Original Article

Investigating the behaviour of hybrid fibre-reinforced reactive powder concrete beams after exposure to elevated temperatures

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\textbf{A B S T R A C T}

This study investigated the structural behaviour of reinforced reactive powder concrete (RPC) beams under service load and fire exposure. The beams were composed of hybrid fibres (50% polypropylene fibres and 50% steel fibres) at different volume fractions relative to nonfibrous-reinforced RPC beams. The bottom and both sides of the beams which were simply supported and loaded with two-point loads were exposed to a controlled fire for 120 min in accordance with ASTM E 119 standard time–temperature curve. The midspan deflection was recorded every 5 min. The experiment also included loading tests on fire-damaged beams after cooling. The nonfibrous-reinforced RPC beams failed during the fire test after 38 min because of the spalling of the reinforcement cover which directly exposed the reinforcing steel to elevated temperatures. By contrast, the beams with hybrid fibres could resist failure during the entire test period. The rate of increase in deflection during fire exposure declined with an increase in hybrid fibre content. Increases in fibre volume fraction from 0.25% to 0.75% and 1.25% decreased the midspan deflection of the reinforced RPC beams by 33% and 36%, respectively. Adding hybrid fibres could considerably improve the residual stiffness of fire-damaged beams.

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1. Introduction

Reactive powder concrete (RPC) is an ultra-high-performance concrete that exhibits excellent mechanical properties and durability characteristics because of its homogeneity, dense microstructure and fibre content [1–5]. Established in the 1990s by French Bouygues Company [6,7], RPC has gained considerable attention due to its excellent durability, high tensile strain and toughness [8–10]. Moreover, RPC is extensively used in structural members, such as high-rise buildings, long-span bridges, piles and deep underground constructions, due to its high strength which greatly reduces dead load and the cross section of structural members [11–14]. Understanding RPC behaviour under different loading conditions is essential...
prior to its practical applications [3,15]. RPC is used widely in construction projects, such as infrastructure projects, bridges, chemical plants and offshore structures, due to its remarkable structural advantages that are unavailable in normal-strength concrete [16]. Khuzae and Ataie [17] used reactive powder concrete to investigate a hollow reinforced concrete T-beams. They used 0–2% steel fibers in concrete mixtures to enhance the ultimate torque of the concrete beams. Nonetheless, the increasing use of RPC in construction projects has raised concerns regarding the fire behaviour of the concrete, especially the phenomenon of spalling [18]. Therefore, several researchers have recommended the addition of polypropylene (PP) fibers (PPFs) or steel fibers to prevent spalling in RPC [19–24].

The term ‘reactive powder concrete’ has been used to describe a superplasticiser, silica fume, cement and very fine sand (<=0.6 mm) mixture with extremely low water–cement ratio [25]. Many studies on RPC have focused on its mechanical properties at room temperature [21,26,27]; other studies on the properties of RPC have been conducted at high temperatures [21,24,28–30]. For example, Kang et al. [31] used rice husk ash to improve the mechanical properties of RPC at room temperature, especially at long-term curing ages. These authors obtained a 28-day strength of 145 MPa. Canbaz [24] achieved a high compressive strength (more than 200 MPa) after exposing concrete samples to 20 °C, 100 °C, 400 °C, 700 °C and 900 °C for 3 h. When RPCs are subjected to high temperatures (fire), numerous complex physicochemical reactions occur and consequently deteriorate the mechanical properties. The main effects of fire include reduced compressive strength, cracking and spalling of concrete [32]. Spalling is common in RPC and can be highly dangerous [33,34]; it is mainly caused by a build-up of pore water pressure within the RPC’s low-permeability microstructure during heating (or thermal stress) [35]. Recent studies have reported that concrete spalling occurs due to increases in internal pressure, thermal cracking and thermal stresses [36,37]. Dong et al. [38] enhanced reinforced RPC using fine stainless wire and noted that adding stainless wire increases the resistance of RPC to crack expansion.

The use of PPFs is a feasible procedure to reduce the risk of spalling [36,39]; these fibres slightly affect the mechanical properties of RPC, but they considerably reduce the spalling tendency of RPC at elevated temperatures [36,40–42]. PPFs melt under 170 °C and create channels through which water vapour pressure builds up within RPC with an increase in temperature [43]. Hiremath and Yaragai [42] investigated the performance of RPC at elevated temperatures between 200 °C and 800 °C by recording the residual mechanical properties after exposure to high temperature. Results demonstrated that 0.1% of fibre content is sufficient to control the spalling of RPC at temperatures reaching 800 °C. The presence of steel fibres can substantially improve the compressive and tensile strengths of RPC at room temperature [20]; therefore, steel fibres can increase the concrete’s resistance to thermal stresses and overcome vapour pressure build-up under high temperatures [44]. When RPC is mixed with PP and steel fibres, its mechanical properties can be enhanced [23], and spalling can thus be prevented [45]. The performance of RPC as a part of a structure at elevated temperatures must be assessed. Loaded reinforced concrete beams exhibit downward thermal bowing when the bottom and both sides are exposed to fire. The nonlinear temperature gradients in a beam’s cross section cause additional deflection. The temperature rise in the beam’s cross section leads to a high reduction in the strengths of RPC and steel reinforcement, thereby causing additional deflection and a considerable decrease in beam stiffness [46]. Conversely, the phenomenon of spalling causes the pieces of concrete to break off from the surface; this condition reduces the cross section of a structural element and possibly exposes the reinforcing steel to high temperatures [47]. The present study applies the transient temperature test which includes applying a constant load (service load) and heating reinforced RPC beams until failure occurs or until the end of test time. This test is the most suitable method for assessing the real behaviour of fire-exposed reinforced RPC beams. This study investigates the effects of hybrid fibres (50% PPFs and 50% steel fibres) at different volume fractions (0%, 0.25%, 0.75% and 1.25%) on the fire resistance of reinforced RPC beams. The residual stiffness and ultimate load capacity of fire-damaged RPC beams after cooling are also investigated. Ozbakalakolu and Lim [48] conducted a comprehensive study to understand the behaviour of fibre-reinforced polymer (FRP)-confined concrete columns. It is shown that the predictions of the proposed model are in close agreement with the test results and the model provides improved predictions of the ultimate conditions of FRP-confined concrete compared to any of the existing models. Islem et al. [49] investigated the influence of larger cross-sectional size and internal steel reinforcement on the stress-strain. The results showed that the stress-strain curves of the monotonically loaded columns exhibited a softening second branch followed by an ascending or about flat third branch. The compressive, flexural, and splitting tensile strengths of RPC containing (50% PPFs and 50% steel fibres) increased gradually with increasing the volume fraction due to adding the steel and PPF fibre as compared with non-fibre RPC. In contrast, the RPC beam without the hybrid fibre has the lowest value of compressive, flexural, and splitting tensile strengths than the other mixtures.

2. Experimental programme

2.1. Materials and mix proportions

The RPC used in this study was manufactured using ordinary Portland cement (ASTM Type I), natural siliceous sand (maximum diameter = 0.6 mm), high-performance superplasticiser (GLENIUM 51), and densified Micro-silica (MEYCO® MS 610) as illustrated in Fig. 1(a and b). Table 1 lists the chemical composition and physical properties of ordinary Portland cement. Table 2 lists the chemical composition and physical properties of densified micro silica. The sieve analysis of the fine aggregate is illustrated in Fig. 2.

Two types of fibre were used: (1) straight steel fibres coated with a thin brass layer (ultimate tensile strength reaching 2600 MPa, diameter of approximately 175 μm and length of approximately 13 mm) and (2) monofilament PPFs (diameter of 18 μm and length of approximately 12 mm), as shown in Fig. 3(a and b). The steel fibre has better tensile strength and modulus of elasticity than PPF. Therefore, the mechani-
Fig. 1 – Superplasticizer (GLENIUM 51) and densified micro silica.

Table 1 – Chemical composition and physical properties of ordinary Portland cement.

<table>
<thead>
<tr>
<th>Limit of Iraqi specification no. 5/1984</th>
<th>Content (%)</th>
<th>Oxides composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>59.19</td>
<td>CaO</td>
</tr>
<tr>
<td>–</td>
<td>4.51</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>–</td>
<td>20.1</td>
<td>SiO₂</td>
</tr>
<tr>
<td>–</td>
<td>3.96</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>5 % Max</td>
<td>3.5</td>
<td>MgO</td>
</tr>
<tr>
<td>2.8 % Max</td>
<td>2.04</td>
<td>SO₃</td>
</tr>
<tr>
<td>4 % Max</td>
<td>3.35</td>
<td>Loss on ignition</td>
</tr>
<tr>
<td>1.5 % Max</td>
<td>–</td>
<td>Insoluble material</td>
</tr>
<tr>
<td>(0.66–1.02)</td>
<td>0.9</td>
<td>Lime saturation factor</td>
</tr>
<tr>
<td>&gt; 5.00</td>
<td>5.25</td>
<td>C₃A</td>
</tr>
<tr>
<td></td>
<td>46.54</td>
<td>C₃S</td>
</tr>
<tr>
<td></td>
<td>22.74</td>
<td>C₃AF</td>
</tr>
<tr>
<td></td>
<td>12.04</td>
<td>Physical properties</td>
</tr>
<tr>
<td>Limit of Iraqi specification No. 5/1984</td>
<td>Tests results</td>
<td>Fineness of hydraulic cement</td>
</tr>
<tr>
<td>&gt; 230 m²/kg</td>
<td>300</td>
<td>Initial setting time</td>
</tr>
<tr>
<td>&gt; 45 min</td>
<td>2h 40 min</td>
<td>Final setting time</td>
</tr>
<tr>
<td>&lt; 10 h</td>
<td>4h 30 min</td>
<td>Compressive strength (MPa) in 3 days</td>
</tr>
<tr>
<td>&gt;15 MPa</td>
<td>17.5 MPa</td>
<td>Compressive strength (MPa) in 7 days</td>
</tr>
<tr>
<td>&gt;23 MPa</td>
<td>28 MPa</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – The physical and chemical properties of microsilica.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Content (%)</td>
<td>0.6–0.8</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.68</td>
</tr>
<tr>
<td>AFS value</td>
<td>34.6</td>
</tr>
<tr>
<td>Chemical composition (%)</td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>98.60</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.12</td>
</tr>
<tr>
<td>MgO</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>0.09</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.02</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.12</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Loi</td>
<td></td>
</tr>
</tbody>
</table>

The physical properties of RPC beams improved due to the addition of steel fibres to the concrete mixtures. The density of PPF is 910 (kg/m³), while the density of steel fibre is 7850 kg/m³ and the tensile strength of PPF is between 320–400 MPa while the tensile strength of steel fibre is 2600 MPa.

The mix proportions used in this study are summarised in Table 3. These proportions can produce RPC with adequate strength and appropriate workability (flow table of 110 ± 5%). The first mixture (M1) was cast without fibre content, whereas the other mixtures (M2, M3 and M4) were cast with different volume fractions of hybrid fibres (0.25%, 0.75% and 1.25%, respectively).
Mixing was performed using a 0.05 m³ horizontal pan-type mixer. The fine sand was added to the mixer. The fibres were slowly added to the rotary mixer to prevent the balling of the fibres. The mixing lasted for 5 min. Required quantities of cement and microsilica were added and mixed for another 5 min. Half of the mixing water was added to the rotary mixer and mixed for 5 min. The superplasticiser and the remaining mixing water were added to the mixture, and the mixing continued for another 5 min. The mixture was placed in moulds and compacted using an internal vibrator (needle vibrator) to decrease the air voids and compress the RPC. The hardened specimens were removed from the moulds after 24 h and cured using hot water (approximately 70 °C) for 3 days. Afterwards, the specimens were placed in water at room temperature and left until the end of water curing (28 days) [50].

### Table 3 – Mix proportions of RPC containing hybrid fibres.

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Fine sand (kg/m³)</th>
<th>Binder materials (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Superplasticiser (kg/m³)</th>
<th>Hybrid fibre (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cement</td>
<td>Micro silica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>1070</td>
<td>963</td>
<td>107</td>
<td>214</td>
<td>32</td>
</tr>
<tr>
<td>M2</td>
<td>1070</td>
<td>963</td>
<td>107</td>
<td>214</td>
<td>32</td>
</tr>
<tr>
<td>M3</td>
<td>1070</td>
<td>963</td>
<td>107</td>
<td>214</td>
<td>32</td>
</tr>
<tr>
<td>M4</td>
<td>1070</td>
<td>963</td>
<td>107</td>
<td>214</td>
<td>32</td>
</tr>
</tbody>
</table>

2.2. **Mechanical properties**

The control specimens for each mix were cast to determine the mechanical properties of the hardened RPC mixes at room temperature. For the compressive, flexural and splitting tensile strength tests, 70 mm cubes, 100 x 100 x 500 mm³ prisms and 150 mm x 300 mm (diameter x length) cylinders were prepared, respectively. A series of tests was conducted to determine the cubic compressive strength (f_c), splitting tensile strength (f_{ct}) and flexural strength (f_f) of RPC at the age of 28 days. The average value of the three specimens for the same mix was adopted for each test.

2.3. **Beam details**

The beams were designed with dimensions that allowed the easiest manufacturing, handling and testing possible. Five reinforced RPC beams, namely, two beams for reference mix (RPC without fibres) and one beam for each of the three mixes, were cast. The cross section (w x h x l) was 150 mm x 200 mm x 2000 mm, and the clear span was 1800 mm. The beams were designed to have extra shear strength to ensure tensile failure. Two steel bars (Ø8 mm, f_y = 4200 MPa) were placed along the lower part of the section to resist the tensile stresses due to bending, whereas Ø6 mm steel bars were used as stirrups (100 mm centre-to-centre spacing) to prevent shear failure. Moreover, two steel bars (Ø6 mm, f_y = 2800 MPa) were placed along the upper part of the section to assist the formation of the required steel cage. The beam details are depicted in Fig. 4.

2.4. **Fire test**

2.4.1. **Test setup**

The fire resistance tests were conducted in a vertical furnace with an external dimension (w x h x l) of 1250 mm x 1250 mm x 2000 mm. The walls were built using ordinary bricks, and the inner wall surface was coated with...
50 mm-thick ceramic wool and 50 mm-thick refractory bricks to achieve favourable heat insulation. The bottom (land) part was constructed using refractory bricks. The top of the oven was covered with two pieces of steel plates and coated with 3 mm-thick ceramic wool as illustrated if Fig. 5 a and b.

The tested beams were placed over the open top of the furnace, in which the axes were aligned to the furnace centre. All beams were simply supported and loaded with two-point loads. A service load was applied by the two sets of weights suspended at the two ends of a load transmission steel beam through tendons and steel frame. A load transmission steel beam was placed over the tested beams. The load at the top face of the reinforced RPC beams was transferred by the two Ø25 mm steel rods welded 600 mm from the support at the bottom of the steel beam (symmetric at the midspan section). The furnace was heated using a gas burner. A digital temperature indicator and type-K thermocouples were used to measure the temperatures at the three points near the beam’s surface and the temperature distribution inside the tested beams. A dial gauge with an accuracy of 0.01 mm was used to measure the midspan deflections of the beams.

### 2.4.2. Test procedure

The fire test was divided into two phases. In the first phase, the beam was loaded by simultaneously placing concrete blocks at both ends of the transmission steel beam. The midspan deflection of the beam versus each load increment was recorded. The tested beams were subjected to a constant applied load (service load) equal to 50% of the ultimate load. Two reference beams were cast—one was for the fire test, and the other was structurally loaded without heating (at room temperature) until failure—to evaluate the flexural behaviour of the reinforced RPC beam and determine the ultimate flexural strength.

In the second phase of the fire test, the furnace gas burner was turned on, and the beam was subjected to increasing temperature. The bottom and both sides of the beam specimens were exposed to a controlled fire for 2h. The furnace temperature was raised in accordance with ASTM E 119 standard time–temperature curve (Fig. 6). The beams were tested until failure or until the end of the test time (2h). During the fire test, the temperature at specific points outside and inside the beams and the midspan deflection readings were recorded at intervals not exceeding 5 min.

### 3. Results and discussion

#### 3.1. Microstructure of RPC beams

This study analysed the microstructure images of RPC beams after exposure to high temperatures using a scanning electron microscope (SEM). Fig. 7 shows that the microstructure of the RPC sample at high temperature was denser than that of the control sample.

The selected images were taken at magnifications of 250×, 500×, 1000× and 2000×, as shown in Fig. 7. SEM test was used in this study to determine the morphology of RPC after exposure to high temperatures. The existence of PPF in RPC led to the formation of different channels due to the melting process of PPF when exposed to high temperatures [42]. Compressive strength test was conducted for all RPC samples with various fibre contents at high temperatures. The compressive strength decreased slightly because of the addition of PPF to the cement. The RPC samples cast with 0.25%, 0.75% and 1.25% had molten channels because of the melting of PPFs. The compressive strength of RPC at 800 °C decreased relative to that of the control sample. This decrease was due to the high density of the internal structure of RPC and the high tem-
temperature accelerating the reaction of materials such that the structure exhibited high density [51,52]. The SEM test was conducted on RPC cubes at temperatures of up to 800 °C to test the microstructure. The test showed numerous cracks because of the thermal expansion of the RPC, resulting in a weak bonding between the cement and the aggregate.

Microcracks occurred, and channels were created by thermal expansion, as observed in the SEM images of RPC. Fig. 7 shows that the RPC with 0.25% PPF content had melted fibre channels because of exposure at high temperatures of up to 800 °C. The RPC with 0.75% and 1.25% PPF had a microcrack in the surface structure and minimal bond in the interface zone between the cement paste and the aggregate. The microstructure of the RPC with 1.25% fibre content illustrated a good interface between the cement paste and the aggregate, but the melting of the fibre created numerous microcracks in the channels. Increased temperature led to continuous weakening; 0.25% fibre content in RPC illustrated weak porous structure and interfacial transition zone (ITZ) between the cement paste and the aggregate at 800 °C. The same results were obtained by Ruan et al. [53]. A dense microstructure and minimum cracks with melted channels were observed in the mix containing 0.25% PPF in RPC at 800 °C. The microstructure of the RPC with 1.25% fibre content had a compressive strength which exceeded that of other PPF contents at high temperatures. The increased number and width of the cracks reduced the compressive strength. Other studies reported that RPC can delay the crack expansion of gaps in nanoparticle sizes. From the economic aspect, this process results in high energy consumption [54–56].

3.2. Mechanical properties

3.2.1. Compressive strength
The results of the 28-day cubic compressive, splitting tensile and flexural strength tests for all mixes are summarised in
Table 4 – Strength of RPC mixes at room temperature.

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>Hybrid fibre (%)</th>
<th>f_{cu} (MPa)</th>
<th>f_{ct} (MPa)</th>
<th>f_{t} (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.00</td>
<td>84</td>
<td>5.9</td>
<td>6.8</td>
</tr>
<tr>
<td>M2</td>
<td>0.25</td>
<td>85</td>
<td>6.3</td>
<td>10.14</td>
</tr>
<tr>
<td>M3</td>
<td>0.75</td>
<td>105.1</td>
<td>7.5</td>
<td>11.24</td>
</tr>
<tr>
<td>M4</td>
<td>1.25</td>
<td>108.6</td>
<td>8.2</td>
<td>12.49</td>
</tr>
</tbody>
</table>

![Fig. 8 – Compressive strength of RPC containing hybrid fibres at 28 days.](image1)

![Fig. 9 – Splitting tensile strength of RPC containing hybrid fibres at 28 days.](image2)

The compressive strengths for the fraction volumes 0.25%, 0.75% and 1.25% were 85, 105.1 and 108.6 MPa, respectively. The same results were found by Hiremath and Yaragal [42]. Increasing of fibre dosage leads to an increased compressive strength value and reduces the spalling phenomenon and improves concrete strength at elevated temperatures. Compressive strength also increases with enhanced hydrated cement paste after evaporation of free water [57]. The compressive strength values of RPC at 200 °C were 108, 112 and 118 MPa for the fibre dosages of 0.1%, 0.5% and 0.5%, respectively. Ahmad et al. [58] used a 75 x 150 mm cylinder to determine compressive strength in accordance with ASTM C 39 [38]. The compressive strength increased from 143 MPa to 155 MPa for the RPC containing 50 and 200 kg/m³ of steel fibres.

3.2.2. Splitting tensile strength

The splitting tensile strengths of RPC reinforced with hybrid fibre contents of 0.25%, 0.75% and 1.25% at room temperature are listed in Table 4. The difference in the splitting tensile strength values is also illustrated in Fig. 9. The increased fibre content led to increased splitting tensile strength at room temperature. The fibre contents of 0.25%, 0.75% and 1.25% had high splitting tensile strength values of 6.3, 7.5 and 8.2 MPa, respectively. The splitting tensile strengths for 0.1, 0.5 and 0.9 fibre dosages were 5.25, 9.8 and 10.99 MPa, respectively, in the study conducted by Hiremath and Yaragal [42].

3.2.3. Flexural strength

The flexural strengths of RPC reinforced with hybrid fibre contents of 0.25%, 0.75% and 1.25% at room temperature are listed in Table 4. The variation in flexural strength values is shown in Fig. 10. The increased fibre content resulted in increased flexural strength at room temperature. The fibre contents of 0.25%, 0.75% and 1.25% had high flexural strength values of 10.14, 11.24 and 12.49 MPa, respectively.

This phenomenon was due to the combined effect of PPFs on the reduction of plastic shrinkage cracking at the concrete’s early age and the effect of steel fibres on the arrest of cracks that developed when the RPC specimen was subjected to an external load. This effect has also been observed by other researchers [59,60]. Tai et al. [21] determined that fire-exposed (200 °C–400 °C) RPC samples with 1% steel fibre content exhibited higher compressive strength than samples at room temperature. Zheng et al. [30] investigated the mechanical properties of steel fibre-reinforced RPC at temperatures between 200 °C and 900 °C. These authors observed that the increase in compressive stress–strain curves does not affect the sample at temperatures less than or equal to 300 °C. Huynh et al. [61] concluded that the failure mode in static tests affects the flexural strength of RPC samples.

The weights of polypropylene and steel fibers in the mix were calculated using the following equation [45]

$$W_f = \frac{V_f D_f}{V_m D_m}$$

where:

- \(W_f\): Fiber weight as a proportion of the weight of the concrete matrix.
- \(V_f\): Fiber volume as a proportion of the whole composite volume.
- \(D_f\): Fiber density (kg/m³).
- \(V_m\): Matrix volume as a proportion of the whole composite volume.
- \(D_m\): Matrix density (kg m³).
Fig. 11 – Load–deflection curve of reference reinforced RPC beam.

Fig. 12 – Effects of hybrid fibres on crack load of RPC beams.

3.3. Structural behaviour of reference beam at room temperature

The load versus midspan deflection of the reference reinforced RPC beam (without fibres) tested under four-point loading until failure is plotted in Fig. 11. In the first stage, the load–deflection curve was linear until the appearance of the first cracks at the bottom of the intermediate region between the two loading points in the tension zone as presented before by Shao et al. [62]. In the second stage, the propagation of the cracks caused further loss of initial stiffness, and nonlinear behaviour was observed up to the yielding of the longitudinal steel reinforcement. The third stage began with the yielding of the steel bars and ended with the beam failure. The stiffness of the beam in this stage was weakened, and failure occurred when the concrete in the compression zone was crushed as presented by Sanchayan and Foster [23]. Isleem et al. [63] investigated the closed-form expressions to predict the stress-strain response of concrete columns. The results show that the model gave a good description of the stress-strain behaviour of concrete columns with various arrangements of hoops. The crack load \( P_{cr} \), yield load \( P_y \) and ultimate load \( P_u \) were 14.7, 36 and 44.1 kN, are extracted from Fig. 11. The reduction in the flexural ultimate strength from 44.1 kN to 22.1 kN was due to expose the specimen to high temperature, therefore the reduction of flexural strength was half value. Fig. 12 show the effects of hybrid fibres on crack load of RPC beams.

Under service loads, normal beams would be under a cracked elastic condition. In this study, a service load of 22.14 kN which was approximately 50% of the ultimate load was selected for the fire test.

Fig. 13 – Load–deflection curve of reinforced RPC beams under service load.

Fig. 14 – Deflection–fire time curves of reinforced RPC beams.

<table>
<thead>
<tr>
<th>Table 5 – Beam test results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam no.</td>
</tr>
<tr>
<td>B1</td>
</tr>
<tr>
<td>B2</td>
</tr>
<tr>
<td>B3</td>
</tr>
<tr>
<td>B4</td>
</tr>
</tbody>
</table>

B1 failed during the fire test.

3.4. Fire resistance of reinforced RPC beams

The load–midspan deflection curves for all RPC beams subjected to two-point load increment up to 22.14 kN during the first phase of the fire test are illustrated in Fig. 13. The midspan deflection–fire time curves of the fire-exposed RPC beams under service load are presented in Fig. 14. Table 5 presents the first \( P_{cr} \) of the RPC beams, the deflection at the service load (\( \delta_s \)) during structural loading and the total deflection at the end of fire time (\( \delta_f \)).

The results showed that adding hybrid fibres substantially affected the load–deflection curve before and after cracking. \( P_{cr} \) increased, whereas \( \delta_s \) decreased. The incorporation of PP and steel fibres led to an increase in the compressive strength, thus increasing the elastic modulus and the tensile strength of RPC. However, these fibres bridged the cracks and transmitted tensile stress across cracks, thereby improving the stiffness of the beam before and after cracking.

When the reference RPC beam under service load was exposed to elevated temperature (fire) in the second phase
of the test, a sharp increase in deflection could be observed from the beginning of the test, and cracking and popping sounds due to spalling could be heard after 7 min. The spalling continued during the test, thereby resulting in the disappearance of concrete cover and then the direct exposure of the steel reinforcement to fire. This result led to a high reduction in the strength of the steel reinforcement. Shortly after the spalling of the concrete cover, the beam failed under the sustained applied load, and the test was stopped at approximately 38 min.

B2 demonstrated reduced spalling and enhanced fire resistance. During the fire test, the beam gradually lost its rigidity and thus exhibited a lower increase in deflection than the reference RPC beam under the same applied load within the same test period. By contrast, B3 and B4 prevented spalling in RPC, which led to a further increase in fire resistance and a decrease in deflection. All hybrid fibre-reinforced RPC beams did not fail until the end of the fire test. This outcome could be attributed to the combined effect of PP and steel fibres on the enhancement of the RPC’s resistance to spalling. Previous research indicated that incorporating PP and steel fibres can effectively improve the compressive and tensile strengths of RPC at elevated temperatures [7,64]. The thermocouples recorded the progression of heat throughout the beam’s cross section during the heating of the bottom and both sides. Fig. 15 demonstrates the temperature–time curves at different locations within the beams. The appearance of the reinforced RPC beams upon cooling is presented in Figures 14, 15 and 16. Fig. 16 shows the reference RPC specimen without fibre, while the volume of fibres 0.25, 0.75, and 1.25% presented in the Figs. 16(b, c, and d), respectively.

3.5. Structural behaviour of fire-damaged RPC beams

All RPC beams that did not fail during the fire test were reloaded with two-point loads until failure to quantify the structural capacities of the fire-damaged RPC beams after cooling. Ultimate loads and beam deflections were measured and examined. The experimental results showed that substantial damage occurred in the reinforced RPC beams after being exposed to elevated temperatures and then cooled to room temperature. Table 6 presents the damaged RPC beam’s δs, ultimate deflection (δu) and Pu. δs was higher in the damaged beams than in the undamaged beams given the reduced stiffness of the former. The stiffness of the beam was defined from the slope of the load–deflection curve. The load–deflection curves of the damaged beams (B2, B3 and B4) are displayed in Fig. 13. The reference beam without the hybrid fibres has a deflection rate more than other beams containing the hybrid fibres. Therefore, the hybrid fibres contributed to decreasing the deflection rate in the beams during exposing to the service load. Kamal et al. [65] concluded that the use of PPF and steel fibres increased the compressive strength in 28 days by 2.5 if compared to the concrete mix without fibres. The residual stiffness and ultimate load capacity of the fire-damaged RPC beams increased with the hybrid fibre content. This outcome might be attributed to the combined effect of the PPF and steel fibres on the reduction of damage and prevention of spalling in RPC beams during the entire fire test.

The bottom and the sides of the RPC beam were exposed to fire whilst the top face was exposed to free air cooling (natural convection). Thus, the main damage occurred in the tension zone of the concrete. The residual tensile strength of RPC was reduced, and a remarkable loss of bond between the reinforcing steel and RPC was observed. However, in all beams that did not suffer significant spalling, the temperature at the bottom steel bars did not exceed 450 °C. Previous research indicated that reinforcing steel recovers most of its mechanical properties after cooling when exposed to this level of elevated temperature [36,40]. Bae et al. [66] concluded that bond strength increases with concrete cover, whereas the increasing rate of bond strength consequently decreases. Although the decrease in the tensile strength of RPC slightly affected the overall stiffness of the reinforced RPC beam, the weak bond strength between the RPC and the reinforcing steel mainly explained the significant stiffness reduction in the damaged beam.
4. Conclusions

Based on the experimental results, the following conclusions are drawn from this study:

i. Hybrid fibres considerably contributed by enhancing the cubic compressive, splitting tensile and flexural strengths of RPC relative to nonfibrous RPC at room temperature. This enhancement increases with the fibres’ volume fraction.

ii. The first crack load of RPC beams under static loads increases with the hybrid fibres’ volume fraction. By contrast, the deflection under service load decreases with an increase in the fibres’ volume fraction.

iii. When a nonfibrous reinforced RPC beam under service load is exposed to fire, the reinforcement covers fully spall and break into small pieces, thus directly exposing the reinforcing steel to fire. Hybrid fibres at low volume fraction (0.25%) reduce spalling, whereas those at high volume fractions (0.75% and 1.25%) completely prevent spalling in RPC. The nonfibrous RPC beam fails in the fire test at 38 min. By contrast, the hybrid fibres at different volume fractions prevent beam failure during the entire test period. The rate of the increase in deflection during the fire test declines with an increase in hybrid fibres’ volume fraction. The increase in hybrid fibres’ volume fraction from 0.25% to 0.75% and 1.25% decreases the total deflection of reinforced RPC beams by 33% and 36%, respectively.

iv. The microstructure of the RPC with 1.25% fibre content illustrated a good interface between the cement paste and the aggregate, but the melting of the fibre created numerous microcracks in the channels.

v. Fire damage decreases with an increase in the hybrid fibres’ volume. The increase in the hybrid fibres’ volume fraction from 0.25% to 0.75% and 1.25% decreases the midspan deflection at service load by 52% and 62.3% and increases the ultimate load by 21.6% and 25.6%, respectively.

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Conflict of interest

None.

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