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Mechanical behavior of recycled fine aggregate concrete after high temperature

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Abstract. This paper reports mechanical behavior of recycled fine aggregate concretes after high temperatures. It is found that compressive strength of recycled fine aggregate concretes decline significantly as the temperature rises. The elastic modulus of recycled fine aggregate concretes decreases with the increase in temperature, and the decrease is much quicker than the decrease in compressive strength. The split tensile strength of recycled fine aggregate concrete decrease as the temperature rises. Through the regression analysis, the relationship of the mechanical behavior with temperature are proposed, including the compressive behavior, elastic modulus and split tensile strength, which are fitting the test data.

Keywords: compressive behavior; split tensile strength; elevated temperature; elastic modulus; recycled fine concrete aggregate

1. Introduction

In recent years, considerable effort has been directed towards investigating the possibility of using coarse recycled concrete aggregate (RCA) as a substitute for natural coarse aggregate (NCA) in concrete construction. This has led to a deeper understanding of the ways and means of processing demolished concrete, mixture design of recycled aggregate concrete (RAC), its physical and mechanical properties for an exhaustive treatment of various aspects of this material (Abbas and Fathifazl 2009, Achtemichuk and Hubbard 2009, Etxeberria *et al*. 2007, Huang *et al*. 2005). But the possibility of using fine recycled concrete aggregate as a substitute for natural sand are relatively limited.

The use of recycled fine concrete aggregate as sand in concrete has been studied by several other researchers (Evangelista and Brio 2009, Padmini *et al*. 2009). Their works have revealed that recycled fine aggregate lowers the quality of the concrete in mechanical strength and durability. Fire represents one of the major risks to building structures (Karataş *et al*. 2017, Rashid and Aboutaha 2014, Irshidat *et al*. 2015). 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, 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 elevates, the residual shear strength and shear modulus declined rapidly whereas the peak strain increased linearly. Laneyrie *et al*. (2016) investigates recycled coarse aggregate concretes after exposure to temperatures up to 750°C by considering laboratory and industrial recycled coarse aggregate, and normal and high-performance concretes. Chen *et al*. (2015) 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). However, the mechanical behavior of recycled fine aggregate concrete after elevated temperatures has rarely been reported. Duan and Poon (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). Peng *et al* (2015) studied the strength and drift capacity of squat recycled concrete shear walls under cyclic loading. 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.

In this study, the effect of elevated temperature on the mechanical behavior of concretes containing recycled fine concrete aggregate has been investigated.

2. Experimental programme

2.1 Materials and mix proportions

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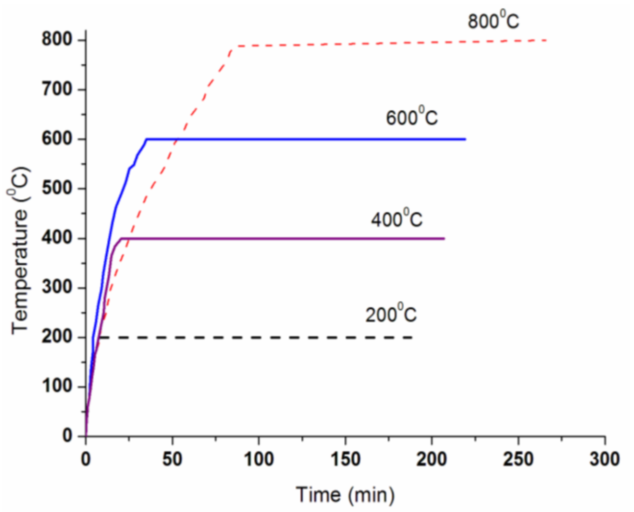


Fig. 1 Time-elevated temperature curves

Fig. 2 Test setup

Two types of fine aggregate were used in this research. One of fine aggregate was natural sand having an absorption ratio of 4.3%, a density of 2.61g/cm^3 and fineness modulus of 2.6. The second type was recycled aggregate obtained from crushing waste concretes from curbs and sidewalks in Nanchang, PR China. And the density, fineness modulus and the absorption ratio of recycled fine aggregate was 2.48g/cm^3, 3.2 and 6.6%, respectively. The physical properties of fine aggregates are shown in Table 1. The chemical composition of recycled fine aggregate is stated in Table 2. Ordinary Portland cement with a 28d compressive strength of 32.5 MPa was used in this investigation. The coarse aggregate used was natural coarse aggregate having an absorption ratio of 0.5%, a density of 2.75 g/cm^3 and crushing value of 5.1%.

Three concrete mixtures consisting of 0%, 50%, 100% recycled aggregate as a partial replacement for sand were prepared, respectively. These mixtures were used to investigate the effect of recycled aggregate on the mechanical properties of concrete exposed to elevated temperatures, respectively. Details of the concrete mixtures are given in Table 3.

Table 1 Physical properties of fine aggregates

Type of fine aggregates	Fineness modulus	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Silt content (%)	Water absorption (%)	Crushing value (%)
River sand	2.6	1460	2610	1.56	4.3	11.1
Recycled sand	3.2	1280	2480	2.5	6.6	18.7

Table 2 Chemical composition of recycled aggregates

Lime (Cao)	Silica (SiO_2)	Alumina (Al_2O_3)	Iron oxide (Fe_2O_3)	Sodium oxide (Na_2O)	Magnesium oxide (MgO)	Potassium Oxide (K_2O)	Sulfur Trioxide ($S0_3$)	Chlorine (Cl)
41.2	38.6	7.1	3.2	2.1	1.4	1.6	1.1	0.04

Table 3 Mix proportions of concretes (kg/m^3)

Mix	recycled aggregate content(%)	Cement	Recycled fine aggregate	Natural sand	Natural coarse aggregate	Mixing water	Added water
NC	0	430	——	555	1295	185	0
RFC50	50	430	264	264	1295	185	25
RFC100	100	430	527	——	1295	185	50

2.2 Materials and mix proportions

Two types concrete specimens were cast for each mixture. Cubic specimens (150×150×150 mm) were prepared to determine the effect of different temperatures on mass loss, splitting tensile strength, while prism specimens (150×150×300 mm) were prepared to determine the compressive strength and modulus of elasticity of concrete. After casting, the concrete specimens were kept in their moulds for 24h at room temperature (20±2°C). After 24 h, the specimens were demoulded and cured in a fog room (20±2°C, 95% relative humidity) for 28 days, and then dried in a room temperature for 7 days. The concrete specimens were heated to 200, 400, 600, 800°C. In order to ensue that the temperatures in the centre of all specimens also reached the target temperatures, the temperature was maintained for 3 h respectively. Fig. 1 showed the time-elevated temperature curves. After completion of the heating regimes, specimens were removed from the furnace and the mass losses of specimens for each temperature were measured. The heated concrete specimens were then cooled to room temperature. The mechanical behavior of all specimens 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.

3. Results and discussion

3.1 Visual observations

Explosive spalling was not observed for all the recycled fine aggregate concrete specimens after exposure to elevated temperatures. The compatibility of thermal expansion between recycled fine aggregate and surrounding cement paste might played a significant role for the absence of explosive spalling. This may have predicted that recycled fine aggregate concrete behaves well when exposed to fire and has a good resistance against explosive spalling. When

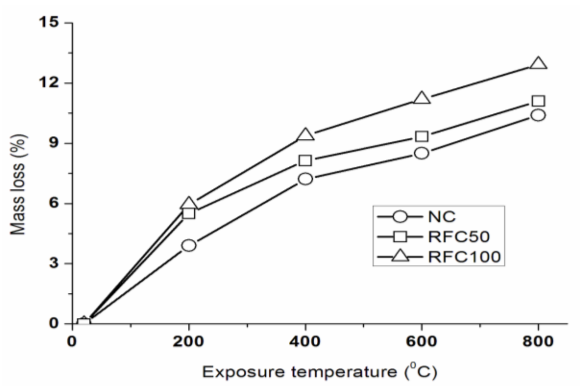


Fig. 3 Effect of elevated temperature on mass loss of concrete

the temperature was below 400℃, no cracks appeared on the specimens; after exposure to the high temperature of 400℃ and 600℃, there were few cracks on the surfaces of the specimens; at 800℃, many cracks appearedon the surfaces of the recycled fine aggregate concrete specimens. Due to change in texture and composition, expansion and crystal destruction of hydration products during heating and cooling, different colours were observed on the recycled fine aggregate concrete specimens after exposure to elevated temperatures. When the temperature was below 400℃, the surfaces of recycled fine aggregate concrete was grey, which was turned to light red,straw yellow, gray white while after exposure to 400℃, 600℃, 800℃.

3.2 Mass loss

The mass loss ratio due to the exposure to elevated temperature, which is defined as the lost mass divided by the original mass is shown in Fig.3. It is observed that the mass loss ratio increases with the increase of target temperature for all the recycled fine aggregate concrete specimens. Taking the RFC100, for example, the mass loss ratio is 5.91%,9.26%,11.12%,12.85% at temperatures of 200℃, 400℃, 600℃, 800℃, respectively. The loss of weight of the recycled fine aggregate concrete specimens is due to loss of free water from concrete which causes shrinkage of cement paste leading to the decomposition of concrete.

3.3 Compressive strength

The variation of the residual compressive strengths with temperature is shown in Fig.4 for recycled fine aggregate concrete. It is revealed from the figure that the compressive strength of recycled fine aggregate concrete decreases with the increase in temperature, and the decrease rate is higher for the temperature above 200℃ than below it. Taking the RFC50, for example, the residual strength at 200℃ retained about 78.9%; however, the values at 400℃, 600℃, 800℃ reduced to about 45.6%, 13.6%, 6.3%, respectively. Further, for a given temperature, the compressive strength of recycled fine aggregate concrete decreased with an increase in the recycled fine aggregate content. And the loss of compressive strength for recycled fine aggregate concrete

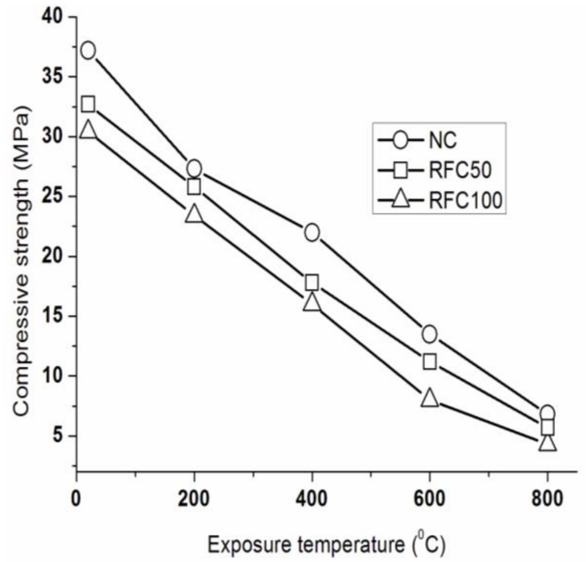


Fig. 4 Effect of elevated temperature on compressive strength of concretes

associated with the increase in temperature may be a result of loss of moisture driven off during heating and the incompatibility of thermal expansion between the cement paste and aggregate.

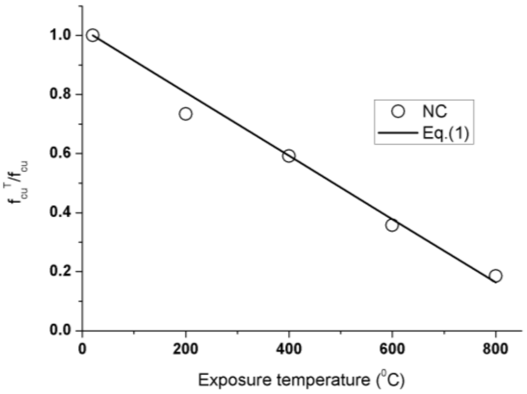
Through the regression analysis, the relationship of the residual normalized compressive strength f_c^T / f_c for recycled fine aggregate concrete with temperature T can be expressed as Eq. (1). As shown in Fig.5, the proposed Eq. (1) fit the test data well.

$$f_c^T / f_c = 1 - (0.858 + 0.075r)\left(\frac{T-20}{800}\right), \quad 20^0C \le T \le 800^0C \tag{1}$$

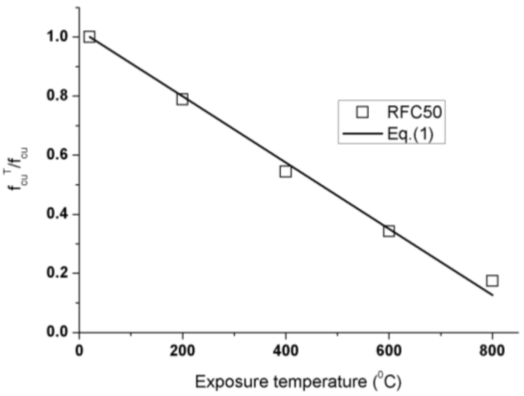
where r is the recycled fine aggregate replacement rate.

3.4 Elastic modulus

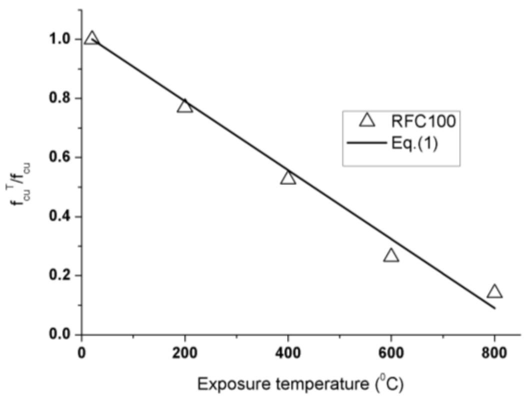
The variation of elastic modulus of recycled fine aggregate concrete with temperature is shown in Fig. 6. As shown in Fig. 6, the elastic modulus of recycled fine aggregate concrete decreases with increasing temperature. Besides, the reduction in elastic modulus of recycled fine aggregate concrete is greater than that in the compressive strength. This might be explained as follows. The void left by the melted recycled fine aggregate after exposure to elevated temperature could effectively release the water vapour, helped to reduce the damage/cracks existing in concrete specimen before compression test and thus prevent the loss of the stiffness. For RFC100, elastic modulus of the specimens after exposure to 200℃ was reduced in average to 67.6% of the unheated recycled fine aggregate concrete. The elastic modulus of recycled fine aggregate concrete at 400℃, 600℃, 800℃ are respectively about 34.8%, 12.3% and 5.4% of the original unheated value. Through the regression analysis, the relationship of the residual normalized elastic modulus E^T/E for recycled fine aggregate concrete with temperature T can be expressed as Eq. (2). As shown in Fig. 7, the proposed Eq. (2) fit the test data well.



(a) NC



(b) RFC50



(c) RFC100

Fig. 5 Regress on the relationship between the residual compressive strength and temperatures

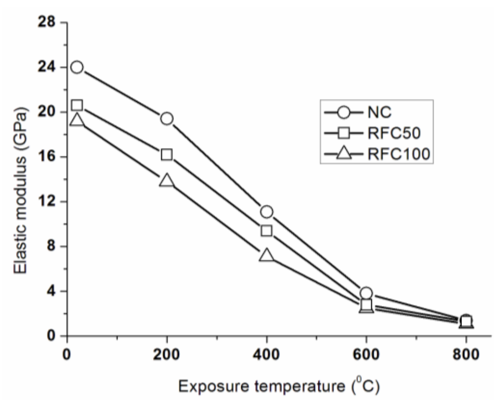
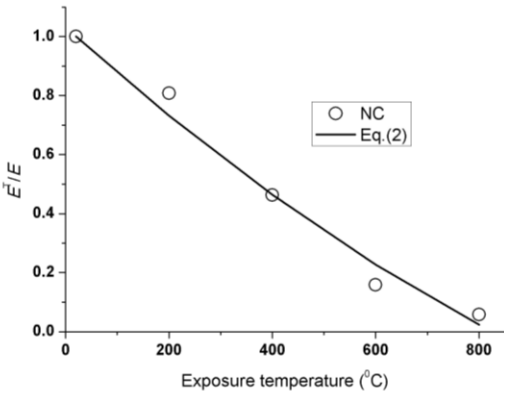
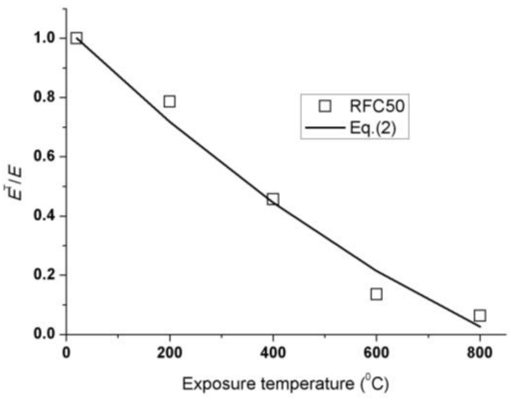


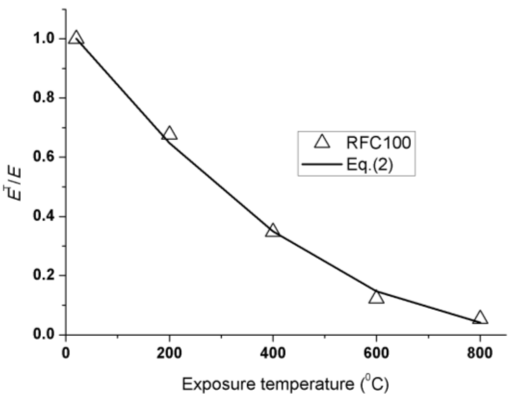
Fig. 6 Effect of elevated temperature on elastic modulus of concretes



(a) NC



(b) RFC50



(c) RFC100

Fig. 7 Regress on the relationship between the residual elastic modulus and temperatures

$$E^T / E = 1 + (-1.25 + 0.169r - 0.656r^2)\left(\frac{T-20}{800}\right) + (0.255 - 0.182r + 0.701r^2)\left(\frac{T-20}{800}\right)^2 \quad (2)$$
$$20^0C \le T \le 800^0C$$

where r is the recycled fine aggregate replacement rate.

3.5 Split tensile strength

The variation of split tensile strength of recycled fine aggregate concrete with temperature is shown in Fig. 8. It is seen from the figure that the split tensile strength of recycled fine aggregate concrete decreases with increasing temperature. And the reduction in split tensile strength of

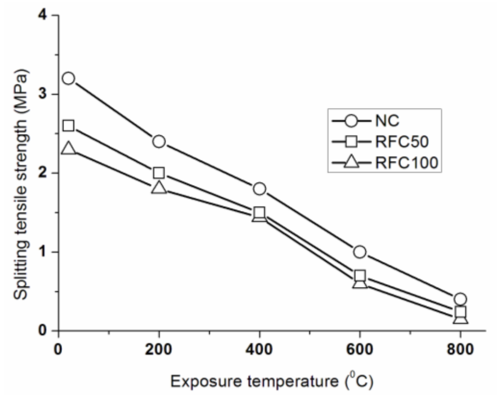
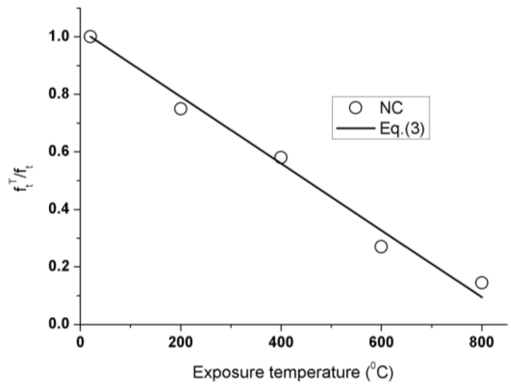
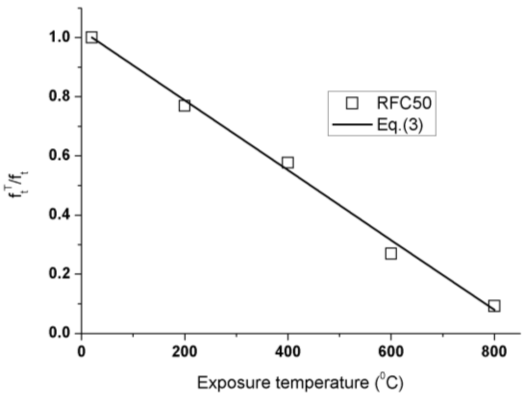


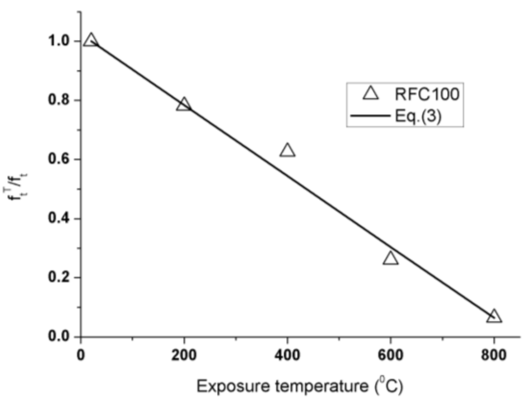
Fig. 8 Effect of elevated temperature on split tensile strength of concretes



(a) NC



(b) RFC50



(c) RFC100

Fig. 9 Regress on the relationship between the residual split tensile strength and temperatures

recycled fine aggregate concrete was greater than that in the compressive strength, especially for temperatures more than 600°C. For a given temperature, the tensile strength of recycled fine aggregate concrete decreased with an increase in the recycled fine aggregate content. Through the regression analysis, the relationship of the residual normalized split tensile strength f_t^T / f_t for recycled fine aggregate concrete with temperature T can be expressed as Eq. (3). As shown in Fig. 9, the proposed Eq. (3) fit the test data well.

$$f_t^T / f_t = 1-(0.928+0.032r)\left(\frac{T-20}{800}\right), \quad 20^0C \le T \le 800^0 C \tag{3}$$

where r is the recycled fine aggregate replacement rate.

4. Conclusions

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

• After exposure to elevated temperature, the heated recycled fine aggregate concrete had different colors. No obvious relation between the color change and the recycled fine aggregate concrete replacement percentage.

• Mass loss of recycled fine aggregate concrete increased gradually with the increase of exposure temperature and that mass loss was affected by the recycled fine aggregate replacement percentage. With the same elevated temperature, the higher the recycled fine aggregate replacement percentage was, the bigger the mass loss.

• Compressive strength of recycled fine aggregate concrete decline significantly as the temperature rises. The recycled sand content has certain effect on compressive strength of recycled fine aggregate concrete. At the same temperature, the compressive strength of recycled fine aggregate concretes declines with the increase of the recycled sand content.

• The elastic modulus of recycled fine aggregate concrete decreased with the increase in temperature, and the decrease is much quicker than the decrease in compressive strength.The split tensile strength of recycled fine aggregate concrete decrease with increasing temperature. And the reduction in split tensile strength of recycled fine aggregate concrete was greater than that in the compressive strength.

• The relationships of the compressive strength, elastic modulus, split tensile strength of fine aggregate concrete after exposure to elevated temperature are also proposed and in good agreement with test results.

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