur at temperatures as low as 200–400 °C [11–13], posing a grave threat to structural integrity by suddenly reducing the cross-sectional area of load-bearing members and exposing internal reinforcement to direct heat.

Extensive research has been conducted on the behavior of both normal-strength and high-performance concrete at elevated temperatures [11–16]. These studies [11–16] have established that the incorporation of fibres, such as steel or polypropylene, can improve the residual properties of concrete after fire exposure. Steel fibres are primarily known for enhancing flexural toughness, crack resistance, and residual strength post-heating by bridging cracks [8]. Polypropylene fibres, on the other hand, have a different mechanism. These fibres melt at a relatively low temperature of approximately 160–165 °C [9,15,16]. Upon melting, they create a network of microchannels within the concrete matrix, which provides pathways for the release of built-up vapor and air pressure, thereby mitigating the risk of explosive spalling.

While studies have independently explored steel fibre-reinforced RPC [14,15] and, to a lesser extent, polypropylene fibre-reinforced RPC [8], the synergistic effect of combining these two fibre types in a hybrid RPC (combination of steel and polypropylene fibers [17–22]) system to specifically address the spalling problem remains a relatively unexplored frontier. The central hypothesis of this research is that a hybrid reinforcement system can leverage the benefits of both fibres: the steel fibres to maintain mechanical integrity and post-cracking ductility, and the polypropylene fibres to provide a pressure-relief mechanism at elevated temperatures. This raises several critical research questions: Can the incorporation of polypropylene fibres effectively create sustainable escape routes for trapped pore pressure without compromising the room-temperature mechanical properties of RPC? What is the optimal volumetric ratio and total content of steel to polypropylene fibres that maximizes fire resistance while minimizing any potential detrimental effects on strength? What is the quantitative residual compressive strength of such a hybrid RPC after exposure to various elevated temperatures?

To address these questions, this study presents a comprehensive experimental investigation into the compressive strength behavior of hybrid fibre-reinforced RPC subjected to elevated temperatures. The aim is to develop an RPC mix design that effectively resists explosive spalling under fire conditions, thereby unlocking its potential for broader application in fire-prone environments. The introduction has placed the study in the broad context of advanced concrete technology and highlighted its importance in overcoming a critical limitation of RPC. The subsequent sections detail the materials and methods, present and discuss the results, and draw conclusive findings on the efficacy of the proposed hybrid fibre solution. As a novelty, this study focuses on exploring the synergistic effect of combining steel and polypropylene fibers in a hybrid RPC system to investigate the residual stress after exposure to high temperatures, particularly in addressing the spalling issue, which has been relatively unexplored in previous research.

2. Recent Studies on Fibre Reinforced RPC at Elevated Temperatures

Fibre-reinforced reactive powder concrete (FRPC) is a high-performance material known for its exceptional mechanical properties and ability to retain significant strength under elevated temperatures. Multiple studies have investigated the effects of temperature on the residual strength and mechanical properties of FRPC, particularly focusing on various types of fibres.

One critical aspect of FRPC's performance at elevated temperatures is its thermal properties, which significantly influence its mechanical response. In the study conducted by Li et al.[17], the focus was on the effect of temperature (20–900 °C) on the thermal properties of steel fiber-reinforced RPC, including thermal conductivity, thermal diffusivity, specific heat capacity, and linear expansion coefficient. The results showed that, with increasing temperature, the thermal conductivity and thermal diffusivity initially decreased and then increased, while the linear expansion coefficient and specific heat capacity initially increased and then decreased. This study[17] did not observe the residual stress of high-performance concrete after exposure to elevated temperatures.

Meanwhile, the study conducted by Zhao et al.[18] and Du et al.[19] investigated the fracture properties of high-performance concrete reinforced with a hybrid combination of steel and plastic fibers after exposure to elevated temperatures. The results showed that the crack initiation toughness of steel–plastic fiber-reinforced concrete increased significantly after high-temperature exposure, and the inclusion of steel–plastic fibers was proven effective in reducing the critical value of crack opening displacement in concrete. When the testing temperature ranged from 200 °C to 600 °C, the anti-cracking effect of steel–plastic fibers on concrete was more pronounced compared to normal concrete. However, these studies did not observe the residual stress of high-performance concrete after exposure to elevated temperatures.

The study conducted by Zheng et al.[20] observed the microstructure and compressive strength of RPC reinforced with a hybrid combination of steel-polypropylene fibers after exposure to high temperatures. The results of the study indicated that the compressive strength of RPC increased up to a heating temperature of 400 °C, but decreased beyond that temperature. Based on microstructural observations, the polypropylene fibers left void traces after heating, and the presence of these voids contributed to the reduction in compressive strength at temperatures above 400 °C. The study conducted by Zheng et al.[20] used 5 × 5 × 5 cm cube specimens, and the combination of steel-polypropylene fibers was very limited. Therefore, the research in Zheng et al.[20] has not yet fully represented the overall behavior of RPC reinforced with hybrid steel–polypropylene fibers after exposure to elevated temperatures.

The study conducted by Li and Liu[21] investigated the flexural stress behavior of RPC reinforced with a hybrid combination of steel and polypropylene fibers after heating. The test results indicated that steel fibers significantly enhanced the tensile performance of RPC; however, in general, increasing the heating temperature caused the tensile stress of steel–polypropylene hybrid fiber-reinforced RPC to decrease linearly. The study[21] focused only on the tensile behavior of fiber-reinforced RPC after heating and did not examine the residual stress following thermal exposure. Investigation on the tensile behaviour of fibre RPC has also been conducted by Abid et al.[23], reporting that flexural strength can be cut in half by 500 °C due to micro-cracking.

The search for better performance has led to testing alternative fibres. Studies on basalt fibres[24,25] and carbon fibres[26] suggest they also help the concrete maintain its integrity under thermal stress. Beyond material choice, advanced methods like controlling how fibres are aligned within the concrete have shown a remarkable ability to improve flexural capacity[27], opening up new engineering possibilities.

In summary, while we have a good understanding of how single fibres behave in RPC under heat, there's a noticeable gap when it comes to combining them. To the best of the authors' knowledge, the work by Mao et al.[27] stands alone in specifically investigating the performance of hybrid fibre systems at elevated temperatures. This suggests that exploring synergistic combinations of fibres could be a key next step for developing more resilient RPC.

Mao et al.[22] evaluated the performance of RPC reinforced with a hybrid combination of steel and polypropylene fibers after exposure to high temperatures using a non-destructive testing (NDT) method. The specimens were prepared in the form of prisms measuring 10 × 10 × 30 mm, and the compressive strength test was performed axially. The NDT was carried out using the ultrasonic pulse velocity (UPV) method in the axial direction. The results showed a loss of mass due to heating and an increase in axial compressive strength up to a heating temperature of 200 °C; however, beyond this temperature, up to 700 °C, the compressive strength decreased. The residual strength tests after heating were conducted using prism specimens instead of cylinders; therefore, the results have not yet accurately represented the mechanical behavior of steel–polypropylene hybrid fiber-reinforced RPC after exposure to elevated temperatures.

3. Materials and Methods

A rigorous experimental program was designed to investigate the effects of hybrid fibre reinforcement on the compressive strength of RPC at elevated temperatures, characterized as residual strength. This section provides a detailed description of the constituent materials, the mix proportions, the specimen preparation and curing regimes, and the testing procedures employed.

3.1. Materials

The RPC mixtures were designed using materials selected for their fineness and reactivity, in accordance with the principles of RPC formulation. The constituent materials were:

- Cement: Ordinary Portland Cement (OPC) conforming to relevant standards was used as the primary binder.
- Silica Sand: High-purity silica sand with a controlled grain size distribution of 150–450 μm was used as the fine aggregate. The narrow grading ensures optimal packing density.
- Silica Fume: Densified silica fume, a by-product of silicon metal production, was incorporated as a microsilica additive. Its ultra-fine particles (approximately 100 times smaller than cement grains) fill the interstitial spaces between cement grains, leading to a denser microstructure and participating in pozzolanic reactions to form additional strength-giving calcium silicate hydrate (C-S-H) gel.
- Marble Powder: an industrial waste material, was used as a micro-filler. With a particle size similar to or finer than cement, it further enhances the particle packing density of the mixture, contributing to the overall compactness of the hardened RPC.
- Superplasticizer: A next-generation polycarboxylate ether (PCE)-based superplasticizer was employed. This high-range water-reducer is crucial for achieving the desired workability at the very low water-to-cement ratio (w/c = 0.20) used in RPC, ensuring proper dispersion of particles and fibres without compromising the water content.
- Fibres: Two types of fibres were utilized:
    - ✓ Steel Fibres: Hooked-end steel fibres with a length of 11.0–13.0 mm and a diameter of 0.10–0.12 mm were used. These fibres have a high tensile strength (typically >2000 MPa) and are intended to improve flexural strength, toughness, and crack control.
    - ✓ Polypropylene (PP) Fibres: Monofilament polypropylene fibres with a length of 24 mm and a diameter of 0.43 mm were used. These

fibres have a melting point of approximately 160–165 °C and are intended to melt during heating, creating channels for pressure release.

All raw materials are visually presented in **Figure 1.**

(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**)

Figure 1. Materials: (**a**) OPC cement, (**b**) silica sand, (**c**) silica fume, (**d**) marble powder, (**e**) superplasticizer, (**f**) steel fibre, (**g**) polypropylene fibre.

3.2. Mix Proportions and Specimen Preparation

The base mix design of the RPC, by weight proportion of cement, is summarized in **Table 1**. The low water-to-cement ratio of 0.20 was maintained constant across all mixes. The superplasticizer dosage was adjusted slightly for each mix to ensure a consistent, cohesive, and flowable mix despite variations in fibre content, which can significantly affect workability.

Table 1. Mix Design of Fibres-Reinforced RPC.

No.	Material	Ratio (by Weight of Cement)
1	Cement	1.00
2	Water	0.20
3	Silica Fume	0.25
4	Sand	1.10
5	Marble Powder	0.10

The fibre variables constituted the core of the experimental plan. Fibres were incorporated into the mixtures at total volumetric fractions (Vf) of 1.0%, 1.5%, and 2.0% of the total concrete volume. For each total fibre volume, four different steel-to-polypropylene (Steel: PP) fibre volume ratios were investigated:

1. **1:0:** 100% steel fibres (reference mix for steel-only reinforcement).
2. **9:1:** 90% steel fibres, 10% polypropylene fibres.
3. **8.5:1.5:** 85% steel fibres, 15% polypropylene fibres.
4. **8:2:** 80% steel fibres, 20% polypropylene fibres.

This matrix resulted in a total of 12 distinct fibre-reinforced mixes. Additionally, a plain RPC mix without any fibres was cast as a control specimen for baseline comparisons.

The mixing procedure was critical to ensure uniform dispersion of fibres and avoid balling. A high-shear mixer was used. The dry powders (cement, silica fume, sand, marble powder) were first mixed for 5 min to achieve homogeneity. Then, water premixed with the superplasticizer was added gradually while mixing continued for another 5–7 min until a uniform paste was formed. Finally, the fibres were slowly added to the mixture to ensure they were evenly distributed throughout the matrix. The mixing was continued for an additional 3–5 min.

Cylindrical specimens with dimensions of 100 mm in diameter and 200 mm in height were cast for compressive strength testing. The fresh concrete was placed into molds in three layers, with each layer being vibrated on a vibrating table to ensure proper compaction and eliminate entrapped air. The specimens were covered with plastic sheets and left in the laboratory for 24 h before demolding.

3.3. Curing Regime

The importance of curing conditions in preparing the RPC specimens was studied by Ahmed et al.[28]. In this study, a two-stage curing regime was employed to optimize the development of the RPC's microstructure:

1. Water Curing: After demolding, the specimens were immersed in a water tank maintained at a temperature of 25 ± 2 °C for 26 days. This allowed for continued hydration of the cement.
2. Steam Curing: On the 27th day, the specimens underwent steam curing. They were placed in a steam curing chamber and subjected to a temperature of 95 ± 2 °C for a duration of 4 hours. This accelerated curing step promotes the pozzolanic reaction between calcium hy-

droxide and silica fume, leading to the formation of additional C-S-H gel and a denser, stronger matrix [9,13].

3.4. Thermal Loading and Testing Procedure

At the age of 28 days, the specimens were subjected to elevated temperatures. The thermal loading protocol was designed to simulate a sustained fire exposure. Specimens were placed in an electric furnace and heated to target temperatures of 200 °C, 300 °C, and 400 °C. The heating rate was controlled at 5 °C per minute to approximate a standard fire curve in its initial phase. Once the target temperature was reached, it was maintained constant for 2 hours to ensure a steady-state thermal condition throughout the specimen, allowing for the full development of thermal stresses and pore pressures. A set of specimens was kept at room temperature (25 °C) for control purposes. The heating design in this study was intended to compare material behavior rather than to represent a specific fire curve, such as ISO 834. The temperatures of 200 °C, 300 °C, and 400 °C were selected to represent the range of low to moderate thermal stresses commonly experienced by structural elements before severe spalling occurs. Based on previous studies [17–22], after 400 °C, the compressive strength of RPC reinforced with a hybrid combination of steel and polypropylene fibers decreases drastically; therefore, the investigation of RPC behavior above 400 °C was not considered a priority. To ensure that the heating process is carried out at the intended temperature, a thermocouple was installed in the furnace to stabilize the temperature during the heating process.

After the 2-hour exposure, the furnace was turned off, and the specimens were allowed to cool down slowly inside the switched-off furnace to avoid thermal shock, which could induce additional cracking. The compressive strength (f'c) tests were conducted three days after the thermal exposure using a universal testing machine, following the relevant standard test method [29]. The load was applied monotonically at a constant rate until failure. The residual compressive strength was calculated as a percentage of the average compressive strength of the corresponding mix cured at room temperature.

3.5. Heating Process

The thermocouple installed in the furnace recorded the heating transient during the initial minutes and ensured that the steady-state condition was maintained for 2 h at the target temperature. **Figure 2** shows the thermocouple maintaining the temperature at 300 °C.

Figure 2. The thermocouple is at a temperature of 300 °C.

Based on the temperature–time data, the heating process of the specimen exhibits a transient temperature phase before reaching a stable temperature condition, as shown in **Figure 3.** Transient temperature refers to a condition in which the temperature is not yet constant but continues to increase or fluctuate over time.

In **Figure 3**, the transient phase is clearly observed within the time range of 5 to approximately 25 min, where the temperature rises rapidly from:

- 100 °C → 175 °C → 200 °C for the 200 °C target
- 100 °C → 175 °C → 200 °C → 300 °C for the 300 °C target
- 100 °C → 175 °C → 200 °C → 300 °C → 400 °C for the 400 °C target

This pattern indicates the initial heating stage when the furnace is still progressing toward the target temperature. During this period:

- The rate of temperature increase is non-linear,
- The temperature is not yet stable, and
- The system remains in a non-steady-state condition, which is characteristic of transient thermal behavior.

After passing through this phase, the temperatures at each target level (200 °C, 300 °C, and 400 °C) remain relatively constant from minute 25 to minute 130, indicating that the system has entered a steady-state temperature condition. The temperature stays stable for approximately two hours, as designed in the thermal exposure procedure.

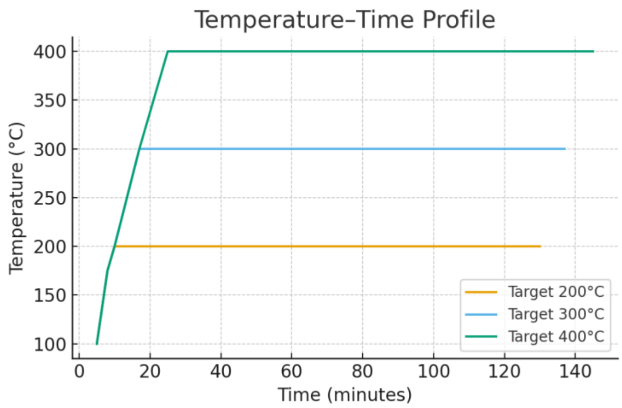

Figure 3. Transient thermal behavior during heating.

4. Results & Discussions

The results obtained from the experimental tests are presented and discussed in this section, focusing on the effects of fibre volume and type at room temperature, and their performance under elevated temperatures.

4.1. Effect of Fibre Volume and Type on Compressive Strength at Room Temperature

The primary role of fibers in concrete is to enhance tensile and flexural performance by bridging cracks. However, their influence on compressive strength [1,2], while secondary, is non-negligible and complex. **Figure 4** illustrates the relationship between fiber content and the compressive strength of RPC at room temperature (25 °C).

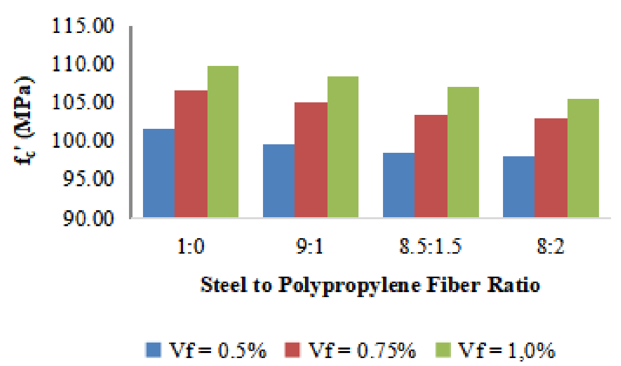

Figure 4. Effect of fiber volume and steel-to-polypropylene ratio on the compressive strength of RPC without thermal loading.

Figure 4 shows that increasing fibre volume enhances the compressive strength (**f_c'**) of RPC. When the steel fibre only (1:0) was added into the concrete mixes by 0.5%, 0.75%, and 1.0% from the total volume, the compressive strengths achieved were 101.6 MPa, 106.68 MPa, and 109.73 MPa, respectively. The increase is attributed to improved resistance to horizontal tensile stresses generated under compressive loading, delaying crack propagation. However, **Figure 4** also shows that the increased content of polypropylene fibre would slightly decrease the compressive strength. This indicates the lower ability of concrete in handling the cracks due to the less influence of the steel fibre.

For the mixes reinforced solely with steel fibers (Steel: PP ratio of 1:0), the compressive strength increased with higher fiber volume: from 101.6 MPa at 0.5% volume, to 106.68 MPa at 0.75%, and 109.73 MPa at 1.0% volume. This improvement can be attributed to the fibers' ability to provide confinement and resist the lateral tensile strains that develop under uniaxial compressive loading. As microcracks initiate and begin to propagate, the steel fibers bridge these cracks, absorbing energy and delaying their coalescence into macroscopic failure planes. This results in a more gradual failure and a measured increase in peak compressive strength.

However, the introduction of PP fibers as a partial replacement for steel fibers led to a slight but consistent decrease in compressive strength across all total fiber volumes, as evident in **Figure 4**. For instance, at a total fiber volume of 1.0%, the compressive strength decreased from 109.73 MPa (100% steel) to approximately 108.41 MPa (90% steel, 10% PP), 106.98 MPa (85% steel, 15% PP), and 105.45 MPa (80% steel, 20% PP). This trend is primarily due to the inferior mechanical properties of polypropylene fibers compared to steel. Polypropylene fibers have a lower tensile strength (500–750 MPa [5] vs. 500–2500 MPa for steel) and a lower modulus of elasticity. Consequently, they are less effective at restraining microcracks under high compressive stresses. Furthermore, the bond between the smooth surface of polypropylene fibers and the cementitious matrix is weaker than the mechanical bond provided by hooked-end steel fibers. The interfacial shear stress (τ) at the fiber-matrix interface can be conceptually described by:

$$\tau = \frac{P}{2\pi r l} \tag{1}$$

where P is the applied tensile load, r is the fiber radius, and l is the fiber length. A smoother fiber surface results in a lower τ, reducing the efficiency of load transfer from the matrix to the fiber.

The concept of a critical fiber volume is important in fiber-reinforced composites. It represents the minimum fiber content required to achieve a composite strength greater than the matrix cracking strength. While Equation (1) provides a theoretical framework for estimating this critical percentage[3], the results in **Figure 4** suggest that the optimal fiber volume for maximizing compressive strength in these RPC mixes lies within the range tested, but the declining trend with increasing PP content indicates a trade-off between room-temperature strength and potential fire resistance.

According to Alkhaly and Hasan[3], the critical percentage of fibers relative to the total mixture weight can be determined using Equation (2):

$$PWc_c = 75\frac{\pi . SG_f}{SG_c}.\frac{d}{l}.K \quad (2)$$

where PWc_c is the critical fiber content (by total mixture weight), SG_f and SG_c are the specific gravities of the fiber and concrete matrix respectively, d/l is the inverse aspect ratio, K is defined as $W_m/(W_m+W_a)$, W_m is the weight fraction of mortar (particles < 5 mm), and W_a is the weight fraction of coarse aggregate (particles > 5 mm)

4.2. Effect of Elevated Temperature on the Residual Compressive Strength of FRPC

4.2.1. Performance of Steel Fiber-Reinforced RPC

The behavior of RPC reinforced solely with steel fibers under high temperatures was concerning, as shown in **Figure 5**. Exposure to elevated temperatures caused a dramatic reduction in residual compressive strength ($\mathbf{f_{res}}$)[11,12]. After exposure to 200 °C, the residual strengths were between 60% to 66% of the original room-temperature strength. This loss escalated to approximately 40% retention at 300 °C, and a mere 20–25% retention after exposure to 400 °C.

This severe degradation is a direct consequence of explosive spalling and microcracking induced by thermal stresses and pore pressure. The dense microstructure of RPC traps moisture and air. Upon heating, the water vaporizes and the air expands. According to the ideal gas law[7] (a simplified representation of which is Boyle's Law, $P_1V_1/T_1 = P_2V_2/T_2$), the pressure inside the pores increases dramatically if the volume is constant. Since the RPC matrix is nearly impermeable, the pressure cannot dissipate easily. When the tensile stress from this internal pressure exceeds the tensile strength of the concrete, spalling occurs. The steel fibers, while excellent for mechanical reinforcement at room temperature, do not mitigate this pressure buildup. They are ineffective in preventing the initial spalling event, which catastrophically reduces the load-bearing cross-section and introduces severe cracking, leading to the observed strength loss. **Figure 5** also indicates that increasing the volume of steel fibers alone did not prevent this strength reduction, confirming that the fundamental issue is pore pressure, not a lack of tensile reinforcement post-cracking.

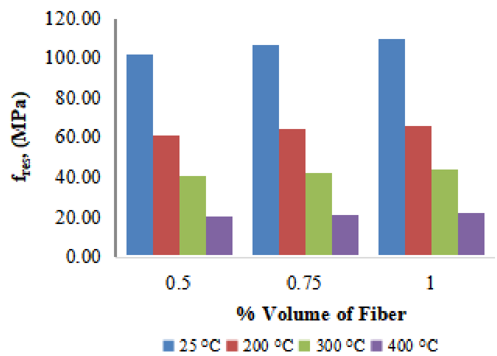

Figure 5. Effect of heating temperature on the compressive strength of steel fiber-only reinforced RPC (1:0 ratio).

Figure 6 illustrates that the increase in heating temperature causes the residual stress of fiber-reinforced RPC to decrease further. This phenomenon is clarified by the regression equation (Equation (3)) showing the decline in RPC compressive strength with increasing heating temperature. This equation has an R^2 near to 1, indicating the validity of the equation.

$$\sigma = -0.2342T + 114.51 \quad (3)$$

Here σ is the compressive strength, T is the temperature, °C.

4.2.2. Performance of Hybrid Steel-PP Fiber-Reinforced RPC

The incorporation of polypropylene fibers into the RPC matrix fundamentally altered its response to high temperatures. At room temperature, as discussed, the hybrid fibers caused a minor (< 10%) strength reduction[8,13] (**Figure 7**), which is generally acceptable for many applications, given the other benefits. This is due to differences in mechanical and physical properties between the two fibers, such as tensile strength, melting point, and density.

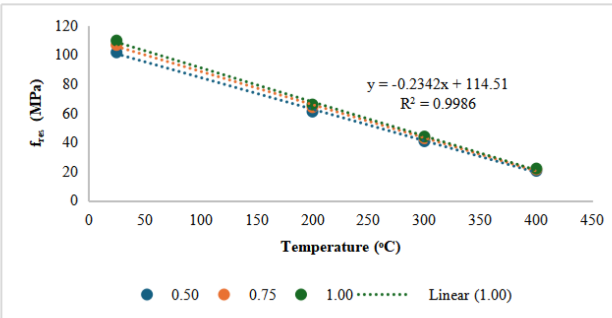

Figure 6. Regression analysis for the relationship between residual strength and temperature (1:0 ratio).

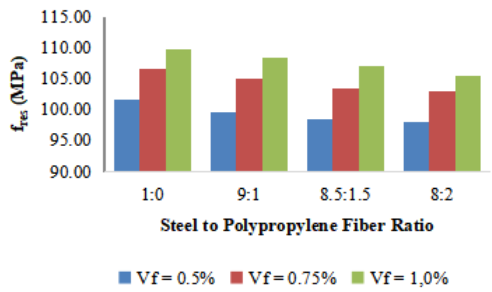

Figure 7. Effect of substituting PP fibres for steel fibres in RPC without thermal loading (at a temperature of 25 °C).

Figure 7 also shows that replacing a greater portion of steel fibers with polypropylene fibers results in a decrease in the compressive strength of steel–polypropylene hybrid fiber-reinforced RPC. However, the partial replacement of steel fibers with polypropylene fibers in RPC has a significant effect on the residual stress of RPC after heating. The effect is that the residual compressive strength of RPC reinforced with a hybrid steel–polypropylene fiber blend after heating is much higher compared to RPC reinforced solely with steel fibers. The results of this study are consistent with the findings reported by He et al. [30] and Ma and Quiel [31].

The true benefit of the hybrid system was revealed under thermal loading, as comprehensively shown in **Figure 8**. The hybrid fiber-reinforced RPC specimens exhibited remarkably higher residual compressive strengths compared to the steel-only counterparts. The residual strengths increased were about 150% (T = 200 °C), 200% (T = 300 °C), and 300% (T = 400 °C), as shown in each subfigure below.

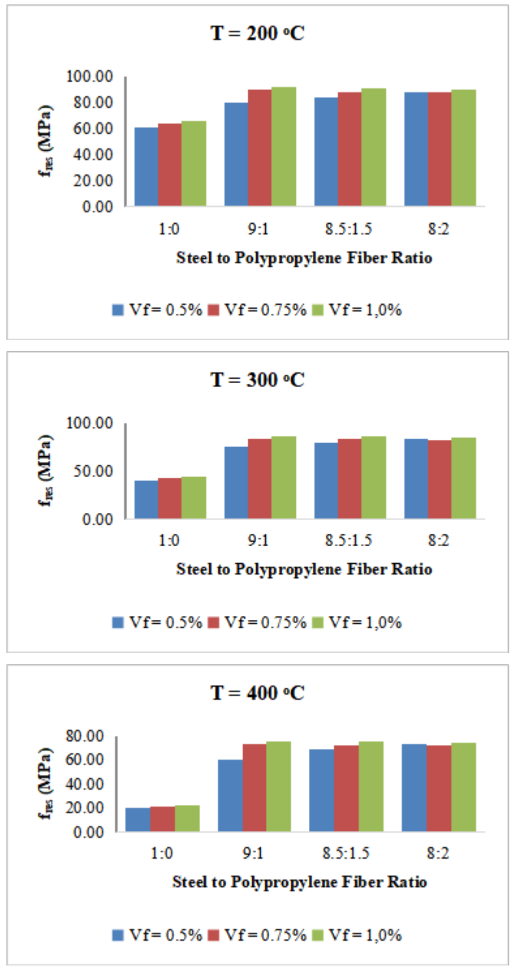

Figure 8. Effect of substituting steel fibres with polypropylene fibres on compressive strength reduction under thermal loading of 200 °C, 300 °C, and 400 °C.

For example, at 400 °C, while the steel-only RPC retained only about 20% of its strength, the hybrid RPC with a Steel: PP ratio of 8:2 and a total fiber volume of 2.0% retained over 85–90% of its original compressive strength. This is a profound improvement. The mechanism is elegantly simple yet highly effective. As the temperature rises during heating, the PP fibers melt at around 165 °C [9,16]. Their melting creates a network of interconnected microchannels and voids throughout the concrete matrix. These channels act as pressure-relief valves, providing escape routes for the expanding water vapor and trapped air. This process drastically reduces the internal pore pressure well before it reaches a critical level that would cause spalling. The addition of polypropylene fibers, although it does not increase the mechanical strength at normal temperatures, is highly effective in preventing explosive spalling during rapid temperature rise due to the vapor escape channels formed when the PP fibers melt [30]. **Figure 9** depicts the condition of the specimens after 2 h burning at 400 °C.

Figure 9. Spalling on the surface of steel fiber–reinforced RPC after burning at 400 °C for 2 hours.

Figure 10 shows the effect of partially replacing steel fibers with polypropylene fibers, indicating a significant increase in the residual compressive strength compared to the steel fiber-reinforced RPC after heating. The microstructural evolution of RPC reinforced with hybrid steel-polypropylene fiber under increasing temperatures involves thermal expansion, phase transformations, and the progressive degradation of the fiber-matrix bond. At 200 °C, steel fibers undergo thermal expansion, generating internal stresses within the matrix due to the mismatch in thermal expansion coefficients [30]. This differential expansion weakens the interfacial bond between the fibers and the matrix. At 300 °C, continued thermal expansion of the steel fibers exacerbates interfacial debonding from the matrix, leading to more pronounced crack formation around the fibers due to increased internal stress. Oxidation accelerates, with iron oxides becoming more prominent on the fiber surface. By 400 °C, the bond strength between steel fibers and the matrix deteriorates significantly due to thermal mismatch and decomposition of hydration products. The spalling process has been mitigated because the air trapped in the pores has escaped through the channels left by the polypropylene fibers. The steel fibers experience surface roughening and the formation of an oxide scale, with extensive oxidation. As the oxide layer thickens, the mechanical interlock between steel fibers and the matrix diminishes. Additionally, carbon diffusion into the oxide layer may occur, altering the steel's microstructural properties and further compromising its mechanical performance [30,32].

The microstructural evolution of polypropylene fibers under elevated temperatures progresses through distinct stages, including softening, melting, and decomposition of PP fibers. At 200 °C, polypropylene fibers begin to melt, forming voids [30–32]. This process generates capillary channels, enhancing permeability and reducing the risk of explosive spalling in high-temperature conditions. As the temperature rises, PP fibers may further undergo drainage or redistribution within the matrix, with the polymer persisting in liquid form within microvoids. Heat-induced polymer chain scission accelerates degradation, releasing low-molecular-weight hydrocarbons and volatile organic compounds (VOCs) [33]. The enhanced thermal resistance of polypropylene fiber at 400 °C may be attributed to the effectiveness of crack formation facilitated by PP fiber melting. The creation of numerous smaller cracks prevents the propagation of larger, more detrimental cracks, thereby preserving structural integrity. Additionally, upon cooling, the residual molten polypropylene finer may fill and bridge microcracks, further contributing to the thermal resilience.

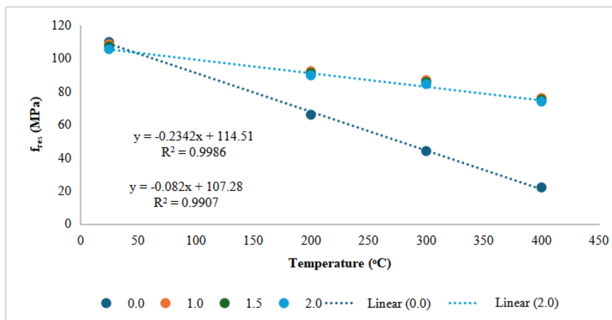

Figure 10. Effect of substituting steel fibres with polypropylene fibres on residual compressive strength.

Unlike steel fibers, polypropylene fibers had a negligible impact on the compressive strength of fiber-reinforced RPC under ambient conditions. However, they played a crucial role in enhancing the thermal resistance of fiber-reinforced RPC, allowing it to withstand temperatures up to 400 °C. With an optimal polypropylene fiber content of 15–20%, polypropylene fibers contributed to structural resilience until elevated temperatures of 400 °C.

By preventing explosive spalling and minimizing internal microcracking due to pressure, the structural integrity of the RPC matrix is largely preserved [30–32]. The remaining steel fibers then continue to perform their function of providing ductility and residual strength. The results indicate that a higher volume of polypropylene fibers (e.g., 15–20% of the total fiber volume) is more effective, as shown in **Figure 11**.

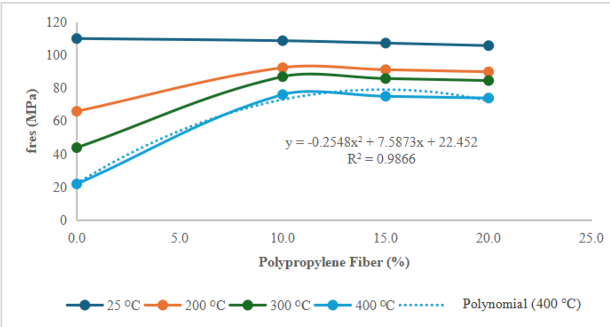

Figure 11. The effect of polypropylene fiber volume on the residual stress after heating.

This synergistic combination addresses the two main aspects of fire resistance: first, preventing the initial, catastrophic damage (spalling) via the polypropylene fibers, and second, maintaining structural capacity after the fire event via the steel fibers. This finding is highly significant for the practical application of RPC in fire-resistant design.

The above explanation indicates that the residual compressive strength of hybrid fiber-reinforced RPC is influenced by three factors: first, the heating temperature; second, the total fiber volume; and third, the volume of steel fibers replaced by polypropylene fibers. Mathematically, this can be expressed as follows:

$$f(T, V_f, V_p) = 0 \tag{4}$$

The equation represents a state equation function that can be mathematically solved using partial differentials as follows:

$$f_{res} = \left(\frac{\partial f_{res}}{\partial T}\right)_{V_f, V_p} \delta T + \left(\frac{\partial f_{res}}{\partial V_f}\right)_{T, V_p} \delta V_f + \left(\frac{\partial f_{res}}{\partial V_p}\right)_{T, V_p} \delta V_p \tag{5}$$

The solution of the partial differential equation is

$$f_{res} = \beta_0 + \beta_1 V_f + \beta_2 V_p + \beta_4 T \tag{6}$$

Where, f_{res} = residual compressive strength, T = temperature, V_f = fiber volume, Vp = polypropylene volume, β_0, β_1, β_2, β_3, β_4 = regression coefficients. $\beta_0 = 123.41$, $\beta_1 = -20.63$, $\beta_2 = 7.54$, $\beta_3 = -0.245$, with determination coeficien R^2 = 0.8228.

A multiple linear regression analysis was performed to evaluate the influence of fiber volume fraction (V_f), steel–PP fiber ratio (V_p), and temperature (T) on the residual compressive strength of Reactive Powder Concrete (RPC). The model in Equation (6) indicates that *temperature* has a strong negative effect, showing a consistent reduction of approximately 2.59 MPa per 100 °C increase, confirming the sensitivity of RPC to thermal degradation. In contrast, both fiber volume (V_f) and hybridization ratio (V_p) contribute positively to the residual strength. The coefficient of $V_f = +10.58$ suggests that adding fiber volume significantly enhances the strength retention capability, especially under elevated temperatures. Likewise, the positive coefficient of $V_p = +4.72$ demonstrates that increasing the proportion of polypropylene fibers relative to steel fibers improves thermal resistance, most likely due to the formation of vapor escape channels once PP fibers melt. The coefficient of determination ($R^2 = 0.828$) shows that the regression model explains approximately 82.8% of the total variability in the experimental data. This indicates a strong predictive capacity for an empirical model derived from a limited dataset. The result supports the suitability of the model for describing the thermal behavior of hybrid-fiber RPC and for estimating compressive strength degradation across different heating levels.

5. Conclusions

Based on the experimental investigation and analysis conducted in this study, the following conclusions can be drawn:

1. The incorporation of fibers significantly influences the mechanical properties of Reactive Powder Concrete (RPC). At room temperature, the compressive strength of RPC increases with the volume of steel fibers, with strengths of 101.6 MPa, 106.68 MPa, and 109.73 MPa achieved for steel fiber volumes of 0.5%, 0.75%, and 1.0%, respectively. This is due to the crack-bridging and confinement effect provided by the fibers. However, the partial substitution of steel fibers with polypropylene fibers leads to a slight reduction in room-temperature compressive strength (up to ~10%), attributable to the lower tensile strength and weaker bond characteristics of polypropylene.
2. Exposure to elevated temperatures has a devastating effect on steel fiber-reinforced RPC due to its dense microstructure, which leads to the buildup of internal

pore pressure and consequent explosive spalling. The residual compressive strength of steel fiber-only RPC plummeted to approximately 60% at 200 °C, 40% at 300 °C, and only 20–25% at 400 °C of its original strength. Increasing the volume of steel fibers alone did not mitigate this strength loss.

3. The hybrid reinforcement of RPC with a combination of steel and polypropylene fibers proves to be a highly effective strategy for enhancing fire resistance. The polypropylene fibers melt at around 165 °C, creating a network of microchannels that allows trapped moisture and air to escape, thereby preventing the buildup of destructive internal pressure and eliminating spalling. As a result, hybrid fiber-reinforced RPC specimens retained 80% to 90% of their original compressive strength after exposure to temperatures as high as 400 °C.
4. The optimal performance under fire conditions was observed with a hybrid fiber system containing 15–20% polypropylene fibers by volume of total fibers. This proportion provides sufficient channels for pressure release without excessively compromising the room-temperature mechanical properties. This research successfully demonstrates that a hybrid steel-polypropylene fiber system can overcome the critical vulnerability of RPC to spalling under high temperatures, thereby significantly broadening its potential for use in structures where fire resistance is a major design consideration, such as in buildings, tunnels, and industrial facilities.
5. The limitation of the use of polypropylene fibers is a maximum of 20% of the total fiber content because the compressive strength continued to decrease as the polypropylene proportion increased.
6. The limitation of the available equipment prevented us from conducting microstructural examinations using either SEM, TGA, or DTA.
7. The regression model demonstrates that temperature is the dominant factor causing reductions in compressive strength of RPC, while the addition of steel–polypropylene hybrid fibers substantially improves thermal resistance. The positive contributions of both fiber volume fraction and hybridization ratio confirm that polypropylene plays a key role in mitigating internal vapor pressure through micro-channel formation. With an R^2 value of 0.828, the model provides a reliable empirical tool for predicting the residual compressive strength of hybrid-fiber RPC exposed to elevated temperatures. This model can therefore serve as a preliminary basis for structural fire-resistance evaluations and for optimizing fiber compositions in high-performance concrete subjected to thermal loads.

Author Contributions

Conceptualization, W.K. and D.C.; methodology, W.K.; validation, W.K., A.P. and D.C.; formal analysis, W.K. and A.P.; investigation, W.K.; writing—original draft preparation, W.K.; writing—review and editing, A.P., D.C., and A.S.; visualization, A.S. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, Contract no: 829/LL3/AL.04/2024.

Institutional Review Board Statement

Not Applicable.

Informed Consent Statement

Not Applicable.

Data Availability Statement

Data will be made available on request.

Acknowledgments

The authors are grateful for the support of the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia, Contract no: 829/LL3/AL.04/2024. The material sponsorship from PT. Indocement Tunggal Prakasa, Tbk and the research facilities in the concrete laboratory of Universitas Tarumanagara are also acknowledged.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

[1] Kushartomo, W., Christianto, D., 2015. Effect of Local Fibres on the Compressive and Flexural Strength of Reactive Powder Concrete with Steam Curing Technique. Journal of Civil Engineering. 22(1), 31–36. DOI: https://doi.org/10.5614/jts.2015.22.1.4 (in Indonesian)

[2] Kushartomo, W., Christianto, D., Suryani, J., 2016. Effect of Steel Fibre Use on the Flexural Toughness of Reactive Powder Concrete. Journal of Civil Engineering. 23(2), 107–112. DOI: https://doi.org/10.5614/jts.2016.23.2 (in Indonesian)

[3] Alkhaly, Y.R., Hasan, M., 2022. Characteristics of Reactive Powder Concrete Comprising Synthesized Rice Husk Ash and Quartzite Powder. Journal of Cleaner Production. 375, 134154. DOI: https://doi.org/10.1016/j.jclepro.2022.134154

[4] Liu, M., Dai, W., Zhong, C., Yang, X., 2023. Study on Mechanical Properties and Microstructure of Manufactured Sand Reactive Powder Concrete with Different Curing Methods. Materials Letters. 335, 133818. DOI: https://doi.org/10.1016/j.matlet.2023.133818

[5] Bentur, A., Mindess, S., 2006. Fibre Reinforced Cementitious Composites. CRC Press: London, UK.

[6] Clyne, T.W., Hull, D., 2019. An Introduction to Composite Materials. Cambridge University Press: Cambridge, UK.

[7] Fu, Y., Li, L., 2011. Study on Mechanism of Thermal Spalling in Concrete Exposed to Elevated Temperatures. Material and Structures. 44, 361–376. DOI: https://doi.org/10.1617/s11527-010-9632-6

[8] Hiremath, P., Yaragal, S.C., 2023. Performance of Polypropylene and Polyester Fibres-Reinforced Reactive Powder Concretes at Elevated Temperatures. Construction and Building Materials. 373, 130862. DOI: https://doi.org/10.1016/j.conbuildmat.2023.130862

[9] Kočí, V., Vejmelková, E., Koňáková, D., et al., 2023. Basic Physical, Mechanical, Thermal and Hygric Properties of Reactive Powder Concrete with Basalt and Polypropylene Fibres after High-Temperature Exposure. Construction and Building Materials. 374, 130922. DOI: https://doi.org/10.1016/j.conbuildmat.2023.130922

[10] Kathirvel, P., Murali, G., 2023. Effect of Using Available GGBFS, Silica Fume, Quartz Powder and Steel Fibres on the Fracture Behavior of Sustainable Reactive Powder Concrete. Construction and Building Materials. 375, 130997. DOI: https://doi.org/10.1016/j.conbuildmat.2023.130997

[11] Arfa, M.M., Sadawy, M.M., Nooman, M.T., et al., 2022. The Influence of Heating on Mechanical and Nuclear Properties of Reactive Powder Concrete as a Protective Shield in Nuclear Facilities. Progress in Nuclear Energy. 143, 104046. DOI: https://doi.org/10.1016/j.pnucene.2021.104046

[12] Canbaz, M., 2014. The Effect of High Temperature on Reactive Powder Concrete. Construction and Building Materials. 70, 508–513. DOI: https://doi.org/10.1016/j.conbuildmat.2014.07.097

[13] Alhasanat, M., Qadi, A., Khashman, O., et al., 2016. Scanning Electron Microscopic Evaluation of Self-Compacting Concrete Spalling at Elevated Temperatures. American Journal of Engineering and Applied Sciences. 9(1), 119–127. DOI: https://doi.org/10.3844/ajeassp.2016.119.127

[14] Zaid, O., Althoey, F., Abuhussain, M.A., et al., 2024. Spalling Behavior and Performance of Ultra-High-Performance Concrete Subjected to Elevated Temperature: A Review. Construction and Building Materials. 411, 134489. DOI: https://doi.org/10.1016/j.conbuildmat.2023.134489

[15] Ashteyat, A., Shhabat, M., Alkhalaileh, A., et al., 2025. Behavior of Ultra-High-Performance Concrete under Elevated Temperatures: A Comprehensive Review of Mechanical, Physical, Thermal, and Microstructural Properties. Results in Engineering. 26, 104960. DOI: https://doi.org/10.1016/j.rineng.2025.104960

[16] Chen, G., He, Y., Yang, H., et al., 2014. Compressive Behavior of Steel Fibre Reinforced Recycled Aggregate Concrete after Exposure to Elevated Temperatures. Construction and Building Materials. 71, 1–15. DOI: https://doi.org/10.1016/j.conbuildmat.2014.08.012

[17] Li, H., Hao, X., Liu, Y., Wang, Q., 2021. Thermal Effects of Steel-Fibre-Reinforced Reactive Powder Concrete at Elevated Temperatures. Magazine of Concrete Research. 73(3), 109–120. DOI: https://doi.org/10.1680/jmacr.19.00105

[18] Zhao, T., Du, H., Ding, M., Wang, C., 2023. Fracture Properties of Plastic-Steel Fiber High-Performance Concrete after High-Temperature Exposure. Journal of Physics: Conference Series. 2463(1), 012031. DOI: https://doi.org/10.1088/1742-6596/2463/1/012031

[19] Du, X., Chen, Y.L., Li, Y.C., et al., 2014. Mechanical Properties of Polypropylene Fibre Concrete after High Temperature. Applied Mechanics and Materials. 662, 24–28. DOI: https://doi.org/10.4028/www.scientific.net/amm.662.24

[20] Zheng, W., Li, H., Wang, Y., 2012. Compressive Behaviour of Hybrid Fibre-Reinforced Reactive Powder Concrete after High Temperature. Materials & Design. 41, 403–409. DOI: https://doi.org/10.1016/j.matdes.2012.05.026

[21] Li, H., Liu, G., 2016. Tensile Properties of Hybrid Fibre-Reinforced Reactive Powder Concrete after Exposure to Elevated Temperatures. International Journal of Concrete Structures and Materials. 10(1), 29–37. DOI: https://doi.org/10.1007/s40069-016-0125-z

[22] Mao, Z., Zhang, J., Ma, Q., et al., 2022. Performance Evaluation of Fibre-Reinforced Reactive Powder Concrete Exposed to High Temperature Combining Nondestructive Test. Journal of Building Engineering. 61, 105266. DOI: https://doi.org/10.1016/j.jobe.2022.105266

[23] Abid, M., Hou, X., Zheng, W., et al., 2019. Effect of Fibres on High-Temperature Mechanical Behavior and Microstructure of Reactive Powder Concrete. Materials. 12(2), 329. DOI: https://doi.org/10.3390/ma12020329

[24] Liu, M., Dai, W., Zhong, C., et al., 2022. Study on Mechanical Properties and Microstructure of Basalt Fibre Reactive Powder Concrete. Buildings. 12(10), 1734. DOI: https://doi.org/10.3390/buildings12101734

[25] Li, F., Lv, T., Wei, S., 2023. Performance, Mechanical Properties and Durability of a New Type of UHPC—Basalt Fiber Reinforced Reactive Powder Concrete: A Review. Polymers. 15(14), 3129. DOI: https://doi.org/10.3390/polym15143129

[26] Helmi, M., Alraimi, A.A.Q., 2024. Effects of Carbon Fibre on Mechanical Properties of Reactive Powder Concrete. Journal of the Civil Engineering Forum. 10(3), 239–248. DOI: https://doi.org/10.22146/jcef.12439

[27] Yang, K., Su, H., Dai, T., et al., 2023. Experimental Study on the Flexural Tensile Properties of Aligned Steel Fibre–Reinforced Reactive Powder Concrete Members. Structural Concrete. 24(1), 1486–1502. DOI: https://doi.org/10.1002/suco.202200172

[28] Ahmed, S., Abed, F., Mannan, M., 2022. Compressive Strength Development of Dune Sand Reactive Powder Concrete under Different Curing Conditions. IOP Conference Series: Earth and Environmental Science. 1026(1), 012017. DOI: https://doi.org/10.1088/1755-1315/1026/1/012017

[29] ASTM C39/39M, 2021. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Available from: https://store.astm.org/c0039_c0039m-20.html (cited 1 August 2025).

[30] He, F., Biolzi, L., Carvelli, V., et al., 2024. A Review on the Mechanical Characteristics of Thermally Damaged Steel and Polypropylene Hybrid Fiber-Reinforced Concretes. Archives of Civil and Mechanical Engineering. 24, 69. DOI: https://doi.org/10.1007/s43452-024-00880-2

[31] Ma, S., Quiel, S., 2023. Fire Resistance of Tunnel Liners with Steel and Polypropylene Fibers. Final Project Report. University Transportation Center for Underground Transportation Infrastructure: Golden, CO, USA. pp. 1–41. Available from: https://rosap.ntl.bts.gov/view/dot/83645/dot_83645_DS1.pdf

[32] Shiri, A.A.A., Darbhanzi, A., 2025. Experimental Study on the Elevated Temperature Performance of Composite Reactive Powder Concrete with Polypropylene Fiber—A Case Study. Journal of Building Pathology and Rehabilitation. 10, 67. DOI: https://doi.org/10.1007/s41024-025-00574-z

[33] Li, Z., Wei, X., Liu, J., et al., 2021. Mechanical Properties and VOC Emission of Hemp Fibre Reinforced Polypropylene Composites: Natural Freezing-Mechanical Treatment and Interface Modification. Fibers and Polymers. 22(4), 1050–1062. DOI: https://doi.org/10.1007/s12221-021-0052-8