FLEXURAL PERFORMANCE OF POLYPROPYLENE FIBER REINFORCED SCORIA AGGREGATE CONCRETE BEAMS AFTER EXPOSURE TO ELEVATED TEMPERATURES

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Abstract

To study the residual strength of concrete beams made from a new type of scoria aggregate after being exposed to fire, six concrete beams were tested, including three normal aggregate concrete (NAC) beams and three scoria aggregate concrete (SAC) beams. First, the beams were exposed to fire for 60 min (2 beams) and 90 min (2 beams) and then subjected to four-point bending tests. The effect of the duration of fire exposure on the load-midspan deflection relationship and the beam failure modes was evaluated with an advanced digital image correlation (DIC) camera. The experimental results indicate that at certain locations, the temperature of the SAC beams after 60 min and 90 min of fire exposure was lower than that of the NAC beams. When the duration of fire exposure was 90 min, the ultimate load capacity of the SAC beams decreased by approximately 11% compared with the ultimate load capacity of the beams at ambient temperature, and the ultimate load capacity of the NAC beams decreased by approximately 17.5% under the same conditions. After a fire, the internal bonds of concrete are damaged, and this damage manifests as concrete spalling, compressive strain, gap spacing, and reinforcement damage after loading. In this study, a numerical model was also developed using the finite element software ABAQUS, and the flexural response of the NAC and SAC beams under different fire times was simulated. The results of the numerical model showed a good agreement with the experimental results. Using the numerical model, the influence of several important parameters on the ultimate capacity of the SAC beams for different fire exposure times was studied.

Keywords: Fire; Scoria aggregate concrete beams; Numerical simulations; Flexural performance; Elevated temperature.

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INTRODUCTION

Concrete is widely used in the field of civil engineering. Traditional normal aggregate concrete (NAC) has high structural performance but is also heavy. Buildings built with NAC are a hidden danger in earthquakes because of their large self-weight (Clarke 1993). Lightweight aggregate concrete reduces dead load and ensures that buildings have sufficient strength, which provides excellent advantages for construction (Bingoel et al. 2013; Lo et al. 2008). Compared to normal concrete, lightweight concrete has a lower density, comparable strength (Al-Khaiat and Haque 1998), lower thermal conductivity (Al-Jabri et al. 2005; Habib et al. 2004), and better fire resistance (Bilodeau et al. 2004). Therefore, lightweight concrete structures can provide more reinforcement at high temperatures. Lightweight aggregate concrete is usually made from manufacturing by-products (such as expansive clay, fly ash, slate, and shale) and natural lightweight aggregates (such as diatomite, pumice, and scoria aggregate) (Posi et al. 2014)， which is more economical and environmentally friendly. Lightweight concrete made of natural aggregate is stronger and denser (Bogas and Gomes 2015), but structures made with such materials can burst when exposed to high temperatures.

Porous structural materials have excellent mechanical and thermal properties. The greater the porosity is, the better the thermal conductivity (Bouguerra et al. 1998). Scoria aggregate is a new type of lightweight aggregate that is porous and lightweight and has a low thermal conductivity (Yang et al. 2017); a substantial amount of scoria aggregate is stored in Jilin, China, but it is not widely used. Excessive stacking pollutes the environment and fails to meet the requirements of green sustainable development. Yasar et al. (2003) measured the compressive and flexural tensile strength of structural lightweight aggregate concrete made with basalt pumice (scoria aggregate) and compared the results with the performance of fresh concrete (including the density, slump, and workability). The experimental results were good, and it was proposed that lightweight concrete could be prepared with slag. In a previous study (Topu 1997), five concrete structures with scoria aggregate particles of different sizes were prepared, and bending and splitting tensile strength tests were carried out to determine their physical and mechanical properties. The results showed that scoria aggregate concrete (SAC) can be safely used to produce semi-lightweight concrete. The study of SAC and its use in construction can drive the local economic development of Jilin, reduce environmental burdens, and achieve sustainable development. Therefore, SAC has broad application potentials (Lemougna et al. 2018). Various aggregate mixing levels can improve the structural performance for different sizes (Chen and Liu 2008). When the volume ratio of coarse scoria aggregate to fine scoria aggregate is 7:3, lightweight SAC has the best structural performance and mechanical properties (Li Wei Shi 2018). Increasing the dosage of volcanic ash can improve the corrosion resistance of concrete (Kaid et al. 2009).

Accidental fires in urban areas cause severe threats to life and property. The flexural performance of concrete beams exposed to fire is complex and nonlinear. The residual load-bearing performance of reinforced concrete structures after fires is the basis for post-fire safety assessment and strengthening the design of structures (Xu et al, 2013; Cai et al, 2019) and is an important issue that must be addressed by the international community.

Kodur et al. (2010) studied the ultimate bearing capacity of three reinforced concrete simply supported beams after a fire. Their test showed that the bending performance of the beam after a fire is still largely retained. The flexural capacity of reinforced concrete beams directly depends on the strength grade of the concrete and the reinforcements provided. High temperatures destroy the bonds in beams and reduce the strength of the reinforcements, which reduces the bearing capacity of beams, but does not affect their failure mode. Yu et al. (2005) performed experimental research on the mechanical properties of ordinary concrete and high-performance concrete after exposure to high temperatures and established a unified calculation method for the mechanical properties of ordinary and high-performance concrete under uniaxial compression after exposure to high-temperature conditions. Sun et al. (2002) demonstrated that the bearing capacity of high-temperature beams in the tension zone and compression zone can be restored after a fire through experimental research. Numerous researchers have made various contributions to the understanding of the mechanical properties of structural members exposed to high temperatures. Sakashita (1997) investigated the effect of fire on fiber-reinforced polymer (FRP)-reinforced concrete (RC) beams with different surface structures and fiber orientations and found that the beams were not damaged at 680 °C. Wang et al. (2020) studied the performance of continuous RC slabs under different fire conditions and analyzed the influences of factors such as compartment fire scenarios, the reinforcement ratio, and the bar arrangement on the deflection and strain. Chung and Consolazio (2005) studied the thermal response of RC structures exposed to elevated temperatures. Lublóy and György (2014) found that the bond strength of concrete members at elevated temperatures degraded more severely than the concrete compressive strength. When severely heated, the strength, stiffness, and other physical properties of concrete and reinforcements change greatly. Rasoul et al. (2020) found that adding polypropylene (PP) fibers to concrete improved the tensile strength and the first cracking load while reducing compressive strength loss after a fire and reducing concrete spalling during a fire. Consequently, adding PP fiber can not only improve the performance of beams after a fire, but also prevent the components from cracking after being exposed to high temperatures. Numerical analysis using finite element programs has also been used investigate the thermal behavior of RC concrete. Ilango and Mahato (2020) used ABAQUS to analyze the performance of PP fiber-reinforced concrete beams with carbon FRP (CFRP) bars at high temperatures, and the results indicated that their performance is higher than that of ordinary reinforced concrete in terms of withstanding temperature loads and strength. Choi and Shin (2011) investigated the effect of protective layer thickness on reinforced concrete under fire and proposed a simplified model to investigate the effect of layer cracking on the temperature gradient of concrete beams, showing that the finite difference method of the model agrees with the experimental results. The relationship between time and the temperature distribution in the beam section was shown to be similar, and independent of the concrete strength. In summary, the number of studies on SAC beams with PP fiber after exposure to high temperatures is limited.

In this study, four-point bending tests of NAC beams and SAC beams were carried out at room temperature, after 60 min of fire exposure and after 90 min of fire exposure. Through static four-point flexural tests of the NAC and SAC beams and with the help of precise digital image correlation (DIC) measurements, the load-midspan deflection curve of the beams, the strain diagram of the SAC beams, the cracking load, the crack size, the yield load, and the ultimate load were obtained. The failure mechanism was studied and the influence of changing the parameters on the failure mechanism was analyzed. At the same time, the finite element software ABAQUS was used to establish an analysis model. The model was verified by the test results, and the influence of different parameters on the analysis model was considered.

EXPERIMENTAL PROGRAM

Test Set-up

The high-strength SAC used in this study was designed in accordance with the Technical Specification for Lightweight Aggregate Concrete (JGJ51-2002) (CABR 2006). The instrumentation follows the conventional structural tests (Fu 2010, Wang 2020, Chen 2019, Liu 2017). The SAC had a design strength of C30 and an average density of 1900 kg/m^3. The SAC was prepared using scoria aggregates (with a bulk density of 815 kg/m^3), P·O42.5 ordinary Portland cement, PP fibers (filamentary, with a length of ~ 9 mm, see Table 1 for the main technical parameters), Class II fly ash, a styrene acrylic emulsion, and tap water in the mixing ratio shown in Table 2.

A total of six beams were designed: three SAC beams (SAC1, SAC2, and SAC3) and three NAC beams (NAC1, NAC2, and NAC3). Each beam had dimensions of 180 mm × 250 mm × 2000 mm (width × height × length) and a cover thickness of 25 mm and was reinforced with 2Φ10 compression bars, 2Φ14 tension bars, and Φ8@150 stirrups. The size of a beam specimen is illustrated in Fig.1, and the basic properties of the steel bars used in the test are listed in Table 3.

K-type thermocouples were mounted over the beam cross-section to measure the temperature inside each beam after exposure to fire, as shown in Fig.2. Five measurement points at the same positions were used for each of the six beams. Tests were conducted under three static loading conditions, i.e., at room temperature, after 60 min of fire exposure, and after 90 min of fire exposure, respectively. Table 4 lists all the test conditions and the corresponding designations.

Table 1

Table 2

Table 3

Table 4

Fig.1

Fig.2

Thermal Tests

Before the flexural tests were performed, both the SAC and NAC beams were exposed to high-temperature conditions in a furnace for 60 and 90 min. The furnace temperature was controlled to follow the ISO 834 (ISO 1999) standard fire curve, and the heating formula is as follows:

$$T = T_0 + 345\log(8t+1) \quad (1)$$

where T_0 is the initial room temperature (℃, a value of 20 ℃ was used in this study); t is the heating time(min).

To replicate a three-sided heating scenario, which is common in most fire incidents, the top surface of each beam was wrapped with fireproof cotton, leaving the remaining three sides exposed. The beam was then placed in the furnace shown in Fig.3, and a high-temperature test was conducted at a controlled heating rate of 10℃/min. Heating was terminated at the designated time of fire exposure, and the beam was allowed to cool in the furnace before removal.

Fig.3

Mechanical Tests

A static load press was used to apply the load at a computer-controlled loading rate. The load was applied in 2-kN increments from 0 to 10 kN, in 5-kN increments from 10 to 80 kN, and in 2-kN increments beyond 80 kN until the specimen was destroyed, as shown in Fig.4.

During the static test, DIC, a non-contact, non-destructive deformation testing device, was used. This high-resolution, high-speed acquisition system was oriented to the speckle surface of a specimen to facilitate rapid and accurate measurement of the beam deflection and strain data.

According to the results of Park et al. (2017), large speckle images with a low volume fraction, as represented by high standard deviation values and a left-sided gray distribution, tend to provide more accurate results for various displacements. The test set up is shown in Fig.5.

Fig.4

Fig.5

TEST RESULTS AND ANALYSIS

Thermal Crack Patterns

Each of the NAC and SAC beams was heated in the furnace for 60 and 90 min. The beams were removed from the furnace after the test. Diagonal cracks on the beam surfaces were observed. As the exposure time increased, the cracks increased in number and size and the gaps became larger, which was mainly caused by thermal expansion. The cracks in the beams after being exposed to fire for 90 min are illustrated in Fig.6. After 90 min of exposure to fire, the cracks on the beam surfaces became longer and wider, and the surfaces became a little redder and slightly spalled. As shown in Fig.6, the number of surface cracks on the SAC3 beam was less than that of the NAC3 beam because the PP fiber melted at 160 ℃, which increased the internal gap of the beams and formed channels to reduce the vapor pressure inside the beams. The addition of PP fiber can prevent the cracking of components after exposure to high temperatures (Cai et al.2020).

Fig.6

Time and Temperature

Fig.7 shows the temperatures of the furnace and beams versus time using data extracted from the thermocouples placed inside and on the surfaces of the beams after the heating tests. Fig.7 (a, c) and (b, d) indicate that after exposure to fire, the NAC beams had a higher internal temperature than the SAC beams. For example, after exposure for 60 and 90 min, the temperatures at point 1 on the SAC beams were 10.68% and 13.77% lower than that at point 1on the NAC beams. This result was obtained because the good thermal performance of the scoria aggregate produced a considerably lower thermal conductivity for the SAC beams compared to the NAC beams, resulting in slower heat transfer at high temperatures and more effective protection of the steel bars.

Fig.7

Failure Modes and Load–Displacement Relationships

Fig.8 shows the final crack patterns and failure modes of the NAC and SAC beams after yielding. The cracks in the beams had approximately uniform spacings and widths ranging from 0.022 mm to 1.5 mm. The concrete in the upper part of the pure bending section was crushed, and some of the beam bars were exposed, indicating a flexural failure mode. As the exposure time increased, cracks from the pure bending zone gradually propagated to the bending shear zone. The tensile strain positions corresponding to the cracks at the bottom of the beam were almost the same after 60 and 90 min of fire exposure, and the compressive strain occurred at nearly symmetrical positions at the top of the beam. As the load increased, the cracks at the bottom developed upward and almost penetrated the entire cross section where the ultimate load was exerted. At this time, the lower part of the beam was clearly cracked under tension with uniformly distributed cracks, and the upper part of the beam was crushed under compression. In Fig.8, the concrete on the lower part of the SAC beam shows large peeling, while the NAC beam does not. The reason for this difference may be that the bonding performance between the scoria and the cement slurry was weaker than that of the stone aggregate after the fire. The aggregate expanded when heated, and the cement slurry shrank due to dehydration after 120 °C. Due to its high porosity and thermal stability, the expansion rate of the scoria aggregate is lower than that of ordinary aggregate, resulting in many cracks in the SAC beams.

The load-midspan deflection curves of the beams are presented in Fig.9, and the test results for the six beams are summarized in Table 5. Fig.9 indicates that the ultimate load of the SAC beams at room temperature reached as high as 130 kN, which was larger than that of the NAC beams (120.5 kN). After 60 min and 90 min of fire exposure, the ultimate load of the NAC beams decreased by 5.9% and 17.51%, respectively, and that of the SAC beams decreased by 5.9% and 11%, respectively. When concrete is exposed to high temperatures, it undergoes a series of chemical and physical changes, including the decomposition of calcium hydroxide. The concrete deteriorates and loses strength as a result of these changes, revealing the damaging effects of high temperatures on reinforcements. This decrease in the ultimate load was attributed to the impact of the fire duration on the strengths of the concrete and steel bars. The relatively small decrease in the ultimate load of the SAC beams after 90 min of fire exposure indicated a relatively high residual bearing capacity. The results in Table 5 indicate that the cracking load for the beams decreased with the exposure time. This result was attributed to the decrease in the compressive strength of the NAC and SAC beams after exposure to elevated temperatures, as well as the ensuing decrease in the tensile strength.

Table 5

Fig.8

Fig.9

DIC Transverse Strain Analysis

Based on the high precision and accuracy of the DIC technique, which is a popular technology, small strain changes on the beam surface can be captures, and the development of surface cracks can be predicted. The acquired photographs were analyzed using DIC software, and the accuracy of the images depended on the change in the gray distribution before and after deformation. Therefore, the results were significantly affected by the size, contrast, and randomness of the speckle pattern. Fig.10 shows the nephogram of the strains on the surface of beams SAC1, SAC2 and SAC3 that were obtained for 10%, 30%, 50%, and 80% of the ultimate bearing capacity F_u of each beam. Exposing SAC2 and SAC3 to fire resulted in a significant change in the color of the corresponding images compared to the results for SAC1. When the load was 30% F_u, the maximum compressive strain of SAC1 was 0.001, and the maximum compressive strain of SAC2 (0.0028) and SAC3 (0.00405) was 180% and 305% both of which are higher than that of SAC1. When the load was 50% F_u, the maximum compressive strain of SAC1 was 0.0014, and the maximum compressive strains of SAC2 (0.0043) and SAC3 (0.0052) was 207% and 271%, both of which are higher than that of SAC1. The maximum cracking strain inherits the cracking position. The vertical comparison of 0.8 F_u in Fig.10 demonstrates that the maximum cracking strain occurred in the quadrant below the loading point, and SAC1, SAC2, and SAC3 showed consistency. It is worth studying the compression zone in the upper part of the beam. SAC1 showed no obvious large strain and instead revealed a more uniform strain. Both SAC2 and SAC3 exhibited an obvious compressive strain, and the position was uniformly distributed. This result was obtained because increasing the exposure time weakened the beams and made them brittle, which severely damaged the bonds between the material particles in the beams and destroyed their integrity.

Fig.10

DIC software was used to analyze the transverse strain of five points on the beam surface, as illustrated in Fig.10. The points were arranged in the center of the beam and evenly distributed vertically. Fig.11 shows the distribution of the SAC strain along with the section height for the SAC beams. When exposed to fire for 60 min, the strain in the SAC beams was approximately linearly correlated with the section height, which conforms to the plane section assumption. After 90 min of fire exposure, the strain of the component increased. Although the SAC strain measurement fluctuated somewhat, the plane section assumption was still met. The neutral axis of the SAC beams was lower after 90 min of exposure than after 60 min of exposure, indicating that the flexural performance of the SAC beams decreased as the exposure time increased.

Fig.11

FINITE ELEMENT SIMULATIONS

To further study the behavior of this new type of concrete, a finite element model was built using ABAQUS(Fu,2020,2018,2008).

Basic Assumptions

When a concrete structure is subjected to fire, the thermal parameters of the material will change as the temperature increases. To simplify the calculation, the simulated temperature field has the following basic assumptions:

1. Heat loss due to water evaporation during fire is not taken into account;

2. There is unbonded slip between reinforcement and concrete;

3. Assuming that the concrete is isotropic, the thermal conductivity in all directions is the same;

4. The thermal expansion of steel and concrete is not considered;

5. The surface temperature T of the component exposed to remains constant during heat exchange.

Thermal Parameters

The thermal parameters proposed for the NSC, SAC and steel used in this study were taken from BS EN1994-1-2 (BSI 2013). In the following formula ((2)-(20)), T is the temperature (℃).

The thermal conductivity of NAC $\lambda_c(T)$(W/(m°C)) can be expressed as follows:

$$\lambda_c(T) = 2 - 0.24\left(\frac{T}{120}\right) + 0.012\left(\frac{T}{120}\right)^2 \quad \left(20°C \le T \le 1200°C\right) \tag{2}$$

The specific heat capacity of NAC $C_c(T)$(J/(kg°C)) is as follows:

$$C_c(T) = 900 + 80\left(\frac{T}{120}\right) - 4\left(\frac{T}{120}\right)^2 \quad \left(20°C \le T \le 1200°C\right) \tag{3}$$

The thermal conductivity of SAC $\lambda_{sc}(T)$(W/(m°C)) is as follows:

$$\lambda_{sc}(T) = \begin{cases} 1.0 - \dfrac{T}{1600} & 20°C \le T \le 800°C \\ 0.5 & T > 800°C \end{cases} \tag{4}$$

The specific heat capacity of SAC $C_{sc}(T)$(J/(kg°C)) can be expressed as follows:

$$C_{sc}(T) = 800 J/(kg\cdot°C) \quad T \le 1200°C \tag{5}$$

The thermal conductivity of reinforcement steel $\lambda_s(T)$(W/(m°C)) is as follows:

$$\lambda_s(T) = \begin{cases} 54 - 3.33\times10^{-2}T & \left(20°C \le T \le 800°C\right) \\ 27.3 & \left(800°C \le T \le 1200°C\right) \end{cases} \tag{6}$$

The specific heat capacity of reinforcement steel $C_s(T)$(J/(kg°C)) is as follows:

$$C_s(T) = \begin{cases} 425 + 7.73\times10^{-1}T - 1.69\times10^{-3}T^2 + 2.22\times10^{-6}T^3 & \left(20°C \le T \le 600°C\right) \\ 666 + \dfrac{13002}{738 - T} & \left(600°C \le T \le 735°C\right) \\ 545 + \dfrac{17820}{T - 731} & \left(735°C \le T \le 900°C\right) \\ 650 & \left(900°C \le T \le 1200°C\right) \end{cases} \tag{7}$$

Post fire Material Model of NAC

The post-fire stress-strain curve of NAC was obtained using the following set of equations, as shown in Fig.12 (a).

The tensile strength of the post-fire NAC was calculated according to a bilinear model proposed by Hu et al. (2014). The tensile strength of post-fire NAC $f_{ct}(T)/f_{ct}$ at $T°C$ is expressed as follows:

$$\frac{f_{ct}(T)}{f_{ct}} = 0.976 + \left[1.56 \times \left(\frac{T}{100}\right) - 4.35 \times \left(\frac{T}{100}\right)^2 + 0.345 \times \left(\frac{T}{100}\right)^3\right] \times 10^{-2} \quad (20°C \le T \le 800°C) \tag{8}$$

where $f_{ct}(T)$ is the uniaxial tensile strength of NAC at high temperatures, N / mm^2, and f_{ct} is the uniaxial tensile strength of NAC at room temperature, N / mm^2.

According to the strength reduction method proposed by Yu et al. (2005), the compression stress-strain curve of NAC after exposure to high temperatures was determined.

The compression peak strain of post-fire NAC $\varepsilon_c(T)$ at $T°C$ can be expressed as follows:

$$\frac{\varepsilon_c(T)}{\varepsilon_{c0}} = \left\{1 + c_4\left[(T-20)/100\right]^2\right\} \tag{9}$$

where ε_{c0} is the compressive peak strain of NAC at room temperature, and c_4 is a constant with a value of 0.037.

The strength reduction factor of post-fire NAC at $T°C$ is as follows:

$$\frac{f_{cc}(T)}{f_{cc}} = \frac{1}{1 + 9 \times \left[(T-20)/800\right]^{c_1}} \tag{10}$$

where $f_{cc}(T)$ is the axial compressive strength of NAC at high temperatures, N/mm^2; f_{cc} is the axial compressive strength of NAC at room temperature, N/mm^2; and c_1 is a constant with a value of 3.55.

The elastic modulus of post-fire NAC $E_c/E_c(T)$ at $T°C$ is:

$$\frac{E_c}{E_c(T)} = 1 + 2.15 \times 10^{-3} \times \left(\frac{T-20}{800}\right)^{4.33} + 3.7 \times 10^{-2} \times \left(\frac{T-20}{100}\right)^2 \quad (20°C \le T \le 800°C) \tag{11}$$

where E_c is the elastic modulus of NAC at room temperature, N/mm^2, and $E_c(T)$ is the elastic modulus of post-fire NAC, N/mm^2.

The compression stress-strain relationship of post-fire NAC can be expressed as follows:

$$y=\begin{cases}\dfrac{9.1f_{cu}^{-\frac{4}{9}}x-x^2}{1+(9.1f_{cu}^{-\frac{4}{9}}-2)x} & x\le 1\\ \dfrac{x}{2.5\times10^{-5}f_{cu}^{3}(x-1)^2+x} & x>1\end{cases}\qquad(12)$$

where $y=\sigma_c/f_{cc}(T)$, $x=\varepsilon_c/\varepsilon_c(T)$; σ_c is the compressive stress of post-fire NAC, N/mm^2; ε_c is the compressive strain of post-fire NAC; and f_{cu} is the cube crushing strength of NAC at room temperature, N/mm^2.

Post fire Material Model of SAC

The constitutive relationship, compressive strength, and splitting strength of SAC at room temperature and after exposure to high temperatures are all based on data from the constitutive test of SAC conducted by our research group. According to the formula proposed by Cai et al. (2021), the stress-strain curve of SAC was obtained, as shown below in Fig.12 (b).

The tensile and splitting strengths of SAC after high-temperature treatment can be respectively expressed as follows:

$$\frac{f_{sc}(T)}{f_{sc}}=0.987+5.142\times10^{-3}\left(\frac{T}{100}\right)-1.69\times10^{-2}\left(\frac{T}{100}\right)^2+6.114\times10^{-4}\left(\frac{T}{100}\right)^3\quad 20°C\le T\le 800°C\qquad(13)$$

$$\frac{f_{st}(T)}{f_{st}}=0.99-9.663\times10^{-3}\left(\frac{T}{100}\right)-2.479\times10^{-2}\left(\frac{T}{100}\right)^2+1.725\times10^{-3}\left(\frac{T}{100}\right)^3\quad 20°C\le T\le 800°C\qquad(14)$$

where $f_{sc}(T)$ is the axial compressive strength of SAC after exposure to elevated temperatures (N/mm^2); f_{sc} is the axial compressive strength of SAC at room temperature (N/mm^2); $f_{st}(T)$ is the splitting tensile strength of SAC after exposure to elevated temperatures (N/mm^2); and f_{st} is the splitting tensile strength of SAC at room temperature (N/mm^2).

The relative peak strain of the specimen was similarly obtained by curve fitting.

$$\frac{\varepsilon_{sc}(T)}{\varepsilon_{sc0}} = 0.987 - 8.14\times10^{-2}\left(\frac{T}{100}\right) + 3.69\times10^{-2}\left(\frac{T}{100}\right)^2 + 7.655\times10^{-4}\left(\frac{T}{100}\right)^3 \quad 20°C \le T \le 800°C \quad (15)$$

where $\varepsilon_{sc}(T)$ is the peak strain of SAC after elevated temperatures; and ε_{sc0} is the peak strain of SAC at room temperatures.

The elastic modulus of post-fire SAC $E_{sc}(T)/E_{sc}$ is as follows:

$$\frac{E_{sc}(T)}{E_{sc}} = 1.045 - 0.1864\left(\frac{T}{100}\right) - 2.428\times10^{-3}\left(\frac{T}{100}\right)^2 + 1.255\times10^{-3}\left(\frac{T}{100}\right)^3 \quad 20°C \le T \le 800°C \quad (16)$$

where $E_{sc}(T)$ is the elastic modulus of SAC after exposure to elevated temperatures (N/mm^2) and E_{sc} the elastic modulus of SAC at room temperature (N/mm^2).

The compression stress-strain relationship of post-fire SAC can be expressed as follows:

$$\begin{cases} y = \dfrac{nx}{n-1+x^n} & x \le 1 \\ y = \dfrac{x}{\alpha\left(x-1\right)^2 + x} & x \ge 1 \end{cases} \quad (17)$$

$$n = \frac{E_{sc}(T)\varepsilon_{sc}(T)}{E_{sc}(T)\varepsilon_{sc}(T) - f_{sc}(T)} \quad (18)$$

where $y=\sigma_{sc}/f_{sc}(T)$, $x=\varepsilon_{sc}/\varepsilon_{sc}(T)$. σ_{sc} is the compressive stress of post-fire SAC, N/mm^2; and ε_{sc} is the compressive strain of post-fire SAC. The parameter n reflects the stress-strain curve characteristics of concrete in the ascending section. The parameter α determines the characteristics of the stress-strain curve of concrete in the descending section. The parameters n and α are listed in Table 6.

Table 6

The reduction coefficient of the yield strength of steel bars after exposure to high temperatures followed the recommended formula proposed by Lu et al. (1993). The stress at each temperature was taken as the yield stress $f_s(T)$, and the yield strain at each temperature was taken as 0.002. The elastic modulus of steel bars after exposure to high temperatures was based on the formula recommended by Yu et al. (2005).

The yield strength reduction factor of reinforcement at $T°C$ can be expressed as follows:

$$\frac{f_s(T)}{f_s}=\begin{cases}1 & 0°C < T \leq 200°C \\ 1.33-1.64\times10^{-3}T & 200°C < T \leq 700°C\end{cases} \tag{19}$$

where $f_s(T)$ is the post-fire yield strength of the reinforcement, N/mm^2; and f_s is the yield strength of the reinforcement at room temperature, N/mm^2.

The elastic modulus of post-fire reinforcement $E_s(T)/E_s$ proposed can be calculated as follows:

$$\frac{E_s(T)}{E_s}=\begin{cases}1 & T \leq 350°C \\ 1.0072-2.014\times10^{-7}T^2+5\times10^{-5}T & T > 350°C\end{cases} \tag{20}$$

where E_s is the elastic modulus of the reinforcement at room temperature, N/mm^2; and $E_s(T)$ is the post-fire elastic modulus of the reinforcement, N/mm^2.

Fig.12

Element Type

Fig.13 shows the established numerical model. The tie command was used to simulate the constraint between a beam and a cushion block. The thermal parameters of the materials were calculated according to the codes, and the exposure of the beam to a three-sided fire was simulated. The heat transfer modes specified in ABAQUS were surface radiation and surface film condition for the exposed surfaces and surface film condition for the unexposed surface. The beam was meshed using a grid size of 25 mm, with eight-node linear heat transfer elements (DC3D8) for concrete and two-node heat transfer elements (DC1D2) for the steel bars. Constitutive relations for the concrete and steel bars at elevated temperatures were input into the model. The contact between the steel bars and concrete was simulated as an embedment zone. The file of the heat transfer simulation analysis results was imported into a predefined field, and the load and analysis steps were carried out.

Fig.13

Model Verification

The temperature fields were established using the model to obtain the cross-sectional temperature distributions of the NAC and SAC beams. Heat loss from water evaporation was neglected. Fig.14 shows the simulated time-temperature curves at specified points on the SAC beams for 60 min of fire exposure. Fig.14 indicates that there is reasonable consistency between the simulation results and the test data, and the maximum temperature difference was approximately 7%. This consistency demonstrates the accuracy of the numerical model in capturing the internal temperature distribution of the concrete cross-section. Fig.15 shows curves of the load vs. the mid-span deflection of the postfire beams plotted using the software postprocessing function. Fig. 15 indicates that the simulation results and the test data are in good agreement. Table 7 lists the fitting degree of the yield load and the ultimate load in simulations and tests, respectively. The fitting difference in the yield load was very small, and the maximum difference occurred at the ultimate load, which was 9.23%.

Through the software processing function, a comparison diagram of the simulated beam strain and the test strain was obtained, and the SAC beam is compared when it is subjected to fire for 60 min and loaded with $0.5F_u$. It can be seen from Fig.16 that the crack strain development positions of the two are similar, the maximum cracking strain occurred in the quadrant below the loading point, which demonstrates the high accuracy of the model.

The temperature distribution along with the section height of the beam after a fire was uneven, so the ultimate bearing capacity could not be calculated according to the conventional calculation. A new calculation model and improved section method were used to calculate the bearing capacity of the beams after fire exposure (Cai et al. 2020). The results are shown in Table 8.

Fig.14

Fig.15

Fig.16

Table 8

PARAMETRIC ANALYSIS USING NUMERICAL MODEL

The parametric study was carried out using the validated numerical model, and the influence of different parameters on the flexural performance of SAC beams exposed to high temperatures was quantified. These parameters were not involved in the experimental study.

Effect of the temperature distribution around beam section

The flexural bearing capacity of the beams subjected to a four-sided fire was compared with that of the beams exposed to fire on three-sides fire and at the bottom. Fig.17 indicates that the ultimate bearing capacity of the SAC beams decreased by 22.4% after being exposed to the four-sided fire for 90 min compared to being exposed to the one-sided fire for the same time. Under the same conditions, the ultimate bearing capacity of the NAC beams decreased by 23%. The effect of fire on the bearing capacity of the beams was more significant, and damage to the reinforcements was inevitable. The possibility of beam cracking and spalling in a four-sided fire is greatly increased.

Fig.17

Effect of Different Fire Times

The load-midspan deflection curves of different fire times were obtained by decreasing the heating time to 30 min and increasing the heating time to 120 min. The reduction in the flexural bearing capacity became more pronounced as the exposure time increased. Figure 18 indicates that the ultimate bearing capacity of the SAC beams decreased from 130 kN (at room temperature) to 76 kN (after 120 min of exposure), corresponding to a reduction of 41.5%. Under the same conditions, the ultimate bearing capacity of the NAC beams decreased by 48.2 %. Fig.18 shows that the ductility of the concrete and reinforcements decreased after 120 min of fire exposure due to the decrease in the elastic modulus of the two materials at high temperatures. Thus, the fire time significantly impacted the safety of the beams.

Fig.18

Effect of different reinforcement ratios

Fig.19 shows the load-midspan deflection curves of the beams with different areas of longitudinal tension bars and reinforcement ratios of 0.79%, 1.18%, and 1.71% (compared with an original reinforcement ratio of 1.18%). The reinforcement ratio also affected the beam flexural performance, where the larger the reinforcement ratio was, the higher the bearing capacity increased with the reinforcement ratio. For example, after 90-min of exposure, the ultimate bearing capacity of the SAC beam with a reinforcement ratio of 0.79% was 21.6% higher than that of the NAC beam due to the large reinforcement ratio, the weakening of the reinforcements with different diameters, and the larger diameter reinforcements being less affected by fire.

Fig.19

Effect of the temperature distribution along the beam length

Load-midspan deflection curves (Fig.21) were obtained for beams exposed to elevated temperatures (60min and 90min) along the full length and along half-and three-quarters of the length (Fig.20). The ultimate bearing capacities of the SAC beams for which half- and three-quarters of the length were exposed to fire for 90 min were 23.8% and 16.5% higher, respectively, than that of the SAC beam with full-length exposure. This difference in the ultimate bearing capacity was attributed to the effect of the temperature on the mechanical properties of the exposed portion of the SAC beam.

Fig.20

Fig.21

CONCLUSIONS

The present study was an experimental and numerical investigation of the flexural performance and failure modes of PP fiber-reinforced SAC beams after exposure to elevated temperatures. Three NAC beams and three SAC beams were tested, where two beams of each type were exposed to fire for 60 and 90 min. The following conclusions were drawn from the results of the study:

1. The advantage offered by the low thermal conductivity of scoria aggregates was revealed by exposing the NAC and SAC beams to fire for 60 and 90 min. After 60 and 90 min of fire exposure, the average temperatures of the five measuring points on the SAC beams were 7.2% and 11.2% lower than those of the NAC beam respectively. These results indicate that SAC can protect steel bars more effectively than NAC in an elevated temperature environment.

2. In a fire, a gap between the scoria aggregate and the cement slurry is generated due to thermal expansion, so that the concrete in the tensile area barely functions. However, the low thermal conductivity of the scoria aggregate reduces the strength of the reinforcements, after 90 min of fire exposure, the ultimate load of the NAC and SAC beams decreased by 17.51%, and 11% respectively, the final SAC beam bearing capacity is higher than that of NAC beams.

3. The plane section assumption is also applicable to the beam after a fire, and the longer the fire time, that is, the higher the temperature, the lower the neutral axis of the beam section, and the greater the height of the compression zone.

4. The failure process of the SAC beams after being exposed to high temperatures was

observed in situ via DIC. The strain on any point in a specimen surface can be precisely measured using DIC. With the increase in load, the transverse strain of the bottom of the beam expands and develops upward, and the model strain is in good agreement with the experimental results. The temperature increased connected the connection particles in the beam, and the connection failure between the scoria aggregate and cement slurry was more obvious.

5. In terms of predicting the yield load and deflection at yield load, a numerical model was proposed to determine the effect of the temperature on the flexural performance of the SAC beams. An analysis using the proposed model produced curves similar to the experimental results. After a period of exposure to conventional fire, a proposed simplified computation can be utilized to predict the fire ultimate capacity of NAC and SAC beams. The computed findings are very close to the experimental results.

6. In numerical analysis, results may observe an error between the prediction and experimentally measured results. This is because of the homogeneity of concrete material that is purely considered in the numerical simulation. In real conditions, concrete has been observed highly heterogeneous nature. This may be caused by insufficient vibration and internal voids. Further refinement is needed for the simulation to find reliable information that helps to improve the numerical simulation results.

ACKNOWLEDGEMENTS

This research was financially supported by the Foundation of China Scholarship Council (No. 201805975002), the Science and Technological Planning Project of Ministry of Housing and Urban–Rural Development of the People's Republic of China (No. 2017-K9-047), and a scientific research projects from the Education Department of Jilin Province (JJKH20210279KJ). The authors wish to acknowledge the sponsors. However, any opinions, findings, conclusions and recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

COMPETING INTERESTS

The authors declare that they have no competing interests.

DATA AVAILABILITY

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table

Table 1 Main technical parameters of polypropylene fiber

Material	Proportion	Tensile strength（N/mm^2）	Elastic modulus（N/mm^2）	Fiber diameter（um）	Ultimate tension	Melting point（℃）
Parameters	1.18	＞736	＞7.18	10~15	15%	160~170

Table 2Mix proportion of concrete (kg/m^3)

Designation	Water	Cement	Sand	Gravel	SA	Fly ash	Ps	Sae	PP fiber
NAC	185	370	596	1192	—	53.6	0.47	5.36	—
SAC	230	496	—	—	1110	53.6	0.47	5.36	1.84

SA= scoria aggregate; Ps= Polycarboxylate superplasticizer; Sae= Styrene acrylic emulsion

Table 3 Basic parameters of the reinforcement

Type of reinforcement	Specification of steels	Yield strength（N/mm^2）	Ultimate strength（N/mm^2）	Elastic modulus（×10^{5}N/mm^2）
Pulled	HRB400	469	583	2.05

Compressed	**HRB400**	**469**	**583**	**2.05**
Stirrup	**HPB300**	**346**	**431**	**2.13**

Table 4 Basic parameters of specimens

Specimen No.	**Concrete strength grade**	**Test conditions**	**Fire exposure time (min)**
NAC1	**C30**	**Room-temperature static test**	**—**
SAC1	**C30**	**Room-temperature static test**	**—**
NAC2	**C30**	**Post-fire static test**	**60min**
SAC2	**C30**	**Post-fire static test**	**60min**
NAC3	**C30**	**Post-fire static test**	**90min**
SAC3	**C30**	**Post-fire static test**	**90min**

Table 5 Summary of test results of six beams

Specimen No.	**Summary data**						
	First cracking load (KN)	**Crack width (mm)**	**Deflection at first cracking load (mm)**	**Deflection at peak load (mm)**	**Yield load (KN)**	**Ultimate Load (KN)**	**Failure mode**
NAC1	**28.32**	**0.041**	**1.88**	**26.46**	**105.89**	**120.51**	**Bending failure**
NAC2	**21.64**	**0.037**	**3.02**	**35.65**	**102.26**	**113.41**	**Bending failure**
NAC3	**12.58**	**0.045**	**2.03**	**37.82**	**91.77**	**99.39**	**Bending failure**
SAC1	**32.13**	**0.028**	**2.36**	**27.99**	**106.49**	**130.26**	**Bending failure**
SAC2	**19.11**	**0.035**	**2.51**	**40.14**	**105.77**	**122.5**	**Bending failure**
SAC3	**14.62**	**0.037**	**2.21**	**44.33**	**98.54**	**115.92**	**Bending failure**

Table 6 Equation parameters of stress-strain curves of SAC after elevated temperatures

T (℃)	**n**	**α**
20	**1.898**	**49.31**
200	**2.17**	**72.44**
400	**1.827**	**9.993**
600	**2.201**	**1.079**
800	**1.991**	**0.676**

Table 7 Comparison of yield load and ultimate load between numerical and experimental results.

Specimen No.	**Yield load (KN)**		**Error%**	**Ultimate load (KN)**		**Error%**
	simulation	**test**		**simulation**	**test**	
NAC1	**110.5**	**105.89**	**4.17**	**132.27**	**120.51**	**8.89**
NAC2	**103.41**	**102.26**	**1.11**	**116.82**	**113.41**	**2.91**
NAC3	**93.23**	**91.77**	**1.56**	**109.36**	**99.26**	**9.23**
SAC1	**112.58**	**106.49**	**5.41**	**125.62**	**130.26**	**3.69**
SAC2	**103.45**	**105.77**	**2.24**	**120.15**	**122.5**	**1.95**
SAC3	**99.32**	**98.54**	**0.78**	**117.63**	**115.92**	**1.45**

Table 8 Summary of calculation and test ultimate loading capacity

Specimen No.	**Calculation（KN）**	**Test（KN）**	**Error%**
NAC1	**124**	**120.51**	**2.8**
NAC2	**109.12**	**113.41**	**3.9**
NAC3	**97.96**	**99.39**	**1.4**
SAC1	**124**	**130.26**	**5.1**
SAC2	**116.56**	**122.5**	**5**
SAC3	**106.64**	**115.92**	**8.7**