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Stress-strain relationship for recycled aggregate concrete after exposure to elevated temperatures

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Abstract. In this paper, the effects of elevated temperatures on the strength and compressive stress-strain curve (SSC) of recycled coarse aggregate concrete with different replacement percentages are presented. 90 recycled coarse aggregate concrete prisms are heated up to 20, 200, 400, 600, 800°C. The results show that the compressive strength, split tensile strength, elastic modulus of recycled aggregate concrete specimens decline significantly as the temperature rise. While the peak strain increase of recycled aggregate concrete specimens as the temperature rise. Compared to the experimental curves, the proposed stress-strain relations for recycled aggregate concrete after exposure elevated temperatures can be used in practical engineering applications.

Keywords: recycled aggregate; concrete; stress-strain relationship; temperature; strength

1. Introduction

In recent years, the reuse of waste concrete as recycled concrete aggregates (RAC) to replace natural aggregates for new concrete had emerged as a feasible technique for recycling waste concrete. And it can help in solving a growing solid waste challenge, preserving natural aggregate resources from depletion.

The use of waste concrete as recycled aggregates in new concrete had been studied by many researchers. Their works were carried out to examine the mechanical properties and durability of recycled aggregate concrete, and structural performance of members cast with recycled aggregate concrete. Pandurangan *et al*. (2016) compared the effect of treatment methods on the bond strength of reinforcement with recycled aggregate concrete and determined the physical properties, mechanical properties, the compressive strength and bond strength. They found that several methods such as acid treatment, thermal treatment, mechanical treatment, etc. were available to improve the quality of recycled concrete aggregate and the bond strength of recycled aggregate concrete. Li *et al.* (2016) studied the strength indexes and failure pattern of a new type of recycled aggregate concrete (RAC) with waste concrete as large-size recycled coarse aggregates (LRCA).

They found that when the maximum size of LRCA was 80 mm, and the incorporation rate of LRCA reached 40%, the cube compressive strength was only decreased by 14%.

When the incorporation rate of LRCA was lower than 30%, no significant reduction appears in cube compressive strength.

The ratio of axial compressive strength to cube compressive strength of RAC with 80 mm maximum size of LRCA was 12% lower than that of corresponding NAC. The difference of splitting tensile strength between this type of RAC and corresponding NAC was lower than 10%. Tam *et al*. (2016) investigated the use of carbon-conditioned recycled aggregate in concrete production. They found that the use of carbon-conditioned recycled aggregate could improve physical and mechanical properties of recycled concrete and provided insight for effective use of recycled aggregate for concrete production. Suman and Rajasekaran (2016) studied mechanical properties of recycled aggregate concrete produced with Portland Pozzolana Cement. Yaragal *et al*. (2016) reported processing Recycled Coarse Aggregates (RCA) using a rod mill. Abdollahzadeh *et al*. (2016) proposed 20 models for predicting compressive strength of recycled aggregate concrete (RAC) containing silica fume by using gene expression programming.

Silva *et al*. (2015) provided a systematic literature review, based on the identification, appraisal, selection and synthesis of publications relating to the effect of incorporating recycled aggregates sourced from construction and demolition wastes, on the creep behavior of concrete. And correction factors of the creep coefficient of concrete with varying recycled aggregate content were presented. Peng *et al*. (2015) studied the strength and drift capacity of squat recycled concrete shear walls under cyclic loading. It was found that increasing of axial load level resulted in a higher peak load but less ultimate drift capacity, and increasing of horizontal web reinforcement had small effect on peak load but could improve the drift capacity. And a simplified analytical method was developed to predict the peak loads of squat walls failed in flexure or a mixed flexural-diagonal compression mode. Duan and Poon

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Table 1 Physical properties of natural coarse aggregates

Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Silt content (%)	Crushing value (%)
5-31.5	1493	2750	0.5	4.1	5.1

Table 2 Physical properties of river sand

Fineness modulus	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption(%)	Silt content (%)
2.6	1460	2570	1.13	1.56

Table 3 Physical properties of recycled coarse aggregates

Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Silt content (%)	Crushing value (%)
5-31.5	1385	2490	4.2	5.5	13.2

Table 4 Mix proportion of the recycled aggregate concrete

Index	Recycled aggregate content (%)	Recycled coarse aggregate (kg·m^{-3})	Cement (kg·m^{-3})	Sand (kg·m^{-3})	Natural coarse aggregate (kg·m^{-3})	Water (kg·m^{-3})
NC	0	0	430	555	1295	185
RAC50	50	625	430	522	625	185
RAC100	100	1178	430	492	0	185

(2014) presented the experimental results of a study on comparing the difference in properties of recycled aggregates (RAs) with varying amounts of old adhered mortar obtained from different sources and evaluating the influence of the different RAs on the mechanical and durability properties of recycled aggregate concrete (RAC). The experimental results show that the performance of RAs from different sources varied greatly and RA of good quality can be used to produce high strength concrete with hardened properties comparable to those of the corresponding natural aggregate concrete. Letelier and Moriconi (2014) analyzed the behavior of three beam-column joints under cyclic loading. The experimental results showed that a behavior under cyclic loading of the concrete made with 30% replacement of natural by recycled aggregates quite similar to ordinary concrete. All these studies covered some topics, such as compressive strength, tensile strength, bond strength of recycled aggregate concrete, shear performance and seismic performance of recycled aggregate concrete members.

Fire represented one of the major risks to building structures. A few studies had been made on the residual mechanical properties of recycled aggregate concrete after to elevated temperatures or fire such as compressive strength, splitting tensile strength. Yang *et al*. (2016) studied the shear behavior of concrete with different levels of recycled coarse aggregate after being subjected to different temperatures. As the temperature elevated, the residual shear strength and shear modulus declined rapidly whereas the peak strain increased linearly. And the shear stress-strain equations for RCA-embedded concrete after exposure to different temperatures. Laneyrie *et al.* (2016) investigated recycled coarse aggregate concrete after exposure to temperatures up to 750℃ by considering laboratory and industrial recycled coarse aggregate, and normal and high performance concretes. The results showed that the residual performances for the recycled concretes were generally similar to but slightly worse than those observed for the reference concrete. The presence of non-cementitious impurities accelerated the damage of concretes with temperature. Chen *et al*. (2014) presented an experimental investigation into the compressive properties of steel fiber reinforced recycled aggregate concrete cylinders after exposure to elevated temperatures, including the compressive strength, Young's modulus (stiffness), stress-strain curve and energy absorption capacity (toughness). The test results showed that both compressive strength and stiffness of the concrete were significantly reduced after exposure to high temperatures. The addition of steel fibers was helpful in preventing spalling, and significantly improved the ductility and the cracking behavior of recycled aggregate concrete (RAC) after exposure to high temperatures. However, the stress-strain equation for recycled aggregate concrete after elevated temperatures had rarely been reported.

In this study, the purposes are to establish a single equation of stress-strain relation for recycled aggregate concrete after elevated temperatures. The influences of recycled coarse aggregate and elevated temperatures on the peak strain, the shape of the stress-strain curve, and the elastic modulus are analyzed.

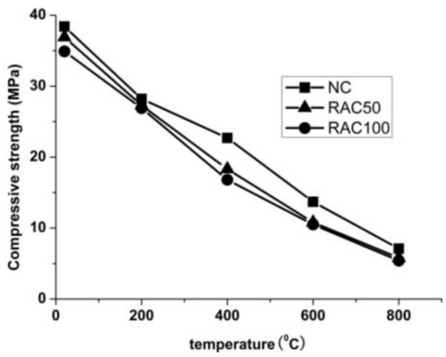
Fig. 1 Test setup

2. Experimental programme

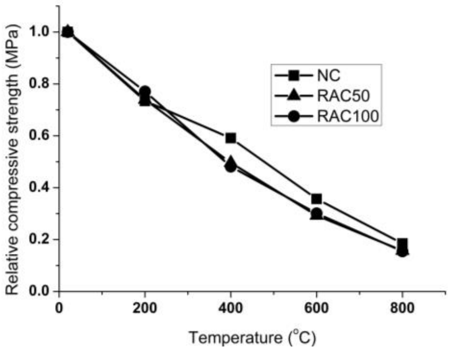
2.1 Materials

Ordinary Portland cement with a 28 day compressive strength of 42.5 MPa was used in this investigation. The coarse aggregate were natural coarse aggregates and recycled coarse aggregates obtained from waste concrete brought from the reclamation depot in Nanchang, PR China, which in the range 5-31.5 mm.

The used fine aggregates were river sand. Table 1 lists the physical properties of natural coarse aggregates. Table 2

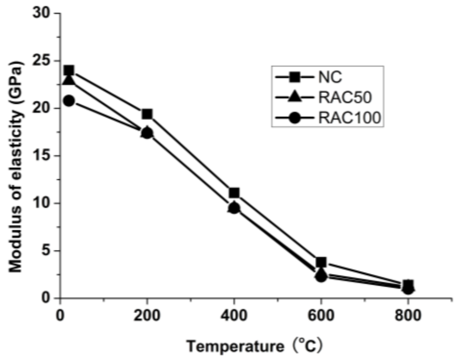


(a) Effect of temperature on compressive strength

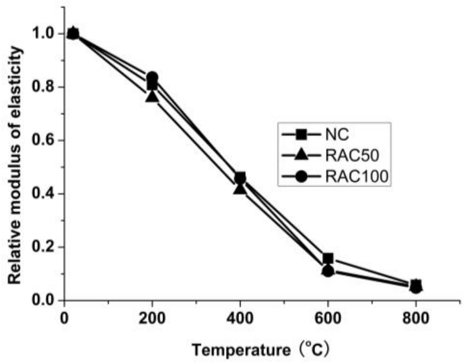


(b) Effect of temperature on relative compressive strength

Fig. 2 Effect of elevated temperature on concrete compressive strength



(a) Effect of temperature on elastic modulus



(b) Effect of temperature on relative elastic modulus

Fig. 3 Effect of elevated temperature on concrete elastic modulus

lists the physical properties of river sand. Table 3 lists the physical properties of recycled coarse aggregate.

2.2 Mix proportions

Table 4 provides the design of the concrete mix. Researchers prepared a total of three different concrete mixes using water-cement ratio of 0.43. The main difference between these mixes is recycled coarse aggregate replacement percentage, which is 0%, 50% and 100%, respectively. The percentage of the substitution is from the volume of aggregate. In the case of a recycled coarse aggregate replacement percentage equals 0%, the concrete is the normal concrete, which served as the reference concrete. Due to the density of recycled coarse aggregate was smaller than that of natural coarse aggregate. Compared to NC, the proportion of the sand used in RAC 50 and RAC 100 decreased.

2.3 Mixing, casting and curing

The preparation and the cure of all the mixes were conducted in the State Key Laboratory for Concrete Material Research at East China Institute of Technology in Nanchang, PR China. For each mix at each temperature, six 100×100×300 mm prisms were cast. All mixing was conducted under laboratory conditions. And the three mixtures kept having the same work ability. The dry cement and aggregates were mixed for 1 min in a 0.05 m^3 laboratory mixer. The mixing continued for further 1 min while about 70% of water was added. The mixing was continued for another 1 min. After 24 h, the specimens were demoulded and cured in a fog room (20±℃, 95% relative humidity) for 28 days. After casting, the concrete specimens were kept in their moulds for 24 h at room temperature (20±2℃). After 24 h, the specimens were demoulded and cured in a fog room (20±2℃, 95% relative humidity) for 28 days, and then dried in a room temperature for 7 days to maintain the normal water content, which was 4.1%.

2.4 Testing

The concrete specimens were heated in an electric furnace to temperatures of 200, 400, 600, 800℃. In order to ensue that the temperatures in the centre of the concrete specimens also reached the target temperature, the temperature was maintained at 200, 400, 600, 800℃ for 3 h respectively.

The heating rate was set to 20℃/min. After completion of the heating regimes, the heated concrete specimens were then cooled to room temperature. The compressive behavior of concrete specimen for each mix proportion was tested according to JGT/T70-2009. The loading setup was a YAW-3000 microcomputer controlled electro-hydraulic servo tester, as shown in Fig. 1. In order to get the complete stress-strain curves, the drift rate of the test specimens was kept constant to 0.3 mm/min. During the experiment, the axial compression and the longitudinal deformation of the test specimens were automatically collected by the computer installed.

3. Results and discussion

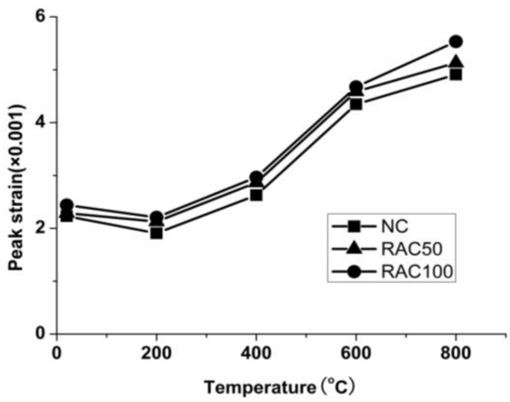


Fig. 4 Effect of elevated temperature on concrete peak strain

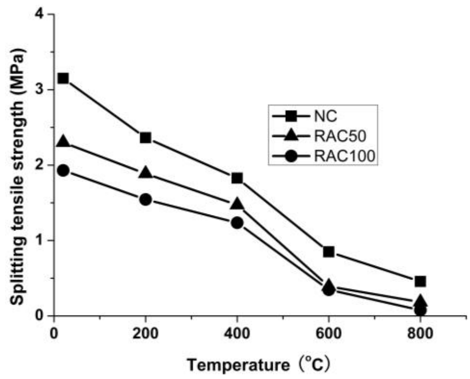
3.1 Residual compressive strength

Fig. 2 shows the variation of the residual compressive strengths for recycled aggregate concrete specimens with temperature. It is shown that the compressive strength of recycled aggregate concrete specimens decline significantly as the temperature rise. The compressive strength at 200℃ was 73.9% and 77.1%, of the original compressive strength (at 20℃) for RAC50, RAC100, respectively; at the same temperature for NC that was 73.4%. The slight decrease in recycled aggregate concrete specimens strength in the temperature range from 20 to 200℃ is attributed to the softening of the cement gel or attenuating the surface forces between gel particles. When the temperature range from 200 to 400℃, the compressive strength of recycled aggregate concrete specimens dropped rapidly. At 400℃, the compressive strength for recycled aggregate concrete specimens was about 50% of that at 20℃. Above 400℃, the recycled aggregate concrete specimens had a larger compressive strength loss. The reason is that the dehydration of the cement paste results in gradual deterioration of the concrete microstructure. With further increase in temperature up to 800℃, the residual compressive strength of NC, RAC50, RAC100 was 18.5%, 15.7%, 15.5%, respectively.

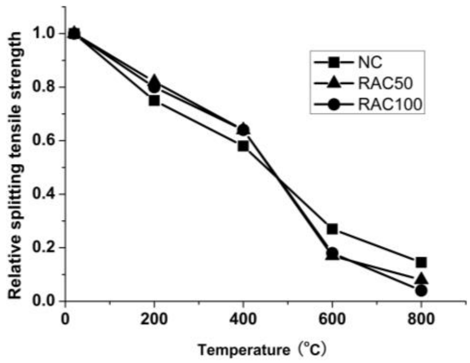
The recycled aggregate replacement rate has certain effect on compressive strength of recycled aggregate concrete specimens. At the same temperature, the compressive strength of recycled aggregate concrete specimens declines with the increase of the recycled aggregate replacement rate.

3.2 Residual elastic modulus in compression

Fig. 3 shows the effect of elevated temperature on residual elastic modulus of recycled aggregate concrete. As it can be seen from Fig. 3, for all concrete specimens, the elastic modulus decreased with the increase in temperature, and the decrease was much quicker than the decrease in compressive strength. At 200℃, the residual elastic modulus of all concrete specimens was about 80.1%. For RAC100 specimens, it was further reduced to 45.7%, 11.1% and 4.8% after exposure to 400℃ and 600℃, 800℃, respectively. Above all, the losses in elastic modulus of recycled aggregate concretes were larger than the losses in compressive strength for the same temperature.



(a) Effect of temperature on tensile strength



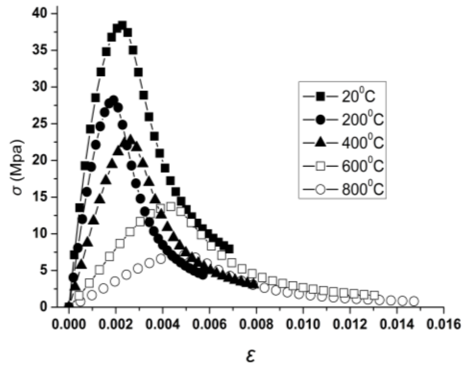
(b) Effect of temperature on relative tensile strength

Fig. 5 Effect of elevated temperature on concrete split tensile strength

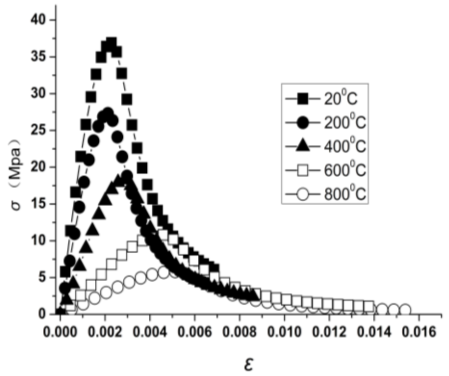
3.3 Peak strain

Fig. 4 presents the peak strains of recycled aggregate concrete specimens were lower than the original unheated values below 200℃. The peak strains of NC, RAC50, RAC100 at 400℃ were 1.18, 1.25 and 1.22 times of that at room temperature. Above 400℃, the peak strain increases rapidly with an increase in temperature, especially in the range of 600-800℃. The peak strain ratios at 600℃ were 1.95, 2.01 and 1.92 for NC, RAC50, RAC100, respectively. And peak strain ratios at 800℃ were 2.2, 2.24 and 2.27 for NC, RAC50, RAC100, respectively. The increase in the peak strain can be attributed to the cracks caused by the thermal incompatibility of aggregate and cement paste at elevated temperature. Fig. 4 reveals that the recycled aggregate replacement rate had some effect on the peak strain. At the same temperature, the peak strains of recycled aggregate concrete specimens with large recycled aggregate replacement rate were greater than that of recycled aggregate concrete specimens with small recycled aggregate replacement rate. Besides, the peak strains of recycled aggregate concrete specimens increase with the increase of the temperature.

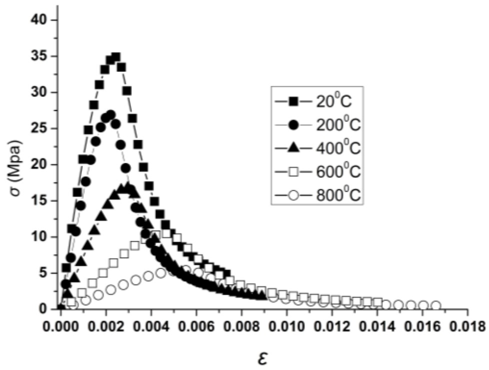
By the regression analysis, the relationship between the normalized peak strain $\varepsilon_0^T / \varepsilon_0$ and temperature T for different original peak strain ε_0 can be expressed with Eq. (1).



(a) Specimen NC



(b) Specimen RAC50



(c) Specimen RAC100

Fig. 6 Stress-strain curves of recycled aggregate concrete at different temperatures

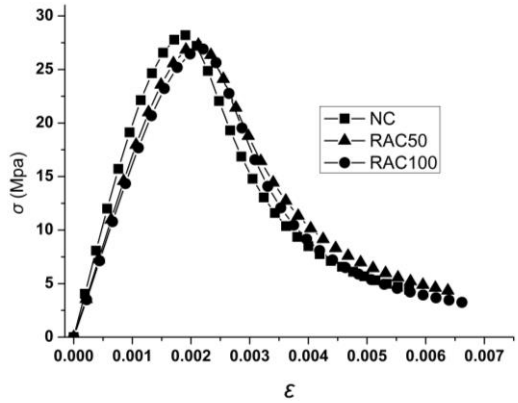
$$\frac{\varepsilon_0^T}{\varepsilon_0} = 0.915 + (0.1416 + 0.2638r - 0.226r^2)\left(\frac{T-20}{800}\right) + 1.311\left(\frac{T-20}{800}\right)^2 \quad (1)$$

$$20^0C \le T \le 800^0C$$

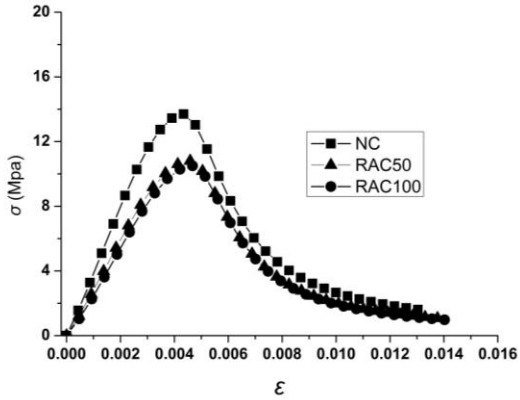
where ε_0^T is the peak strain of recycled aggregate concrete at elevated temperature, ε_0 is the peak strain of recycled aggregate concrete at 20℃, r is the recycled aggregate replacement rate, T is temperature in ℃.

3.4 Residual split tensile strength

Fig. 5 shows the effect of elevated temperature on residual split tensile strength of recycled aggregate concrete specimens. It can be seen that the split tensile strength of



(a) T=200℃



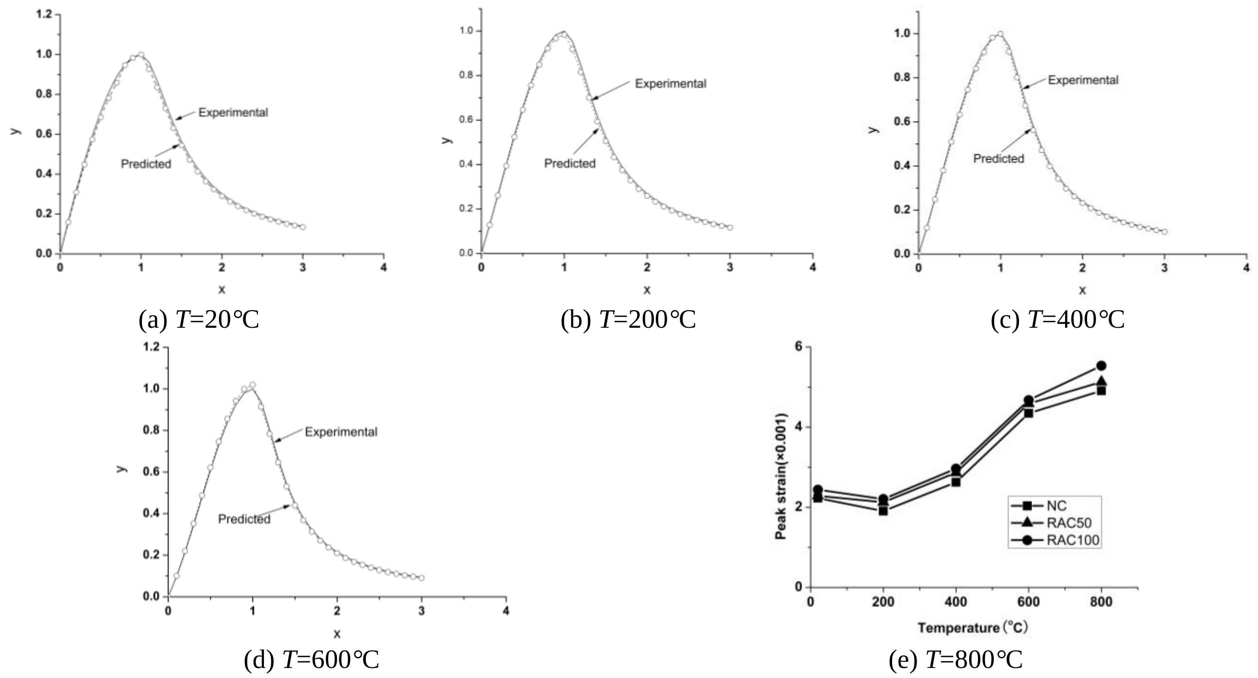
(b) T=600℃

Fig. 7 Stress-strain curves of recycled aggregate concrete after exposure to elevated temperature

recycled aggregate concrete specimens decreased with an increase in elevated temperature. After exposure to 200℃, the split tensile strength of NC, RAC50, RAC100 dropped by 25%, 18%, and 20%, respectively. As the elevated temperature increased to 400℃, the split tensile strength of recycled aggregate concrete specimens decreased drastically, with values of only 58%, 64% and 63.9% of the original strength for NC, RAC50, RAC100, respectively. With a further increase in elevated temperature to 600℃, the split tensile strength of NC, RAC50, RAC100 dropped by 73%, 83%, and 82%, respectively. After exposure to 800℃, the split tensile strength of NC, RAC50, RAC100 were just 14.5%, 8% and 4% of the initial strength, respectively. The reduction in split tensile strength may be attributed to the macrocracks and microcracks that occur in fire-damaged concrete. The recycled aggregate replacement rate had significant effect on the split tensile strength of recycled aggregate concrete specimens. The split tensile strength of NC was clearly higher than that of RAC50, RAC100 after to exposure to temperature at 200℃, 400℃, 600℃, 800℃.

3.5 Residual compressive stress-strain curves

Fig. 6 shows the residual complete stress-strain curves of recycled aggregate concrete at different temperatures. It can be seen that the elevated temperature has remarkable influences on the stress-strain curves of recycled aggregate



(a) T=20℃ (b) T=200℃ (c) T=400℃

(d) T=600℃ (e) T=800℃

Fig. 8 Comparison of the normalized stress-strain curves of RAC100

concrete. The shape of complete stress-strain curves of recycled aggregate concrete at different temperatures was different, and the shape of that varied with the temperature. And it also exhibited the compressive strength and modulus of elasticity decreased with the increasing temperature. After 200℃, the curvature of each ascending branch of recycled aggregate concrete decreased with the increasing temperature. Meantime, the peak strain value of increased recycled aggregate concrete with the temperature increased, which was particularly significant when the recycled aggregate is used with a replacement ratio of 100%. For RAC100, the peak strain at 800℃ was 2, 27 times the strain at room temperature. Roughly speaking, the stress-strain curves of glass fine aggregate concrete can be divided into three characteristic parts. The first part represents the linear portion and the second represents the nonlinear portion of the ascending branch, and the third part is the descending branch.

Fig. 7 shows the complete stress-strain curves of recycled aggregate concrete after exposure to elevated temperature. At the same temperature, all the concretes present very similar stress-strain curves regardless of the recycled aggregate replacement ratio. With the increase of recycled aggregate replacement ratio, it allows the increase of curvature of each ascending branch of recycled aggregate concrete. Consequently this increase leads to an increase in the peak strain value which is particularly significant when the recycled aggregate is used with a replacement ratio of 100%. Besides, the stress-strain curves of recycled aggregate concrete were that the shape of the descending branch was also similar for concretes with different recycled aggregate replacement ratio. Also the slope of their descending branch decreases when the percentage of recycled aggregate replacement ratio is increased.

4. Suggestion of the stress-strain relations

Numerous mathematical equations for the complete stress-strain relationship of unheated concrete have been suggested by many researchers (Guo and Zhang 1982, Hognestad *et al*. 1995, Yi *et al*. 2003, Wee *et al*. 1982). In this study the analytical expression suggested by Guo and Zhang (1982), adopted by Chinese Code GB50010 (2010), is used for recycled aggregate concrete at different temperatures by redefining some parameters. The normalized stress-strain relation of recycled aggregate concrete at different temperatures is approximated by the following equation

$$y=\begin{cases} ax+(3-2a)x^2+(a-2)x^3, 0\le x<1 \\ \dfrac{x}{b(x-1)^2+x}, x\ge 1 \end{cases} \quad (2)$$

In Eq. (2), $x=\varepsilon/\varepsilon_0$, $y=\sigma/f_c$, a and b are constants to be determined. The parameter a and b are the independent factors that control the shapes of the ascending and descending curves, respectively. According to Guo and Zhang (1982), the parameter a reflects the initial elastic modulus of recycled aggregate concrete. The parameter b is related to the area under the descending portion of the dimensionless stress-strain curve.

Based on the experimentally obtained stress-strain curves of recycled aggregate concrete at different temperatures, the parameters a and b were obtained by a data regression analysis. The results are given as follows

$$a=1.723-(1.951+0.083r)\left(\frac{T-20}{800}\right)+1.343\left(\frac{T-20}{800}\right)^2$$

$$20^0C\le T\le 800^0C \quad (3)$$

$$b=3.563+(3.605+2.317r)\left(\frac{T-20}{800}\right)-1.299\left(\frac{T-20}{800}\right)^2$$

where *T* is temperature in °C, *r* is the recycled aggregate replacement rate.

In Fig. 8(a)-(e), a comparison between the experimentally obtained and the approximated stress-strain curves provided by Eq. (2) is shown for RAC100 at different temperature. The approximate stress-strain curves agree quite well with those obtained experimentally. Hence, the approximate stress-strain relations for recycled aggregate concrete after exposure elevated temperatures can be used in practical engineering applications.

5. Conclusions

Based on the experimental results, the following conclusions can be drawn:

• The compressive strength of recycled aggregate concrete specimens decline significantly as the temperature rise. The recycled aggregate replacement rate has certain effect on compressive strength of recycled aggregate concrete specimens.

• The elastic modulus decreased with the increase in temperature, and the decrease is much quicker than the decrease in compressive strength. The split tensile strength of recycled aggregate concrete specimens decreased with an increase in elevated temperature. The peak strains of recycled aggregate concrete specimens increase with the increase of the temperature.

• The elevated temperature has remarkable influences on the stress-strain curves of recycled aggregate concrete. The shape of complete stress–strain curves of recycled aggregate concrete at different temperatures was different, and the shape of that varied with the temperature. At the same temperature, all the recycled aggregate concretes present very similar stress-strain curves regardless of the recycled aggregate replacement ratio.

• Equation for complete stress-strain relationship in compression of recycled aggregate concrete after exposure elevated temperatures is proposed to, which can be used directly in many practical engineering applications.

Acknowledgments

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