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

Bin Cai[1], Ning Lv[2] Feng Fu[3] C.Eng, F.ASCE

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.

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[1] Professor, School of Civil Engineering, Jilin Jianzhu University, Changchun 130118, Jilin, China. caibin@jlju.edu.cn

[2] Research student, School of Civil Engineering, Jilin Jianzhu University, Changchun 130118, Jilin, China. caibin666@163.com

[3] Senior Lecturer in Structural Engineering, School of Mathematics, Computer Science and Engineering, City, University of London, London, UK. (Corresponding author): feng.fu.1@city.ac.uk

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

56   strength of structural lightweight aggregate concrete made with basalt pumice (scoria aggregate)

57   and compared the results with the performance of fresh concrete (including the density, slump, and

58   workability). The experimental results were good, and it was proposed that lightweight concrete

59   could be prepared with slag. In a previous study (Topu 1997), five concrete structures with scoria

60   aggregate particles of different sizes were prepared, and bending and splitting tensile strength tests

61   were carried out to determine their physical and mechanical properties. The results showed that

62   scoria aggregate concrete (SAC) can be safely used to produce semi-lightweight concrete. The study

63   of SAC and its use in construction can drive the local economic development of Jilin, reduce

64   environmental burdens, and achieve sustainable development. Therefore, SAC has broad

65   application potentials (Lemougna et al. 2018). Various aggregate mixing levels can improve the

66   structural performance for different sizes (Chen and Liu 2008). When the volume ratio of coarse

67   scoria aggregate to fine scoria aggregate is 7:3, lightweight SAC has the best structural performance

68   and mechanical properties (Li Wei Shi 2018). Increasing the dosage of volcanic ash can improve the

69   corrosion resistance of concrete (Kaid et al. 2009).

70   Accidental fires in urban areas cause severe threats to life and property. The flexural

71   performance of concrete beams exposed to fire is complex and nonlinear. The residual load-bearing

72   performance of reinforced concrete structures after fires is the basis for post-fire safety assessment

73   and strengthening the design of structures (Xu et al, 2013; Cai et al, 2019) and is an important

74   issue that must be addressed by the international community.

75   Kodur et al. (2010) studied the ultimate bearing capacity of three reinforced concrete simply

76   supported beams after a fire. Their test showed that the bending performance of the beam after a

77   fire is still largely retained. The flexural capacity of reinforced concrete beams directly depends on

78   the strength grade of the concrete and the reinforcements provided. High temperatures destroy the

79   bonds in beams and reduce the strength of the reinforcements, which reduces the bearing capacity

80   of beams, but does not affect their failure mode. Yu et al. (2005) performed experimental research

81   on the mechanical properties of ordinary concrete and high-performance concrete after exposure

82   to high temperatures and established a unified calculation method for the mechanical properties of

83   ordinary and high-performance concrete under uniaxial compression after exposure to

84   high-temperature conditions. Sun et al. (2002) demonstrated that the bearing capacity of

85   high-temperature beams in the tension zone and compression zone can be restored after a fire

86   through experimental research. Numerous researchers have made various contributions to the

87   understanding of the mechanical properties of structural members exposed to high temperatures.

88   Sakashita (1997) investigated the effect of fire on fiber-reinforced polymer (FRP)-reinforced

89   concrete (RC) beams with different surface structures and fiber orientations and found that the

90   beams were not damaged at 680 ℃. Wang et al. (2020) studied the performance of continuous RC

91   slabs under different fire conditions and analyzed the influences of factors such as compartment fire

92   scenarios, the reinforcement ratio, and the bar arrangement on the deflection and strain. Chung and

93   Consolazio (2005) studied the thermal response of RC structures exposed to elevated temperatures.

94   Lublóy and György (2014) found that the bond strength of concrete members at elevated

95   temperatures degraded more severely than the concrete compressive strength. When severely heated,

96   the strength, stiffness, and other physical properties of concrete and reinforcements change greatly.

97   Rasoul et al. (2020) found that adding polypropylene (PP) fibers to concrete improved the tensile

98   strength and the first cracking load while reducing compressive strength loss after a fire and

99   reducing concrete spalling during a fire. Consequently, adding PP fiber can not only improve the

100   performance of beams after a fire, but also prevent the components from cracking after being

101   exposed to high temperatures. Numerical analysis using finite element programs has also been used

102   investigate the thermal behavior of RC concrete. Ilango and Mahato (2020) used ABAQUS to

103   analyze the performance of PP fiber-reinforced concrete beams with carbon FRP (CFRP) bars at

104   high temperatures, and the results indicated that their performance is higher than that of ordinary

105   reinforced concrete in terms of withstanding temperature loads and strength. Choi and Shin (2011)

106   investigated the effect of protective layer thickness on reinforced concrete under fire and proposed a

107   simplified model to investigate the effect of layer cracking on the temperature gradient of concrete

108   beams, showing that the finite difference method of the model agrees with the experimental results.

109   The relationship between time and the temperature distribution in the beam section was shown to be

110   similar, and independent of the concrete strength. In summary, the number of studies on SAC beams

111   with PP fiber after exposure to high temperatures is limited.

112   In this study, four-point bending tests of NAC beams and SAC beams were carried out at room

113   temperature, after 60 min of fire exposure and after 90 min of fire exposure. Through static

114   four-point flexural tests of the NAC and SAC beams and with the help of precise digital image

115   correlation (DIC) measurements, the load-midspan deflection curve of the beams, the strain diagram

116   of the SAC beams, the cracking load, the crack size, the yield load, and the ultimate load were

117   obtained. The failure mechanism was studied and the influence of changing the parameters on the

118   failure mechanism was analyzed. At the same time, the finite element software ABAQUS was used

119   to establish an analysis model. The model was verified by the test results, and the influence of

120   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

143	**Table 3**
144	**Table 4**
145	**Fig.1**
146	**Fig.2**

147 ***Thermal Tests***

148   Before the flexural tests were performed, both the SAC and NAC beams were exposed to

149 high-temperature conditions in a furnace for 60 and 90 min. The furnace temperature was

150 controlled to follow the ISO 834 (ISO 1999) standard fire curve, and the heating formula is as

151 follows:

152 $$T=T_0+345\log(8t+1) \tag{1}$$

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

154 heating time(min).

155   To replicate a three-sided heating scenario, which is common in most fire incidents, the top

156 surface of each beam was wrapped with fireproof cotton, leaving the remaining three sides

157 exposed. The beam was then placed in the furnace shown in Fig.3, and a high-temperature test was

158 conducted at a controlled heating rate of 10℃/min. Heating was terminated at the designated time

159 of fire exposure, and the beam was allowed to cool in the furnace before removal.

160   **Fig.3**

161 ***Mechanical Tests***

162   A static load press was used to apply the load at a computer-controlled loading rate. The load

163 was applied in 2-kN increments from 0 to 10 kN, in 5-kN increments from 10 to 80 kN, and in

164 2-kN increments beyond 80 kN until the specimen was destroyed, as shown in Fig.4.

165   During the static test, DIC, a non-contact, non-destructive deformation testing device, was

166 used. This high-resolution, high-speed acquisition system was oriented to the speckle surface of a

167 specimen to facilitate rapid and accurate measurement of the beam deflection and strain data.

168   According to the results of Park et al. (2017), large speckle images with a low volume fraction, as

169   represented by high standard deviation values and a left-sided gray distribution, tend to provide

170   more accurate results for various displacements. The test set up is shown in Fig.5.

171   **Fig.4**
172   **Fig.5**

173   **TEST RESULTS AND ANALYSIS**

174   ***Thermal Crack Patterns***

175   Each of the NAC and SAC beams was heated in the furnace for 60 and 90 min. The beams

176   were removed from the furnace after the test. Diagonal cracks on the beam surfaces were observed.

177   As the exposure time increased, the cracks increased in number and size and the gaps became

178   larger, which was mainly caused by thermal expansion. The cracks in the beams after being

179   exposed to fire for 90 min are illustrated in Fig.6. After 90 min of exposure to fire, the cracks on

180   the beam surfaces became longer and wider, and the surfaces became a little redder and slightly

181   spalled. As shown in Fig.6, the number of surface cracks on the SAC3 beam was less than that of

182   the NAC3 beam because the PP fiber melted at 160 $℃$, which increased the internal gap of the

183   beams and formed channels to reduce the vapor pressure inside the beams. The addition of PP

184   fiber can prevent the cracking of components after exposure to high temperatures (Cai et al.2020).

185   **Fig.6**

186   ***Time and Temperature***

187   Fig.7 shows the temperatures of the furnace and beams versus time using data extracted from

188   the thermocouples placed inside and on the surfaces of the beams after the heating tests. Fig.7 (a, c)

189   and (b, d) indicate that after exposure to fire, the NAC beams had a higher internal temperature

190   than the SAC beams. For example, after exposure for 60 and 90 min, the temperatures at point 1

191   on the SAC beams were 10.68% and 13.77% lower than that at point 1on the NAC beams. This

192   result was obtained because the good thermal performance of the scoria aggregate produced a

193   considerably lower thermal conductivity for the SAC beams compared to the NAC beams,

194   resulting in slower heat transfer at high temperatures and more effective protection of the steel

195   bars.

196   **Fig.7**

197   ***Failure Modes and Load–Displacement Relationships***

198   Fig.8 shows the final crack patterns and failure modes of the NAC and SAC beams after

199   yielding. The cracks in the beams had approximately uniform spacings and widths ranging from

200   0.022 mm to 1.5 mm. The concrete in the upper part of the pure bending section was crushed, and

201   some of the beam bars were exposed, indicating a flexural failure mode. As the exposure time

202   increased, cracks from the pure bending zone gradually propagated to the bending shear zone. The

203   tensile strain positions corresponding to the cracks at the bottom of the beam were almost the same

204   after 60 and 90 min of fire exposure, and the compressive strain occurred at nearly symmetrical

205   positions at the top of the beam. As the load increased, the cracks at the bottom developed upward

206   and almost penetrated the entire cross section where the ultimate load was exerted. At this time, the

207   lower part of the beam was clearly cracked under tension with uniformly distributed cracks, and the

208   upper part of the beam was crushed under compression. In Fig.8, the concrete on the lower part of

209   the SAC beam shows large peeling, while the NAC beam does not. The reason for this difference

210   may be that the bonding performance between the scoria and the cement slurry was weaker than that

211   of the stone aggregate after the fire. The aggregate expanded when heated, and the cement slurry

212 shrank due to dehydration after 120 ℃. Due to its high porosity and thermal stability, the expansion

213 rate of the scoria aggregate is lower than that of ordinary aggregate, resulting in many cracks in the

214 SAC beams.

215   The load-midspan deflection curves of the beams are presented in Fig.9, and the test results for

216 the six beams are summarized in Table 5. Fig.9 indicates that the ultimate load of the SAC beams at

217 room temperature reached as high as 130 kN, which was larger than that of the NAC beams (120.5

218 kN). After 60 min and 90 min of fire exposure, the ultimate load of the NAC beams decreased by 5.9%

219 and 17.51%, respectively, and that of the SAC beams decreased by 5.9% and 11%, respectively.

220 When concrete is exposed to high temperatures, it undergoes a series of chemical and physical

221 changes, including the decomposition of calcium hydroxide. The concrete deteriorates and loses

222 strength as a result of these changes, revealing the damaging effects of high temperatures on

223 reinforcements. This decrease in the ultimate load was attributed to the impact of the fire duration on

224 the strengths of the concrete and steel bars. The relatively small decrease in the ultimate load of the

225 SAC beams after 90 min of fire exposure indicated a relatively high residual bearing capacity. The

226 results in Table 5 indicate that the cracking load for the beams decreased with the exposure time.

227 This result was attributed to the decrease in the compressive strength of the NAC and SAC beams

228 after exposure to elevated temperatures, as well as the ensuing decrease in the tensile strength.

229   **Table 5**

230   **Fig.8**

231   **Fig.9**

232 *DIC Transverse Strain Analysis*

233   Based on the high precision and accuracy of the DIC technique, which is a popular technology,

234 small strain changes on the beam surface can be captures, and the development of surface cracks can

235 be predicted. The acquired photographs were analyzed using DIC software, and the accuracy of the

236 images depended on the change in the gray distribution before and after deformation. Therefore, the

237 results were significantly affected by the size, contrast, and randomness of the speckle pattern.

238 Fig.10 shows the nephogram of the strains on the surface of beams SAC1, SAC2 and SAC3 that

239 were obtained for 10%, 30%, 50%, and 80% of the ultimate bearing capacity F_u of each beam.

240 Exposing SAC2 and SAC3 to fire resulted in a significant change in the color of the corresponding

241 images compared to the results for SAC1. When the load was 30% F_u, the maximum compressive

242 strain of SAC1 was 0.001, and the maximum compressive strain of SAC2 (0.0028) and SAC3

243 (0.00405) was 180% and 305% both of which are higher than that of SAC1. When the load was 50%

244 F_u, the maximum compressive strain of SAC1 was 0.0014, and the maximum compressive strains of

245 SAC2 (0.0043) and SAC3 (0.0052) was 207% and 271%, both of which are higher than that of

246 SAC1. The maximum cracking strain inherits the cracking position. The vertical comparison of 0.8

247 F_u in Fig.10 demonstrates that the maximum cracking strain occurred in the quadrant below the

248 loading point, and SAC1, SAC2, and SAC3 showed consistency. It is worth studying the

249 compression zone in the upper part of the beam. SAC1 showed no obvious large strain and instead

250 revealed a more uniform strain. Both SAC2 and SAC3 exhibited an obvious compressive strain, and

251 the position was uniformly distributed. This result was obtained because increasing the exposure

252 time weakened the beams and made them brittle, which severely damaged the bonds between the

253 material particles in the beams and destroyed their integrity.

254 **Fig.10**

255 DIC software was used to analyze the transverse strain of five points on the beam surface, as

256 illustrated in Fig.10. The points were arranged in the center of the beam and evenly distributed

257 vertically. Fig.11 shows the distribution of the SAC strain along with the section height for the SAC

258 beams. When exposed to fire for 60 min, the strain in the SAC beams was approximately linearly

259 correlated with the section height, which conforms to the plane section assumption. After 90 min of

260 fire exposure, the strain of the component increased. Although the SAC strain measurement

261 fluctuated somewhat, the plane section assumption was still met. The neutral axis of the SAC beams

262 was lower after 90 min of exposure than after 60 min of exposure, indicating that the flexural

263 performance of the SAC beams decreased as the exposure time increased.

264 **Fig.11**

265 **FINITE ELEMENT SIMULATIONS**

266 To further study the behavior of this new type of concrete, a finite element model was built

267 using ABAQUS(Fu,2020,2018,2008).

268 *Basic Assumptions*

269 When a concrete structure is subjected to fire, the thermal parameters of the material will

270 change as the temperature increases. To simplify the calculation, the simulated temperature field has

271 the following basic assumptions:

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

273 2. There is unbonded slip between reinforcement and concrete;

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

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

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

277 exchange.

278   *Thermal Parameters*

279   The thermal parameters proposed for the NSC, SAC and steel used in this study were taken

280   from BS EN1994-1-2 (BSI 2013). In the following formula ((2)-(20)), T is the temperature ($\mathrm{^\circ C}$).

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

282
$$\lambda_c(T) = 2 - 0.24\left(\frac{T}{120}\right) + 0.012\left(\frac{T}{120}\right)^2 \quad \left(20°C \leq T \leq 1200°C\right) \tag{2}$$

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

284
$$C_c(T) = 900 + 80\left(\frac{T}{120}\right) - 4\left(\frac{T}{120}\right)^2 \quad \left(20°C \leq T \leq 1200°C\right) \tag{3}$$

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

286
$$\lambda_{sc}(T) = \begin{cases} 1.0 - \dfrac{T}{1600} & 20°C \leq T \leq 800°C \\ 0.5 & T > 800°C \end{cases} \tag{4}$$

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

288
$$C_{sc}(T) = 800J / (kg\cdot°C) \quad T \leq 1200°C \tag{5}$$

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

290
$$\lambda_s(T) = \begin{cases} 54 - 3.33 \times 10^{-2}T & \left(20°C \leq T \leq 800°C\right) \\ 27.3 & \left(800°C \leq T \leq 1200°C\right) \end{cases} \tag{6}$$

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

292
$$C_s(T) = \begin{cases} 425 + 7.73 \times 10^{-1}T - 1.69 \times 10^{-3}T^2 + 2.22 \times 10^{-6}T^3 & \left(20°C \leq T \leq 600°C\right) \\ 666 + \dfrac{13002}{738 - T} & \left(600°C \leq T \leq 735°C\right) \\ 545 + \dfrac{17820}{T - 731} & \left(735°C \leq T \leq 900°C\right) \\ 650 & \left(900°C \leq T \leq 1200°C\right) \end{cases} \tag{7}$$

293   *Post fire Material Model of NAC*

294   The post-fire stress-strain curve of NAC was obtained using the following set of equations, as

295   shown in Fig.12 (a).

296   The tensile strength of the post-fire NAC was calculated according to a bilinear model

297   proposed by Hu et al. (2014). The tensile strength of post-fire NAC $f_{ct}(T)/f_{ct}$ at $T°C$ is expressed as

298   follows:

299
$$\frac{f_{ct}(T)}{f_{ct}} = 0.976 + \left[1.56 \times \left(\frac{T}{100} \right) - 4.35 \times \left(\frac{T}{100} \right)^2 + 0.345 \times \left(\frac{T}{100} \right)^3 \right] \times 10^{-2} \quad (20°C \leq T \leq 800°C) \qquad (8)$$

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

301   uniaxial tensile strength of NAC at room temperature, N/mm^2.

302   According to the strength reduction method proposed by Yu et al. (2005), the compression

303   stress-strain curve of NAC after exposure to high temperatures was determined.

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

305
$$\frac{\varepsilon_c(T)}{\varepsilon_{c0}} = \left\{ 1 + c_4 \left[(T - 20)/100 \right]^2 \right\} \qquad (9)$$

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

307   value of 0.037.

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

309
$$\frac{f_{cc}(T)}{f_{cc}} = \frac{1}{1 + 9 \times \left[(T - 20)/800 \right]^{c_1}} \qquad (10)$$

310   where $f_{cc}(T)$ is the axial compressive strength of NAC at high temperatures, N/mm^2; f_{cc} is the axial

311   compressive strength of NAC at room temperature, N/mm^2; and c_1 is a constant with a value of 3.55.

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

313
$$\frac{E_c}{E_c(T)} = 1 + 2.15 \times 10^{-3} \times \left(\frac{T - 20}{800} \right)^{4.33} + 3.7 \times 10^{-2} \times \left(\frac{T - 20}{100} \right)^2 \quad (20°C \leq T \leq 800°C) \qquad (11)$$

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

315   modulus of post-fire NAC, N/mm^2.

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

317
$$y = \begin{cases} \dfrac{9.1f_{cu}^{-\frac{4}{9}}x - x^2}{1 + (9.1f_{cu}^{-\frac{4}{9}} - 2)x} & x \leq 1 \\ \dfrac{x}{2.5 \times 10^{-5} f_{cu}^3 (x-1)^2 + x} & x > 1 \end{cases} \tag{12}$$

318   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

319   compressive strain of post-fire NAC; and f_{cu} is the cube crushing strength of NAC at room

320   temperature, N/mm^2.

321   ***Post fire Material Model of SAC***

322   The constitutive relationship, compressive strength, and splitting strength of SAC at room

323   temperature and after exposure to high temperatures are all based on data from the constitutive test

324   of SAC conducted by our research group. According to the formula proposed by Cai et al. (2021),

325   the stress-strain curve of SAC was obtained, as shown below in Fig.12 (b).

326   The tensile and splitting strengths of SAC after high-temperature treatment can be respectively

327   expressed as follows:

328
$$\frac{f_{sc}(T)}{f_{sc}} = 0.987 + 5.142 \times 10^{-3}\left(\frac{T}{100}\right) - 1.69 \times 10^{-2}\left(\frac{T}{100}\right)^2 + 6.114 \times 10^{-4}\left(\frac{T}{100}\right)^3 \quad 20°C \leq T \leq 800°C \tag{13}$$

329
$$\frac{f_{st}(T)}{f_{st}} = 0.99 - 9.663 \times 10^{-3}\left(\frac{T}{100}\right) - 2.479 \times 10^{-2}\left(\frac{T}{100}\right)^2 + 1.725 \times 10^{-3}\left(\frac{T}{100}\right)^3 \quad 20°C \leq T \leq 800°C \tag{14}$$

330   where $f_{sc}(T)$ is the axial compressive strength of SAC after exposure to elevated temperatures

331   (N/mm^2); f_{sc} is the axial compressive strength of SAC at room temperature (N/mm^2); $f_{st}(T)$ is the

332   splitting tensile strength of SAC after exposure to elevated temperatures (N/mm^2); and f_{st} is the

333   splitting tensile strength of SAC at room temperature (N/mm^2).

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

335 $$\frac{\varepsilon_{sc}(T)}{\varepsilon_{sc0}} = 0.987 - 8.14 \times 10^{-2} \left(\frac{T}{100}\right) + 3.69 \times 10^{-2} \left(\frac{T}{100}\right)^2 + 7.655 \times 10^{-4} \left(\frac{T}{100}\right)^3 \quad 20°C \leq T \leq 800°C \quad (15)$$

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

337 SAC at room temperatures.

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

339 $$\frac{E_{sc}(T)}{E_{sc}} = 1.045 - 0.1864 \left(\frac{T}{100}\right) - 2.428 \times 10^{-3} \left(\frac{T}{100}\right)^2 + 1.255 \times 10^{-3} \left(\frac{T}{100}\right)^3 \quad 20°C \leq T \leq 800°C \quad (16)$$

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

341 E_{sc} the elastic modulus of SAC at room temperature (N/mm^2).

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

343 $$\begin{cases} y = \dfrac{nx}{n-1+x^n} & x \leq 1 \\ y = \dfrac{x}{\alpha(x-1)^2 + x} & x \geq 1 \end{cases} \quad (17)$$

344 $$n = \frac{E_{sc}(T)\varepsilon_{sc}(T)}{E_{sc}(T)\varepsilon_{sc}(T) - f_{sc}(T)} \quad (18)$$

345 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

346 compressive strain of post-fire SAC. The parameter n reflects the stress-strain curve characteristics

347 of concrete in the ascending section. The parameter α determines the characteristics of the

348 stress-strain curve of concrete in the descending section. The parameters n and α are listed in Table

349 6.

350 **Table 6**

351 The reduction coefficient of the yield strength of steel bars after exposure to high temperatures

352 followed the recommended formula proposed by Lu et al. (1993). The stress at each temperature

353 was taken as the yield stress $f_s(T)$, and the yield strain at each temperature was taken as 0.002. The

354 elastic modulus of steel bars after exposure to high temperatures was based on the formula

355   recommended by Yu et al. (2005).

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

357
$$\frac{f_s(T)}{f_s} = \begin{cases} 1 & 0°C < T \le 200°C \\ 1.33 - 1.64 \times 10^{-3}T & 200°C < T \le 700°C \end{cases} \quad (19)$$

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

359   the reinforcement at room temperature, N/mm^2.

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

361
$$\frac{E_s(T)}{E_s} = \begin{cases} 1 & T \le 350°C \\ 1.0072 - 2.014 \times 10^{-7}T^2 + 5 \times 10^{-5}T & T > 350°C \end{cases} \quad (20)$$

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

363   post-fire elastic modulus of the reinforcement, N/mm^2.

364   **Fig.12**

365   ***Element Type***

366   Fig.13 shows the established numerical model. The tie command was used to simulate the

367   constraint between a beam and a cushion block. The thermal parameters of the materials were

368   calculated according to the codes, and the exposure of the beam to a three-sided fire was simulated.

369   The heat transfer modes specified in ABAQUS were surface radiation and surface film condition for

370   the exposed surfaces and surface film condition for the unexposed surface. The beam was meshed

371   using a grid size of 25 mm, with eight-node linear heat transfer elements (DC3D8) for concrete and

372   two-node heat transfer elements (DC1D2) for the steel bars. Constitutive relations for the concrete

373   and steel bars at elevated temperatures were input into the model. The contact between the steel bars

374   and concrete was simulated as an embedment zone. The file of the heat transfer simulation analysis

375   results was imported into a predefined field, and the load and analysis steps were carried out.

376   **Fig.13**

377   *Model Verification*

378   The temperature fields were established using the model to obtain the cross-sectional

379   temperature distributions of the NAC and SAC beams. Heat loss from water evaporation was

380   neglected. Fig.14 shows the simulated time-temperature curves at specified points on the SAC

381   beams for 60 min of fire exposure. Fig.14 indicates that there is reasonable consistency between the

382   simulation results and the test data, and the maximum temperature difference was approximately

383   7%. This consistency demonstrates the accuracy of the numerical model in capturing the internal

384   temperature distribution of the concrete cross-section. Fig.15 shows curves of the load vs. the

385   mid-span deflection of the postfire beams plotted using the software postprocessing function. Fig.

386   15 indicates that the simulation results and the test data are in good agreement. Table 7 lists the

387   fitting degree of the yield load and the ultimate load in simulations and tests, respectively. The

388   fitting difference in the yield load was very small, and the maximum difference occurred at the

389   ultimate load, which was 9.23%.

390   Through the software processing function, a comparison diagram of the simulated beam strain

391   and the test strain was obtained, and the SAC beam is compared when it is subjected to fire for 60

392   min and loaded with $0.5F_u$. It can be seen from Fig.16 that the crack strain development positions of

393   the two are similar, the maximum cracking strain occurred in the quadrant below the loading point,

394   which demonstrates the high accuracy of the model.

395   The temperature distribution along with the section height of the beam after a fire was uneven,

396   so the ultimate bearing capacity could not be calculated according to the conventional calculation. A

397   new calculation model and improved section method were used to calculate the bearing capacity of

398   the beams after fire exposure (Cai et al. 2020). The results are shown in Table 8.

403   **PARAMETRIC ANALYSIS USING NUMERICAL MODEL**

404   The parametric study was carried out using the validated numerical model, and the influence of

405   different parameters on the flexural performance of SAC beams exposed to high temperatures was

406   quantified. These parameters were not involved in the experimental study.

407   *Effect of the temperature distribution around beam section*

408   The flexural bearing capacity of the beams subjected to a four-sided fire was compared with

409   that of the beams exposed to fire on three-sides fire and at the bottom. Fig.17 indicates that the

410   ultimate bearing capacity of the SAC beams decreased by 22.4% after being exposed to the

411   four-sided fire for 90 min compared to being exposed to the one-sided fire for the same time. Under

412   the same conditions, the ultimate bearing capacity of the NAC beams decreased by 23%. The effect

413   of fire on the bearing capacity of the beams was more significant, and damage to the reinforcements

414   was inevitable. The possibility of beam cracking and spalling in a four-sided fire is greatly

415   increased.

416   **Fig.17**

417   *Effect of Different Fire Times*

418   The load-midspan deflection curves of different fire times were obtained by decreasing the

419   heating time to 30 min and increasing the heating time to 120 min. The reduction in the flexural

420   bearing capacity became more pronounced as the exposure time increased. Figure 18 indicates that

421   the ultimate bearing capacity of the SAC beams decreased from 130 kN (at room temperature) to 76

422 kN (after 120 min of exposure), corresponding to a reduction of 41.5%. Under the same conditions,

423 the ultimate bearing capacity of the NAC beams decreased by 48.2 %. Fig.18 shows that the

424 ductility of the concrete and reinforcements decreased after 120 min of fire exposure due to the

425 decrease in the elastic modulus of the two materials at high temperatures. Thus, the fire time

426 significantly impacted the safety of the beams.

427   **Fig.18**

428 *Effect of different reinforcement ratios*

429   Fig.19 shows the load-midspan deflection curves of the beams with different areas of

430 longitudinal tension bars and reinforcement ratios of 0.79%, 1.18%, and 1.71% (compared with an

431 original reinforcement ratio of 1.18%). The reinforcement ratio also affected the beam flexural

432 performance, where the larger the reinforcement ratio was, the higher the bearing capacity increased

433 with the reinforcement ratio. For example, after 90-min of exposure, the ultimate bearing capacity

434 of the SAC beam with a reinforcement ratio of 0.79% was 21.6% higher than that of the NAC beam

435 due to the large reinforcement ratio, the weakening of the reinforcements with different diameters,

436 and the larger diameter reinforcements being less affected by fire.

437   **Fig.19**

438 *Effect of the temperature distribution along the beam length*

439   Load-midspan deflection curves (Fig.21) were obtained for beams exposed to elevated

440 temperatures (60min and 90min) along the full length and along half-and three-quarters of the

441 length (Fig.20). The ultimate bearing capacities of the SAC beams for which half- and

442 three-quarters of the length were exposed to fire for 90 min were 23.8% and 16.5% higher,

443 respectively, than that of the SAC beam with full-length exposure. This difference in the ultimate

444 bearing capacity was attributed to the effect of the temperature on the mechanical properties of the

445   exposed portion of the SAC beam.

446   **Fig.20**
447   **Fig.21**

448   **CONCLUSIONS**

449   The present study was an experimental and numerical investigation of the flexural performance

450   and failure modes of PP fiber-reinforced SAC beams after exposure to elevated temperatures. Three

451   NAC beams and three SAC beams were tested, where two beams of each type were exposed to fire

452   for 60 and 90 min. The following conclusions were drawn from the results of the study:

453   1. The advantage offered by the low thermal conductivity of scoria aggregates was revealed by

454   exposing the NAC and SAC beams to fire for 60 and 90 min. After 60 and 90 min of fire exposure,

455   the average temperatures of the five measuring points on the SAC beams were 7.2% and 11.2%

456   lower than those of the NAC beam respectively. These results indicate that SAC can protect steel

457   bars more effectively than NAC in an elevated temperature environment.

458   2. In a fire, a gap between the scoria aggregate and the cement slurry is generated due to

459   thermal expansion, so that the concrete in the tensile area barely functions. However, the low

460   thermal conductivity of the scoria aggregate reduces the strength of the reinforcements, after 90 min

461   of fire exposure, the ultimate load of the NAC and SAC beams decreased by 17.51%, and 11%

462   respectively, the final SAC beam bearing capacity is higher than that of NAC beams.

463   3. The plane section assumption is also applicable to the beam after a fire, and the longer the

464   fire time, that is, the higher the temperature, the lower the neutral axis of the beam section, and the

465   greater the height of the compression zone.

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

467   observed in situ via DIC. The strain on any point in a specimen surface can be precisely measured

468   using DIC. With the increase in load, the transverse strain of the bottom of the beam expands and

469   develops upward, and the model strain is in good agreement with the experimental results. The

470   temperature increased connected the connection particles in the beam, and the connection failure

471   between the scoria aggregate and cement slurry was more obvious.

472   5. In terms of predicting the yield load and deflection at yield load, a numerical model was

473   proposed to determine the effect of the temperature on the flexural performance of the SAC beams.

474   An analysis using the proposed model produced curves similar to the experimental results. After a

475   period of exposure to conventional fire, a proposed simplified computation can be utilized to predict

476   the fire ultimate capacity of NAC and SAC beams. The computed findings are very close to the

477   experimental results.

478   6. In numerical analysis, results may observe an error between the prediction and

479   experimentally measured results. This is because of the homogeneity of concrete material that is

480   purely considered in the numerical simulation. In real conditions, concrete has been observed highly

481   heterogeneous nature. This may be caused by insufficient vibration and internal voids. Further

482   refinement is needed for the simulation to find reliable information that helps to improve the

483   numerical simulation results.

484   **ACKNOWLEDGEMENTS**

492 **COMPETING INTERESTS**

493 The authors declare that they have no competing interests.

494 **DATA AVAILABILITY**

495 Some or all data, models, or code that support the findings of this study are available from the

496 corresponding author upon reasonable request.

497 **References**

498 Al-Jabri, K. S., A. W. Hago, A. S. Al-Nuaimi, and A. H. Al-Saidy. (2005). Concrete blocks for thermal

499 insulation in hot climate. *Cement & Concrete Research.* 35(8): 1472-1479.

500 Al-Khaiat, H., and M. N. Haque. (1998). Effect of initial curing on early strength and physical

501 properties of a lightweight concrete. *Cement & Concrete Research.* 28(6): 859-866.

502 Bilodeau, A., V. K. R. Kodur, and G. C. Hoff. (2004). Optimization of the type and amount of

503 polypropylene fibres for preventing the spalling of lightweight concrete subjected to

504 hydrocarbon fire. *Cement and Concrete Composites.* 26(2): 163-174.

505 Bingoel, A. F., A. Tortum, and R. Gul. (2013). Neural networks analysis of compressive strength of

506 lightweight concrete after high temperatures. *Materials and Design.* 52: 258-264.

507 Bogas, J. A., and T. Gomes. (2015). Mechanical and Durability Behaviour of Structural Lightweight

508 Concrete Produced with Volcanic Scoria. *Arabian Journal for ence and Engineering.* 40(3):

509 705-717.

510 Bouguerra, A., A. Ledhem, F. D. Barquin, R. M. Dheilly, and M. Quéneudec. (1998). Effect of

511 microstructure on the mechanical and thermal properties of lightweight concrete prepared

512 from clay, cement, and wood aggregates. *Cement & Concrete Research.* 28(8): 1179-1190.

513 BSI (British Standards Institution). (2013). *Eurocode 4: Design of composite steel and concrete*

514 *structures. Part 1–2: General rules; structural fire design.* BS ENV 1994-1-2. London: BSI.

515 CABR (China Academy of Building Research). (2006). *Technical specification for lightweight*

516 *aggregate concrete (JGJ51-2002J215-2002).* China: CABR.

517 Cai, B., B. Li, and F. Fu. (2020). Finite Element Analysis and Calculation Method of Residual Flexural

518 Cai, B., B. Zhang, and F. Fu. (2019). Post-fire reliability analysis of concrete beams retrofitted with

519 CFRPs: a new approach. *Structures and Buildings.* 173(11): 888-902.

520 Cai, B., Y. Tao, and F. Fu. (2021). Residual Stress-strain relationship of scoria aggregate concrete with

521 addition of PP fiber after fire exposure. *Fire,*.

522 Capacity of Post-fire RC Beams. *International Journal of Concrete Structures and Materials*,

523 14(1): 58-75.

524 Chen X, Wan D, Jin, L Qian,K Fu F (2019), Experimental studies and Microstructure Analysis for Ultra

525 High-Performance Reactive Powder Concrete, Construction & Building Materials 2019, 229,

526 116924

527 Chen, B., and J. Liu. (2008). Experimental application of mineral admixtures in lightweight concrete

528 with high strength and workability. *Construction and Building Materials.* 22(6): 1108-1113.

529   Choi, E. G., and Y. S. Shin. (2011). The structural behavior and simplified thermal analysis of

530   normal-strength and high-strength concrete beams under fire. *Engineering Structures.* 33(4):

531   1123-1132.

532   Chung, J. H., and G. R. Consolazio. (2005). Numerical modeling of transport phenomena in reinforced

533   concrete exposed to elevated temperatures. *Cement and Concrete Research.* 35(3): 597-608.

534   Clarke, J. L. (1993). Structural lightweight aggregate concrete. CRC Press, London. 33: 45-47.

535   Fu F (2020), Fire induced Progressive Collapse Potential assessment of Steel Framed Buildings using

536   machine learning, Journal of Constructional Steel Research 2020, 166, 105918

537   Fu F, Parke GAR (2018),Assessment of the Progressive Collapse Resistance of Double-Layer Grid

538   Space Structures Using Implicit and Explicit Methods,International Journal of Steel Structures,

539   pp 18(3), pp. 831–842

540   Fu, F., Lam, D., Ye, J.(2008) Modelling semi-rigid composite joints with precast hollowcore slabs in

541   hogging moment region,Journal of Constructional Steel Research, 2008, 64(12), pp. 1408–

542   1419

543   Fu, F., Lam, D., Ye, J.(2010) Moment resistance and rotation capacity of semi-rigid composite

544   connections with precast hollowcore slabs,Journal of Constructional Steel Research, 2010,

545   66(3), pp. 452–461

546   Habib, U. R. D., R. Şahin, and R. Gul. (2004). The effects of different cement dosages, slumps, and

547   pumice aggregate ratios on the thermal conductivity and density of concrete. *Cement and*

548   *Concrete Research*. 34(5): 845-848.

549   Hu, C. P., Y. Y. Xu, Y. Luo, Y. L. Zheng, B. L. Lin. (2014). Experimental study on the tensile strength

550   of concrete after high temperature. *Journal of Huaqiao University (Natural Science).* 35(2):

551   196-201.

552   Ilango, S., and S. Mahato. (2020). Behaviour of polypropylene fibre-reinforced concrete beam with

553   CFRP reinforcement under elevated temperature. *Asian Journal of Civil Engineering.* 21:

554   677-694.

555   ISO. (1999). *Fire resistance tests -Elements of building construction. Part 1: General requirements.*

556   ISO 834-1. Geneva: ISO.

557   Kaid, N., M. Cyr, S. Julien, and H. Khelafi. (2009). Durability of concrete containing a natural

558   pozzolan as defined by a performance-based approach. *Construction & Building Materials.*

559   23(12): 3457-3467.

560   Kodur, V. K. R., M. B. Dwaikat, and R. S. Fike. (2010). An approach for evaluating the residual

561   strength of fire-exposed RC beams. *Magazine of Concrete Research*. 62(7): 479-488.

562   Lemougna, P. N., K. T. Wang, Q. Tang, A. N. Nzeukou, N. Billong, U. C. Melo, and C. Xue. (2018).

563   Review on the use of volcanic ashes for engineering applications. *Resources Conservation &*

564   *Recycling.* 137: 177 -190.

565   Li, W. S., X. Wang, J. L. Xia, Y. X. Zhou, and G. H. Li. (2018). Study on the impact of the aggregate

566   system on natural volcanic lightweight aggregate concrete performance. *Building Science.*

567   34(3): 76-81.

568   Liu F, Fu F, Wang Y, Liu Q (2017), Fire performance of non-load-bearing light-gauge slotted steel stud

569   walls,Journal of Constructional Steel Research 137, 228-241

570   Lo, T. Y., F. C. Sham, H. Z. Cui, and W. C. P. Tang. (2008). Study of short-term shrinkage and creep of

571   lightweight concrete. *Materials Research Innovations.* 12(3): 151-154.

572   Lu, Z. D., Z. B. Long, and Y. H. Zhou. (1993). Experimental study on fire response of simple supported

573   reinforced concrete beams. *Journal of Civil Engineering*. 26(3): 47-54.

574   Lublóy, É., and B. György. (2014). Temperature effects on bond between concrete and reinforcing steel.

575   *Zbornik radova Građevinskog fakulteta.* 30: 27-35.

576   Park J, S. Y., T. H. Kwon, and K. Park. (2017). Assessment of speckle-pattern quality in digital image

577   correlation based on gray intensity and speckle morphology. *Optics and Lasers in Engineering.*

578   91: 62-72.

579   Posi, P., S. Lertnimoolchai, V. Sata, T. Phoo-ngernkham, and P. Chindaprasirt. (2014). Investigation of

580   properties of lightweight concrete with calcined diatomite aggregate. *Ksce Journal of Civil*

581   *Engineering.* 18(5): 1429-1435.

582   Rasoul, Z., M. S. Radhi, A. J. Alsaad, and H. Muhannad. (2020). Elevated temperature performance of

583   reinforced concrete beams containing waste polypropylene fibers. *Case Studies in Thermal*

584   *Engineering*. 21: 100705.

585   Sakashita, M. (1997). Deflection of continuous fiber reinforced concrete beams subject to loaded

586   heating in non-metallic (FRP) reinforcement for concrete structures. *Proceedings of 3th*

587   *international symposium, Japan Concrete Institute.* 2: 51-58.

588   Sun, J. F., X. D. Shi, and Z. H. Guo. (2002). Experimental study on mechanical properties of 3-face

589   heated reinforced concrete beams at elevating temperature and after cooling. *Building*

590   *Structure.* 32(1): 34-36.

591   Topu, L. B. (1997). Semi lightweight concretes produced by volcanic slags. *Cement and Concrete*

592   *Research.* 27(1): 15-21.

593   Wang L, Shen N, Zhang M, Fu F, Qian K (2020), Bond performance of Steel-CFRP Bar reinforced

594   Coral Concrete beams, Construction and Building Materials 2020, 245, 118456

595   Wang, Y., Y. Q. Jiang, Z. H. Huang, L. Z. Li, Y. Huang, Y. J. Zhang, G. Y. Zhang, X. Y. Zhang, and Y. K.

596   Duan. (2020). Post-fire behaviour of continuous reinforced concrete slabs under different fire

597   conditions - ScienceDirect. *Engineering Structures.* 226: 111342.

598   Xu, Y. Y., B. Wu, R. H. Wang, M. Jiang, and Y. Luo. (2013). Experimental study on residual

599   performance of reinforced concrete beams after fire. *Journal of Building Structures.* 34(8):

600   20-29.

601   Yang, D. L., B. Li, W. S. Lin, J. L. Xia, Y. X. Zhou. (2017). Domestic and overseas research and

602   utilization on lightweight aggregate concrete prepared with scoria. *The World of Building*

603   *Materials*. 38(2): 26-30.

604   Yasar, E., C. D. Atis, A. Kilic, and H. Gulsen. (2003). Strength properties of lightweight concrete made

605   with basaltic pumice and fly ash. *Materials Letters.* 57(15): 2267-2270.

606   Yu, Z. W., F. X. Ding, J. P. Luo. (2005). Experimental research on mechanical properties of different

607   type of concrete after high temperature. *Journal of Safety and Environment.* 5(5): 1-6.

608 **Table**

609 **Table 1 Main technical parameters of polypropylene fiber**

Material	Proportion	Tensile strength （N/mm²）	Elastic modulus （N/mm²）	Fiber diameter （um）	Ultimate tension	Melting point （℃）
Parameters	1.18	＞736	＞7.18	10~15	15%	160~170

610 **Table 2 Mix proportion of concrete (kg/m³)**

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

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

612 **Table 3 Basic parameters of the reinforcement**

Type of reinforcement	Specification of steels	Yield strength （N/mm²）	Ultimate strength （N/mm²）	Elastic modulus （×10⁵N/mm²）
Pulled	HRB400	469	583	2.05

Compressed	HRB400	469	583	2.05
Stirrup	HPB300	346	431	2.13

613

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

614

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

615

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

T (°C)	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

616

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

617

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

618