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Influence of high temperature on mechanical properties of concrete containing recycled fine aggregate

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Abstract. This paper presents the results of an experimental study to investigate the influences of high temperatures on the mechanical properties of concrete containing recycled fine aggregate. A total of 150 concrete prisms (100×100×300mm) and 150 concrete cubes (100×100×100 mm) are cast and heated under five different temperatures (20℃, 200℃, 400℃, 600℃, 800℃) for test. The results show that the mass loss, compressive strength, elastic modulus, splitting tensile strength of concrete specimens containing recycled fine aggregate decline significantly as the temperature rise. At the same temperature, the compressive strength, splitting tensile strength, elastic modulus of concrete specimens containing recycled coarse aggregate and recycled fine aggregate (RHC) is lower than that of concrete specimens containing natural coarse aggregate and recycled fine aggregate (RFC). The shape of stress–strain curves of concrete specimens at different temperatures is different, and the shape of that become flatter as the temperature rises. Normal concrete has better energy absorption capacity than concrete containing recycled fine aggregate.

Keywords: recycled fine aggregate; concrete; elastic modulus; temperature; strength

1. Introduction

Technology of recycled aggregate concrete (RAC) has attracted widely attention due to its distinguished environmental benefits, economic advantage and social returns. Now most of the research work focus on mechanical properties of recycled coarse aggregate concrete, such as compressive strength, tensile strength, flexural strength and elastic modulus (Xiao *et al*. 2012, Sagoe-Crentsil *et al*. 2001, Liu *et al*. 2011, Poon *et al*. 2002). And the durability of recycled coarse aggregate concrete has also been studied by many researchers (Kou *et al*. 2011, Kou *et al*. 2012). These research found that recycled coarse aggregate concrete has lower strength, lower elastic modulus, larger shrinkage and larger creep. Moreover, Xiao *et al*. (2005) studied the compressive stress-strain curves of recycled coarse aggregate concrete and put forward the formula for the peak strain and the stress-strain relationship of recycled coarse aggregate concrete. Besides, the mix designs of recycled coarse aggregate concrete and the mechanical performance of members cast with recycled coarse aggregate concrete have been studied (Tam *et al*. 2005, Ajdukiewicz *et al*. 2002, Yang and Han 2006, Choi and Yun 2012).

Katkhuda and Shatarat (2016) studied the shear behavior of reinforced treated recycled aggregate concrete beams and found that treated recycled aggregate improved slightly the shear capacity of the beams in comparison with natural and untreated recycled aggregate. Gonzalez and Moriconi (2015) analyzed the behavior of three beam–column joints under cyclic loading. Ma *et al.* (2015) presented and analyzed the crack status, failure modes, hysteresis loops, skeleton curves, energy dissipation capacity and ductility of steel reinforced recycled concrete columns. The results show that the steel reinforced recycled concrete short column has poor ductility and brittle shear failure, and that the steel reinforced recycled concrete long column has excellent ductility and ductile flexural failure. These results showed that concrete with coarse recycled aggregates can be used in engineering structures.

The fire resistance behaviour and design of concrete structures are one of the key issues. Mohammad *et al*. (2015) investigates the post heating behavior of concrete beams reinforced with fiber reinforced polymer (FRP) bars, namely carbon fiber reinforced polymer (CFRP) bars and glass fiber reinforced polymer (GFRP) bars investigates the post heating behavior of concrete beams reinforced with fiber reinforced polymer (FRP) bars, namely carbon fiber reinforced polymer (CFRP) bars and glass fiber reinforced polymer (GFRP) bars. Farhad and Bijan (2015) developed the bond constitutive relationships for normal and high-strength concrete subjected to fire. Raizal and Riyad (2014) proposed the confinement model that reflected the effects of elevated temperature on the mechanical properties of CFRP strengthened circular RC column. Yu and Lu (2015) studied influence of softening curves on the residual fracture toughness of post-fire normal-strength concrete. A few studies have been made on the residual mechanical properties of recycled coarse aggregate concrete after to elevated temperatures or fire such as compressive strength,

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splitting tensile strength (Zega *et al*. 2006, Zega *et al*. 2009, Xiao *et al*. 2007, Vieira *et al*. 2011, Cree *et al*. 2013). 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, stress–strain curve and energy absorption capacity. The test results showed that both compressive strength and stiffness of the concrete are 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. Laneyrie *et al*. (2016) investigates recycled coarse aggregate concretes after exposure to temperatures up to 750℃ by considering laboratory and industrial recycled coarse aggregate, and normal and high performance concretes. The test results showed that the residual performances for the recycled concretes were generally similar to but slightly worse than those observed for the reference concretes. The presence of non-cementitious impurities accelerates the damage of concretes with temperature. 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 elevates, the residual shear strength and shear modulus declined rapidly whereas the peak strain increased linearly. It was found that the aforementioned mechanical parameters are minimally influenced by the recycled coarse aggregate content at ambient temperature (about 20℃). After exposure to high temperatures, the recycled coarse aggregate content affects the shear strength insignificantly but increases the peak strain slightly. The object of these investigations was to determine the strength and deformation of recycled coarse aggregate concrete after exposed to high temperatures.

The use of recycled fine concrete aggregate as sand in concrete has been studied by several other researchers. Pedro *et al*. (2017) analysed the effects of the variation of different types of recycled concrete aggregates on structural concrete. Vinay *et al*. (2017) study deals with utilization of coarse recycled concrete aggregate and fine recycled concrete aggregate in high performance concrete mixes. Fan *et al*. (2016) studied the properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. Zhao *et al*. (2015) studied the influence of fine recycled concrete aggregates on the fresh properties, mechanical properties and interfacial transition zone (ITZ) microstructure of mortars. (Evangelista and de Brito 2009, Padmini *et al*. 2009). Their works have revealed that recycled fine aggregate lowers the quality of the concrete in mechanical strength and durability. Recycled concrete fine aggregates can be a promising solution for sustainable development. For buildings, the high temperature performance is critical to estimate fire resistance. However, the mechanical properties of recycled fine aggregate concrete after high temperatures have rarely been reported. In this study, the influences of high temperatures on the mass loss, compressive strength, splitting tensile strength, elastic modulus, stress-strain curve, and the energy absorption capacity are presented and analyzed. The results present in this paper are valuable for achieving a better understanding of the role of recycled fine aggregate in the performance of concrete after exposure to high temperatures, and should be helpful to expand the application of recycled fine aggregate concrete in structures.

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)	Silt content (%)
2.6	1460	2570	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 Physical properties of recycled fine aggregates

Fineness modulus	Water absorption (%)	Apparent density (kg/m^3)	Silt content (%)
3.2	16.6	2480	4.27

2. Experimental programme

2.1 Materials

Ordinary Portland cement with a 28d compressive strength of 42.5 MPa was used in this investigation. The coarse aggregate used 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 and recycled fine aggregates obtained from waste concrete brought from the reclamation depot in Nanchang, PR China. Table 1 lists the physical properties of natural coarse aggregates. Table 2 lists the physical properties of riversand. Tables 3, 4 lists the physical properties of recycled coarse aggregate and recycled fine aggregate, respectively.

2.2 Mix proportions

Table 5 provides the design of the concrete mix. The main difference between these mixes are recycled coarse aggregate replacement percentage and recycled fine aggregate replacement percentage, which is 0%, 50% and 100%, respectively. In the case of a recycled coarse aggregate replacement percentage and recycled fine aggregate replacement percentage equal 0%, the concrete is the normal concrete, which served as the reference concrete. Due to the high water absorption of recycled aggregates, it

Table 5 Mix proportion of the recycled aggregate concrete (kg·m^{-3})

Mix	Recycled fine aggregate content(%)	Recycled coarse aggregate content (%)	Cement	Recycled coarse aggregate	Recycled fine aggregate	Natural sand	Natural coarse aggregate	Mixing water	Additional water
NC	0	——	430	——	——	555	1295	185	0
RFC50	50	——	430	——	264	264	1295	185	25
RFC100	100	——	430	——	527	——	1295	185	50
RHC50	50	50	430	625	264	264	625	185	35
RHC100	100	100	430	1178	527	——	——	185	70

Fig. 1 Heated setup

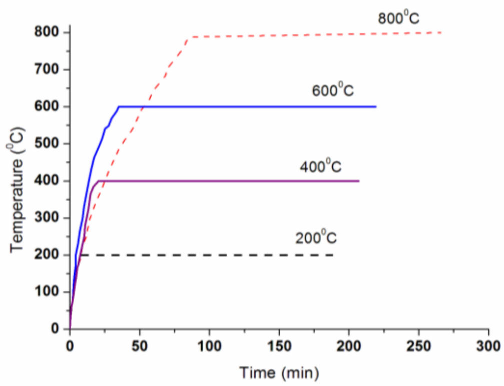


Fig. 2 Time-elevated temperature curves

was necessary to increase the total quantity of added water to assure the same effective water–cement ratio. This part of the water is called additional water, which was calculated from the measured effective water absorption (the water absorption from natural state to saturated surface dry) of the aggregates. The slump of the various mixes is approximately the same. The slump of NC, RFC50, RFC100, RHC50, RHC100 is 71 mm, 70 mm, 68 mm, 69 mm, 68 mm, respectively.

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 and six 100×100×100 mm cubes were cast. All mixing was conducted under laboratory conditions. 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±2℃, 95% relative humidity) for 28 days. After casting, the concrete specimens were kept in their moulds for 24h at room temperature(20±2℃). After 24h, 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.

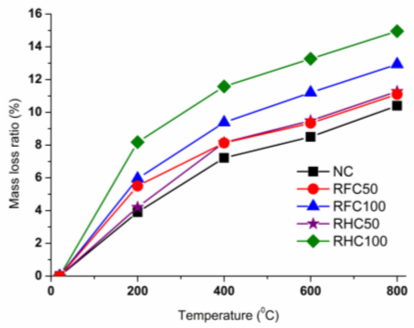
2.4 Testing

The concrete specimens were heated in an electric furnace to temperatures of 200, 400, 600, 800℃ as shown in Fig. 1; and the temperature was maintained at 200, 400, 600, 800℃ for 3h respectively. Fig. 2 showed the time-elevated temperature curves. After completion of the heating regimes, the heated concrete specimens were then cooled to room temperature. The mechanical 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. 2. 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 vertical deformation of the test specimens were automatically collected by the computer installed.

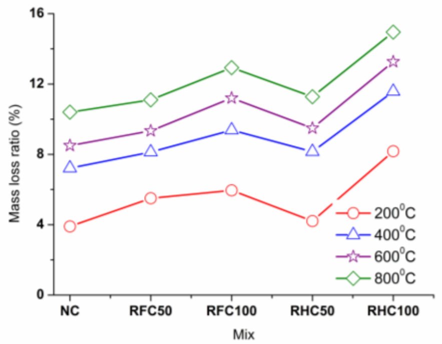
3. Results and discussion

3.1 Color change and mass loss

The color of concrete containing recycled fine aggregates is different after exposure to various temperatures. The surface of specimens is light grey at ambient temperature, then is turned to light red, straw yellow, gray white after exposure to 200℃, 400℃, 600℃, 800℃. The colour change of the specimens is associated with the chemical and physical changes experienced by the concrete materials after exposure to high temperatures. The influence of high temperature on the mass loss of all concrete specimens is shown in Fig. 3. It is shown that the mass loss of concrete specimens increase with the temperature increases. In the case of RHC50, the mass loss ratio is 4.21%, 8.15%, 9.49%, 11.28% after exposure to 200℃, 400℃, 600℃, 800℃, respectively. And the mass loss of RHC100 is the highest at various temperatures; however, the mass loss of NC is the lowest at various temperatures. The loss of weight of concrete is due to loss



(a) Influence of temperature on mass loss



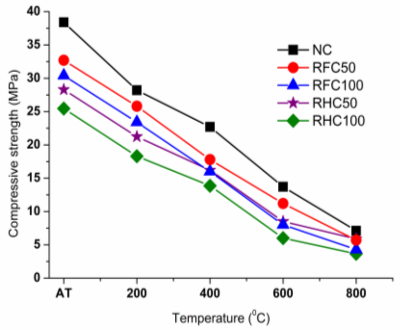
(b) Influence of recycled fine aggregate content on mass loss

Fig. 3 Influence of elevated temperature on concrete mass loss

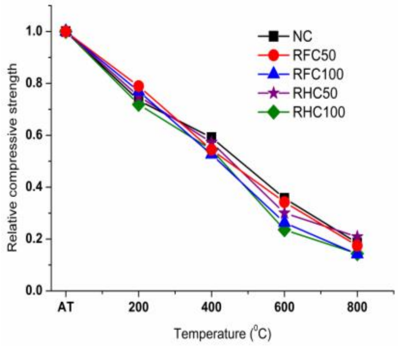
of free water and chemically bond water (in C-S-H, CH) is also decomposed from concrete which causes shrinkage of cement paste leading to the decomposition of concrete. It indicates that the recycled fine aggregate content has some influence on the mass loss of concrete after exposure to high temperature.

3.2 Compressive strength

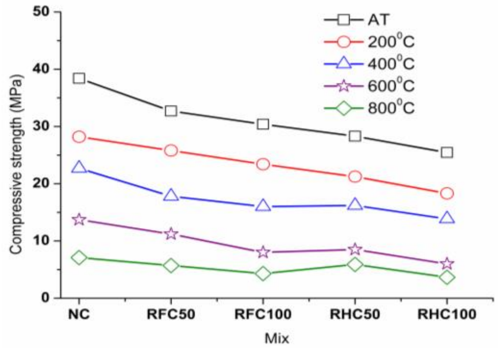
Fig. 4 shows the influence of high temperature on the residual compressive strengths of all concrete specimens. It is shown that the compressive strength of RHC specimens at ambient temperature (AT) is lower than RFC specimens. The compressive strength of NC specimen at ambient temperature (AT) is higher than RFC specimens and RHC specimens. With rising of temperature, the compressive strength of concrete containing natural coarse aggregate and recycled fine aggregate (i.e., RFC) specimens decrease. For RFC50, the compressive strength reduces to 78.9%, 54.4%, 34.3%, 17.4% of the unheated concrete (at AT) after exposure to 200℃, 400℃, 600℃, 800℃, respectively. For RFC100, the compressive strength reduces to 76.9%, 52.6%, 26.3%, 14.5% of the unheated concrete (at AT) after exposure to 200℃, 400℃, 600℃, 800℃, respectively. A similar behavior plays out in the concrete containing recycled coarse aggregate and recycled fine aggregate (i.e., RHC) specimens. When the temperature rises to 200℃, the compressive strength for RHC50, RHC100 reduces to 75.1%, 71.9%, respectively. And with further increase in temperatures, the compressive strength of RHC specimens continue to decrease. For RHC50, the compressive strength



(a) Influence of temperature on compressive strength



(b) Influence of temperature on relative compressive strength



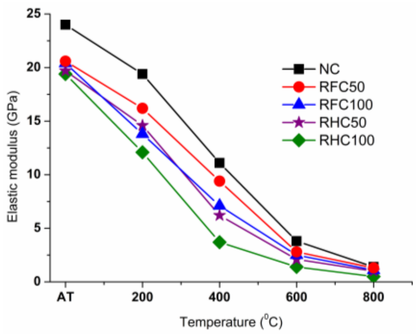
(c) Influence of recycled fine aggregate content on compressive strength

Fig. 4 Compressive strength of concrete at different temperatures (AT=ambient temperature around 20℃)

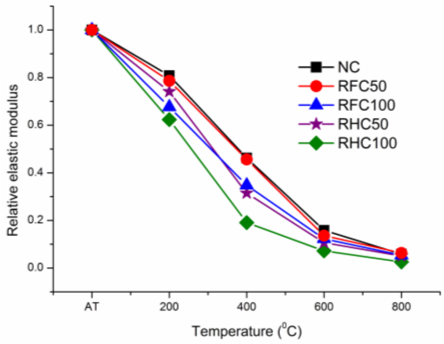
reduces to 57.2%, 30.1%, 20.8% after exposure to 400℃, 600℃, 800℃, respectively. The compressive strength degradation of concrete specimens may be attributed to that calcium silicate hydrate (C-S-H) decomposes after exposure to elevated temperatures. For RHC100, the compressive strength reduces to 54.5%, 23.6%, 14.3% after exposure to 400℃, 600℃, 800℃, respectively. At the same temperature, the compressive strength of RHC specimens is lower than that of RFC specimens. It can be also seen that the compressive strength decreases with the recycled fine aggregate replacement rate increase irrespective of temperature.

3.3 Elastic modulus in compression

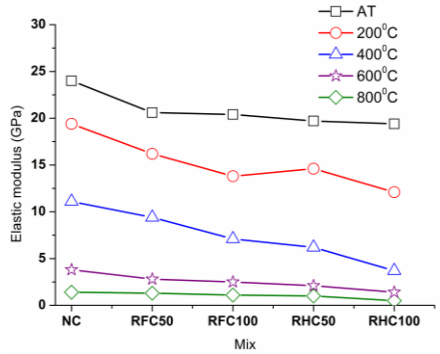
The influences of high temperature on the residual elastic modulus in compression of all concrete specimens



(a) Influence of temperature on elastic modulus



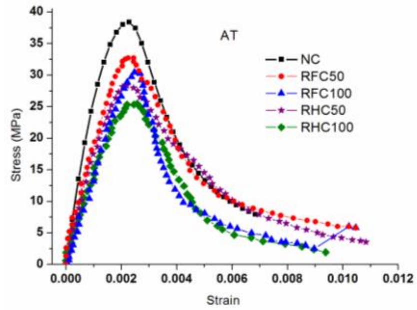
(b) Influence of temperature on relative elastic modulus



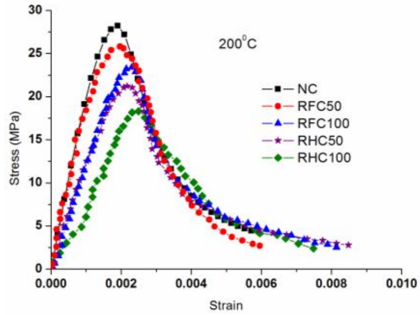
(c) Influence of recycled fine aggregate content on elastic modulus

Fig. 5 Elastic modulus of concrete at different temperatures (AT=ambient temperature around 20℃)

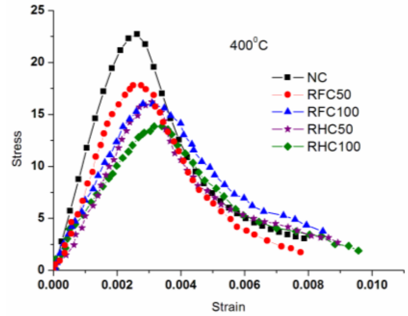
are shown in Fig. 5. It is shown that similar to the compressive strength, the elastic modulus of RHC specimens is lower than NC specimens and RFC specimens at ambient temperature (AT). And the elastic modulus of RFC specimens is lower than NC specimens at ambient temperature (AT). The concrete specimens show similar behavior, namely, the elastic modulus decreases with the temperature increases. For NC, the elastic modulus reduces to 80.8%, 46.3%, 15.8%, 5.8% of the unheated concrete after exposure to 200℃, 400℃, 600℃, 800℃, respectively. For RFC50, the elastic modulus reduces to 78.6%, 45.6%, 13.6%, 6.3% of the unheated concrete after exposure to 200℃, 400℃, 600℃, 800℃, respectively. For RFC100, the elastic modulus reduces to 67.6%, 34.8%, 12.3%, 5.4% of the unheated concrete after exposure to 200℃, 400℃, 600℃, 800℃, respectively. For RHC50, the elastic modulus reduces to 74.1%, 31.5%, 10.7%, 5.1% of the unheated concrete after exposure to 200℃, 400℃,



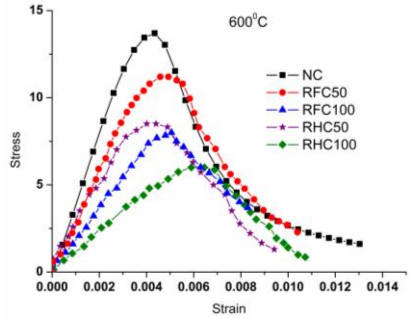
(a) Stress-strain curve of unheated concrete at AT



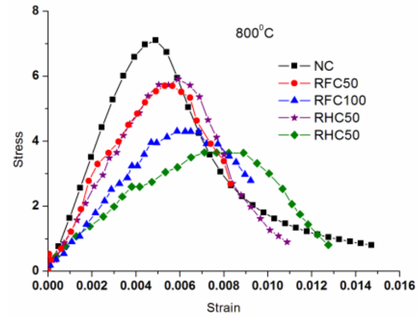
(b) Stress-strain curve of concrete after exposure to 200℃



(c) Stress-strain curve of concrete after exposure to 400℃



(d) Stress-strain curve of concrete after exposure to 600℃



(e) Stress-strain curve of concrete after exposure to 800℃

Fig. 6 Stress-strain curve of concrete after exposure to different temperatures (AT=ambient temperature around 20℃)

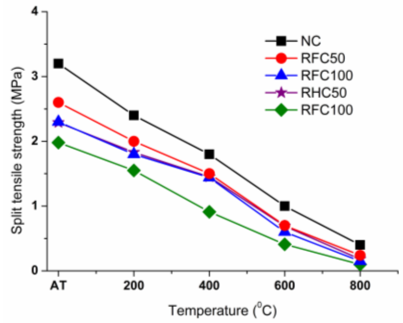
600℃, 800℃, respectively. For RHC100, the elastic modulus reduces to 62.4%, 19.1%, 7.2%, 2.6% of the unheated concrete after exposure to 200℃, 400℃, 600℃, 800℃, respectively. The reduction in elastic modulus of RHC specimens is more than that of RFC specimens and NC specimens. Fig. 5 is also shown that the elastic modulus decreases with the recycled fine aggregate replacement rate increase irrespective of temperature.

3.4 Compressive stress-strain curves

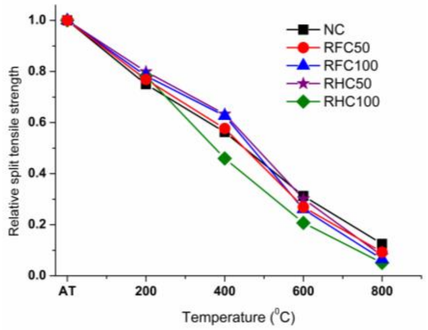
Fig. 6 shows the influence of high temperature on the compressive stress–strain curves of concrete specimens. It can be seen that the high temperature has remarkable influences on the stress–strain curves of concrete specimens. The shape of stress–strain curves of concrete specimens at different temperatures is different, and the shape of that varies with the temperature. Besides, the compressive stress–strain curves become flatter as the temperature rises. With the increase of the temperature, the slope of the each ascending branch of stress-strain curves is generally reduced. And the peak strain increases with the temperature rises. In the case of RFC100, the peak strains after exposure to 600℃ and 800℃ are 2.05 times and 2.38 times the a strain at ambient temperature. The peak strain of RFC specimens with higher recycled fine aggregate replacement rate is higher than that with lower recycled fine aggregate replacement rate. It is the same to RHC specimens, which is more obvious at higher exposure temperatures (i.e., 600℃ and 800℃). At the same temperature and recycled fine aggregate replacement rate, the peak strain of RHC specimens is higher than that of RFC specimens.

3.5 Splitting tensile strength

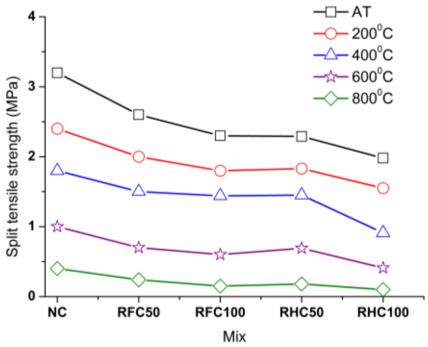
The influence of high temperature on the residual splitting tensile strengths of all concrete specimens is shown in Fig. 7. It is shown that similar to those of compressive strength and elastic modulus, the splitting tensile strength of RHC specimens at ambient temperature (AT) are also lower than RFC specimens and NC specimen. The splitting tensile strength of RFC specimens at ambient temperature (AT) is lower than NC specimens. Similarly, the splitting tensile strength of concrete specimens decreases with the increase of temperature. When exposure to 200℃, the splitting tensile strength reduces to 75%, 76.9%, 78.3%, 79.9%, 78.3% of the unheated concrete (at AT) for NC, RFC50, RFC100, RHC50, RHC100, respectively. After exposure to 400℃, the splitting tensile strength reduces to 56.3%, 57.7%, 62.7%, 63.3%, 45.9% for NC, RFC50, RFC100, RHC50, RHC100, respectively. After exposure to 600℃, the splitting tensile strength reduces to 31.3%, 26.9%, 26.1%, 30.1%, 20.7% for NC, RFC50, RFC100, RHC50, RHC100, respectively. With further increase in temperatures, the splitting tensile strength of RHC specimens continues to decrease sharply. After exposure to 800℃, the splitting tensile strength reduces to 12.5%, 9.2%, 6.5%, 7.8%, 5.1% for NC, RFC50, RFC100, RHC50, RHC100, respectively. The calcium silicate hydrate (C-S-H) which provides the



(a) Influence of temperature on splitting tensile strength



(b) Influence of temperature on relative splitting tensile strength



(c) Influence of recycled fine aggregate content on splitting tensile strength

Fig. 7 Splitting tensile strength of concrete at different temperatures (AT=ambient temperature around 20℃)

strength of the cement paste will decompose as the temperature increases, which causes the cement paste to loosen. It can lead to a great decrease in the residual splitting tensile strength. The splitting tensile strength of RHC specimens is lower than that of RFC specimens at various temperatures. It can be also seen that the splitting tensile strength decreases with the recycled fine aggregate replacement rate increase irrespective of temperature.

3.6 Energy absorption capacity (toughness)

The energy absorption capacity (toughness) of concrete in compression has been defined as the total area under stress-strain curve calculated up to a strain value (Nataraja *et al*. 1999, Lau *et al*. 2006). In this paper, the strain value is defined as the strain at 20% of the peak stress of the descending branch of stress-strain curve. Fig. 8 shows the influence of high temperature on energy absorption capacity

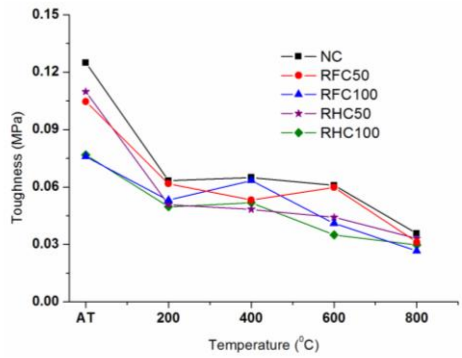


Fig. 8 Influence of recycled fine aggregate content on toughness

(toughness) of concrete specimens. It can be seen that the NC specimens has the high toughness at various temperature, which indicates normal concrete has better energy absorption capacity than concrete containing recycled fine aggregate. The toughness of RFC50 is higher than of RHC50 at the range of 200℃ -600℃. However, the toughness of RFC50 is lower than of RHC50 at the ambient temperature and 800℃, respectively. Similarly, the toughness of RFC100 is higher than that of RHC50 at the range of 200℃ -600℃; the toughness of RFC100 is lower than that of RHC100 at the ambient temperature and 800℃, respectively. At the same temperature, the toughness of concrete specimens decreases as the recycled fine aggregate replacement rate increases.

5. Conclusions

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

• The color of concrete containing recycled fine aggregates is found to be influenced by the intensity of to temperature of exposure. The surface of specimens is light grey at ambient temperature, then is turned to light red, straw yellow, gray white after exposure to 200℃, 400℃, 600℃, 800℃. The mass loss of concrete specimens containing recycled fine aggregate increase with the temperature increases. The recycled fine aggregate content has some influence on the mass loss of concrete specimens containing recycled fine aggregate after exposure to high temperature.

• Generally, the mechanical properties (compressive strength, elastic modulus, splitting tensile strength) of concrete containing recycled fine aggregate decrease with the increase in temperature. The degradation of concrete specimens may be attributed to that calcium silicate hydrate (C-S-H) decomposes after exposure to elevated temperatures.And the compressive strength, splitting tensile strength, elastic modulus of concrete specimens containing recycled coarse aggregate and recycled fine aggregate (RHC) is lower than that of concrete specimens containing natural coarse aggregate and recycled fine aggregate (RFC) at various temperature.

•The high temperature has remarkable influences on the stress–strain curves of concrete containing recycled fine aggregate. At the same temperature and recycled fine aggregate replacement rate, the peak strain of RHC specimens is higher than that of RFC specimens. Normal concrete has the high toughness at various temperatures which indicates normal concrete has better energy absorption capacity than concrete containing recycled fine aggregate.

Acknowledgments

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