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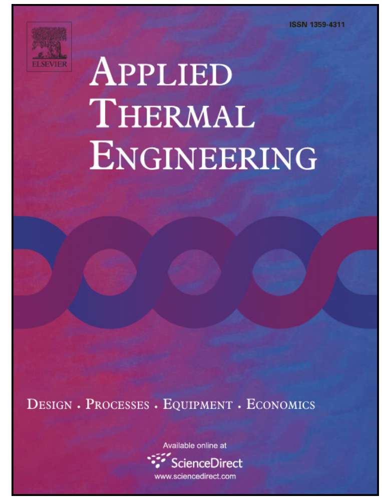

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Thermal properties of coarse RCA concrete at elevated temperatures

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Abstract

An experimental investigation was carried out on the thermal properties of concrete made with coarse recycled concrete aggregate (RCA) in the temperature range from room temperature to 800 °C. Three different concrete mixtures were produced with replacement percentages of 0%, 50% and 100% coarse RCA. The thermal properties at elevated temperatures, including thermal conductivity, specific heat and thermal expansion were obtained from the tests. Test results in this paper show that the thermal conductivity of coarse RCA concrete decreases with increasing coarse RCA content. The development trends of thermal conductivity and specific heat with temperature are similar among concretes with different coarse RCA content. For thermal expansion, the concrete with 50% coarse RCA has a larger value than the concrete containing 0% and 100% coarse RCA at temperatures above 500 °C. Based on the test data, simplified equations were proposed to express the elevated-temperature thermal properties of coarse RCA concrete.

Keywords: Concrete; Coarse recycled concrete aggregate; Thermal conductivity; Specific heat; Thermal expansion; Elevated temperatures.

1. Introduction

A large amount of construction and demolition waste has been generated all over the world in recent years [1, 2], of which waste concrete is the main component. Crushing waste concrete to produce coarse recycled concrete aggregates (RCA) for new concrete is regarded as an effective way to deal with the problem of increasing construction waste [3, 4]. This new concrete is henceforth termed 'coarse RCA concrete' for simplicity in this paper. To date, coarse RCA concrete has mainly been applied to non-structural project, such as pavement base and back-fill for retaining walls [5, 6]. In the past few years, our research group has also carried out research on both material [7, 8] and structural [9-14] performances of the coarse RCA concrete, proving that it is feasible to apply the coarse RCA concrete to composite structural members, such as concrete-filled steel tubular columns or composite slabs. This also has been confirmed by some researches on reinforced concrete beams [15, 16], columns [17] and joints [18]. Given the increasing use of coarse RCA concrete in structural members, it is critically important to study its properties at elevated temperatures, including thermal, mechanical and deformation properties.

For evaluating fire resistance performance of structures made with coarse RCA concrete, the temperature distribution in the structural members under fire exposure should be calculated first. The elevated-temperature thermal properties of coarse RCA concrete are essential for such a calculation. These thermal properties that determine the temperature distribution include thermal conductivity and specific heat at elevated temperatures. Thermal expansion is another important thermal property that influences the thermal stresses in the concrete at elevated temperatures.

Concrete is a composite material produced with aggregates, cement, water and superplasticizer. Aggregates, representing almost 70% of the volume in concrete, have an important effect on the elevated-temperature thermal properties of concrete [19, 20]. Coarse RCA concrete may have different thermal properties when compared to concrete made with coarse natural aggregate (NA), as coarse RCA has higher mortar content, more porosity and cracks than coarse NA. Currently, the information on the elevated-temperature thermal properties of coarse RCA concrete is still limited. Laneyrie et al. [21] tested the thermal conductivity and specific heat of coarse RCA concrete for temperature up to 300 °C. Two water/cement (w/c) ratios of 0.3 and 0.6 and two coarse RCA replacement percentages of 0% and 100% were considered in the experiment. It was concluded that the thermal conductivity of concrete with 100% coarse RCA was about 10-20% lower than that of coarse NA concrete in 20-300 °C range, which was attributed to the higher porosity of coarse RCA concrete.

From the view of the literature reported above, no information is available on the high-temperature thermal expansion of coarse RCA concrete, which is essential for prediction of thermal strain of concrete under fire condition. Additionally, previous researches of the temperature's influences on the thermal conductivity and specific heat of coarse RCA concrete are confined to 300 °C below. However, taking a concrete column with a 400 mm square cross section as an example, the temperatures of almost 60% of the cross section are higher than 300 °C after being subjected to ISO-834 standard fire curve [22] (see Appendix A) for a period of 2 h. It should be noted that 2h is the required minimum fire resistance time for concrete columns in high-rise buildings [23]. Therefore, further studies are needed to extend the temperature range. First, about 72-85% of compressive strength and all modulus of elasticity are lost at 800 °C. Second, taking above column as an example, only about 10% of cross section are higher than 800 °C. Considering the above factors, the highest temperature is chosen to be 800 °C in this study.

The main objective of this paper is to systematically study the elevated-temperature thermal properties of coarse RCA concrete consisting of thermal conductivity, specific heat and thermal expansion. For this purpose, three different concrete mixes with coarse RCA replacement percentages of 0%, 50% and 100% were produced. The measured temperatures were in the range of room temperature to 800°C. Finally, based on the test results, simplified formulas to express the relationships of thermal properties with the temperatures for coarse RCA concrete are proposed.

2. Test program

2.1. Materials and mixes

The materials employed in the concrete mixtures were given as follows:

Cement: ASTM Portland cement (strength grade 42.5 MPa) was employed in the production of concrete. Its specific density was 3.17 in this study.

Superplasticizer: A superplasticizer AS-I was employed to obtain suitable workability. Its density was 1200 kg/m^3.

Natural aggregates: River sand (0-4.75mm) with a fineness modulus of 2.30 and coarse NA (4.75-26.5mm) were employed as the natural aggregates in the concrete mixes.

Coarse RCA: The coarse RCA was obtained from a building structure built around 15 years ago in Harbin whose parent concrete had a cube compressive strength of 41.5MPa. To obtain the suitable size of coarse RCA, the waste concrete was crushed via two steps. The mechanical excavator was used for the first-stage crushing on the demolition site, and then the jaw crusher was employed for the secondary-stage crushing in the laboratory.

The coarse NA and RCA used in this study were all siliceous aggregates. For comparison purposes, the similar gradations of coarse NA and RCA were maintained in all concrete mixes (Table 1). Before mixing, the properties of coarse NA and RCA were measured according to JGJ-52-2006 [24] and these are given in Table 2. It can be observed that the coarse RCA has a lower dry density, higher water absorption and index of crushing than those of coarse NA because of the adhered mortar on coarse RCA's surface and the cracks caused by crushing.

Before mixing, the coarse RCA was immersed in water for about 24 h and then left in the air for about 1 h to achieve a saturated surface dry (SSD) condition [8, 9]. The pre-wetted method was used to compensate the low workability problem for concrete with coarse RCA [4, 11-14].Three different concrete compositions were produced with different replacement percentages of 0%, 50% and 100% coarse RCA. The water/cement (w/c) ratio was maintained at 0.45. The mix proportions of the coarse RCA concrete are presented in Table 3.

2.2. Specimens casting and curing

The mixes were produced in the following steps: the natural and recycled aggregates were firstly mixed for about 1 min; secondly, 1/3 water was added for 1 min mixing; finally cement, superplasticizer and the remaining water were added for another 2 min mixing [7]. For each concrete mix, 6 concrete prisms with 100 mm×100 mm×300 mm and 15 concrete cubes with 100 mm×100 mm×100 mm were casted. These specimens were demolded about 24 h after casting and put into a standard curing room for 28 days, then they were air-dried in the laboratory for about 20 months until thermal property tests. Compressive strength was measured using 100 mm×100 mm×100 mm cubes at different ages, as shown in Table 4.

2.3. Experimental apparatus and procedures

2.3.1. Thermal conductivity

The experimental apparatus employed to measure the thermal conductivity of coarse RCA concrete at elevated temperatures was a QTM-500 Thermal Conductivity Meter made by Kyoto Electronics. This test apparatus mainly includes the power supply, an electric furnace, a hot wire, a thermocouple and a data acquisition system (Fig. 1). The test method adopted by this device is a hot-wire method in accordance with GB/T 10297-2015 [25], which is a transient method based on the idealized 'one-dimensional radial heat flow' model. In this model, the hot wire is assumed to be an infinite thin and infinite long line heat source. It produces a constant quantity of heat per unit time and per unit length and generates a transient temperature field. The thermal conductivity of specimen can be calculated from the slope of a straight line of temperature rise versus natural logarithm of the time using the following equation [25, 26]:

$$\lambda = \frac{Q}{4\pi[T(t_2) - T(t_1)]} \ln\left(\frac{t_2}{t_1}\right) \tag{1}$$

where λ is the thermal conductivity in W/mK, Q is the power of the heating line per unit length in W/m, t_1 and t_2 are the beginning and ending time of heating in s, $T(t_1)$ and $T(t_2)$ are the temperatures measured at times t_1 and t_2 in K.

Specimens with the dimensions of 200 mm×100 mm×50 mm were sliced from 100 mm×100 mm×300 mm prims and prepared to measure its thermal conductivity. The specimens were ground smooth with sand paper in order to ensure a good contact between two specimens. The layout of the specimens is shown in Fig. 1.

Thermal conductivity testing was measured under temperatures from 20 to 790°C with about 100 °C increments. For the room-temperature measurement, 3 tests were conducted for each concrete specimen. Since concrete is a non-homogeneous material, measurement was performed at different locations of each specimen. Meanwhile, the room-temperature density was calculated from mass and volume of each specimen. For the high-temperature measurement, the measurements of thermal conductivity were conducted on the same specimen used at room temperature. The specimens were heated at a rate of 3-4 °C/min to the target temperature followed by about 2 h stabilizing time in order to obtain uniform temperature distribution within the specimens, and then two measurements were obtained at each temperature. The average of the two values was defined as the final result. This process continued until 790 °C and it took about 23 h to complete the measurement of the thermal conductivity of a specimen.

2.3.2. Specific heat

Measurement of specific heat was using a MHTC 96 Differential Scanning Calorimeter (DSC) made by Setaram in accordance with ASTM E1269-11 [27], as shown in Fig. 2. The specific heat was determined through obtaining three DSC curves of empty crucible, standard reference material and sample. Sapphire was chosen as standard reference material. The specific heat can be calculated from the following equation:

$$C_{\mathrm{p}} = C_{\mathrm{pc}} \frac{m_{\mathrm{c}}(A_{\mathrm{s}} - A_{\mathrm{b}})}{m_{\mathrm{s}}(A_{\mathrm{c}} - A_{\mathrm{b}})} \tag{2}$$

where C_p is the specific heat of sample in J/gK, C_{pc} is the specific heat of reference material in J/gK, m_s and m_c are the mass of sample and standard reference material respectively in mg, A_s, A_c and A_b are the heat flow of sample, reference material and empty crucible respectively in μV.

The specimen used for specific heat test was in powder form about 300 mg by grinding the concrete (Fig. 2). Specific heat measurements were taken in 25-800°C temperature range. The heating rate was set at 10°C/min until 800°C under an argon atmosphere. The values for specific heat were based on the average values of two specimens for each mix.

2.3.3. Thermal expansion

The thermal expansion of coarse RCA concrete was measured by RPZ-03P Automatic High Temperature Dilatometer in accordance with GB/T 7320-2008 [28], as shown in Fig. 3. Thermal induced dimension change was transferred through a corundum rod attached to the specimen. The linear variable differential transducer (LVDT) was employed to measure the specimen length change with increasing temperatures. The coefficient of thermal expansion can be calculated using the following equation:

$$\varepsilon = \frac{\Delta L}{L_0} \tag{3}$$

where ε is the thermal strain in %, ΔL is the length change of the sample in mm, L_0 is the initial length of the sample at room temperature in mm.

Specimens of 20 mm×20 mm×100 mm size that sliced from the 100 mm×100 mm×300 mm prim were used for measuring the thermal expansion (Fig. 3). In order to truly reflect the thermal expansion of concrete, the sliced sample included both aggregate and cement paste. The samples were smoothened to have flat and parallel ends in thermal-expansion testing. For each specimen, heating rate was kept at 2°C/min from 20°C to 800°C. Two thermal-expansion tests were performed for each mix up to 800°C.

3. Results and discussion

Appendix B (Tables B1-B4) list the thermal conductivity, density, specific heat and thermal expansion of all the concretes employed in this study, including both average values and corresponding coefficient of variations (COV). For the room-temperature thermal conductivity, the average values and corresponding coefficient of variations (COV) were obtained based on the three measurements for each specimen. For the elevated-temperature thermal properties, these values were obtained from the averages of two test specimens. The coefficient of variation (COV) larger than 10% is highlighted in gray in the tables. Generally, the coefficient of variations (COV) of thermal properties of RCA-50 and RCA-100 are larger than that of RCA-0, mainly due to the heterogeneity in coarse RCA concrete. Similarly, the higher scatter of coarse RCA concrete in compressive strength was noted by Etxeberria et al. [29], as compared with that of coarse NA concrete. The high dispersion observed in specific-heat data of RCA-50 and RCA-100 (Table B3) may be related to the high heterogeneity in powder sample, when compared with the block sample for thermal conductivity and thermal expansion measurements.

3.1. Thermal conductivity and density (mass/volume) at room temperature

The thermal conductivity and density of each specimen at room temperature are listed in Table B1. The effect of coarse RCA replacement percentage on the thermal conductivity and density is given in Fig. 4. As shown in Table B1 and Fig. 4, the thermal conductivity of coarse RCA concrete at room temperature decreases from 1.97 W/mK to 1.44 W/mK while replacement percentages varies from 0% to 100%, corresponding density decreases from 2402.2 kg/m^3 to 2126.6 kg/m^3. On average, the thermal conductivity and density of 100% coarse RCA concrete are 80% and 91% of the reference values of coarse NA concrete, respectively. These decreases are related to the old mortar adhered to the coarse RCA's surface which makes concrete more porosity and less density.

3.2. Thermal conductivity at elevated temperatures

The thermal conductivity of coarse RCA concrete is plotted in Fig. 5(a) for temperatures between 20 and 790 °C. Generally, the thermal conductivity of coarse RCA concrete decreases with increasing temperature. For concretes with different coarse RCA content, thermal conductivity diminishes substantially with the increase of temperature from about 20 to 400 °C. The fast decrease of thermal conductivity in the 20-400 °C range is because of loss of the free and pore water in concrete. Above 400 °C, a slow reduction in thermal conductivity occurred mainly due to the departure of strongly held moisture within hydrated calcium silicate [30]. Similar trend has been found in other researches on high-performance concrete [20, 30-31].

In order to analyze the effect of coarse RCA replacement percentage on the thermal conductivity at elevated temperatures, the trends in thermal conductivity based on coarse RCA replacement percentage are given in Fig. 5(b). It can be observed that the thermal conductivity of concrete decreases obviously with the increment of coarse RCA content. For instance, the thermal conductivity of concrete containing 50% and 100% coarse RCA decreases 21.2% and 35.0% when compared with coarse NA concrete at 500 °C, respectively.

The elevated-temperature thermal conductivity of coarse RCA concrete in this study is also compared with the test results of Laneyrie [21] and the models suggested by Eurocode 2 [32] and ASCE (Siliceous) [33], as illustrated in Fig. 6(a). The test results of Laneyrie [21] were obtained from the thermal conductivity of 0% and 100% coarse RCA concrete for temperature under 300 °C, and the models provided in Eurocode 2 [32] and ASCE [33] were derived based on the coarse NA concrete. As seen, the thermal conductivity of all concretes decreases with the increasing temperature. For temperature below 300 °C, the results obtained from this study for 0% and 100% coarse RCA concrete are close to the experimental results of Laneyrie et al. [21]. It also can be observed in Fig. 6(a) that there are considerable variations in the results of this study and models in Eurocode 2 and ASCE, mainly due to the differences in the moisture content, materials (cement, aggregate) and measurement techniques. Results reported by related research indicate that moisture content, aggregate type and cement paste are the major factors influencing the thermal conductivity of concrete [34, 35]. At lower temperatures, the thermal conductivity of concrete increases with increasing moisture content because the thermal conductivity of void water is higher than that of air. Concrete produced with high crystallinity aggregates shows higher thermal conductivity than concrete using amorphous aggregates. The measuring methods can also have an influence on the thermal conductivity. For example, the steady-state methods get a lower value for moist concrete than transient methods mainly due to the moisture migration caused by temperature gradient [31]. It should be noted that the moisture content and measurement technique are not clearly specified by Eurocode 2 and ASCE. The effect of aggregate type (siliceous, carbonate) on the thermal conductivity is considered in ASCE model.

Given the obvious influence of coarse RCA content on the elevated-temperature thermal conductivity and the aforementioned variations, three separate regression expressions are developed for thermal conductivity of concretes with 0%, 50% and 100% coarse RCA, as shown in Eqs. (4)-(6).

0% coarse RCA concrete

$$\lambda_c = \begin{cases} 2.04 - 2.22(T/1000) + 1.58(T/1000)^2 & 20℃ \le T \le 500℃ \\ -0.00034T + 1.49 & 500℃ \le T \le 790℃ \end{cases} \tag{4}$$

50% coarse RCA concrete

$$\lambda_c = \begin{cases} 1.85 - 3.38(T/1000) + 3.64(T/1000)^2 & 20℃ \le T \le 500℃ \\ -0.00026T + 1.20 & 500℃ \le T \le 790℃ \end{cases} \tag{5}$$

100% coarse RCA concrete

$$\lambda_c = \begin{cases} 1.64 - 2.73(T/1000) + 2.46(T/1000)^2 & 20℃ \le T \le 500℃ \\ -0.00025T + 1.01 & 500℃ \le T \le 790℃ \end{cases} \tag{6}$$

where λ_c is the thermal conductivity of coarse RCA concrete at elevated temperatures in W/mK, T is the specimen's temperature in ^{o}C. As shown in Fig. 6(b), the relationships proposed by Eq. (4)-(6) fit the test results well.

3.3. Specific heat

The specific heat of coarse RCA concrete is shown in Fig. 7(a) for temperatures between 25 and 800 °C. The specific heat of coarse RCA concrete is in the range of 0.87-1.33 J/gK at room temperature. For all concretes, the changes in specific heat at elevated temperatures are similar. There are two major peaks in the 25-800 °C range. The first major peak at about 200 °C is attributed to the vaporization of free water [30]. The second major peak occurred near about 550 °C mainly due to the quartz transformation of siliceous aggregate in the temperature range [30, 36].

Fig. 7(b) shows the effect of coarse RCA content on the specific heat of specimens at elevated temperatures. The coarse RCA content has an influence on the high-temperature specific heat of coarse RCA concrete, but its influence is fluctuating. The main reason for this phenomenon is the high scatter of the specific heat results, as previously stated, the coefficient of variations of specific heat data are larger than those of the thermal conductivity and thermal expansion. Until now, differential scanning calorimeter (DSC) adopted in this study is the predominant method for measuring the specific heat of concrete [20, 37]. For each measurement, 300 mg powder samples, including both aggregate and cement paste, were obtained by grinding the cubic concrete specimens. It is well known that concrete is a heterogeneous material with fine and coarse aggregates that is held together by the hardened cement paste. In concrete, even the weight of a single coarse aggregate with size range of 19.0-26.5 mm can reach about 20 g, 70 times of the sample weight. Therefore it is believed that the random sampling is one of the main reasons resulting in such dispersion. No firm conclusions regarding the effect of coarse RCA content on the elevated-temperature specific heat can thus be made until far more test results are obtained.

Fig. 8(a) compares the results of this study, in terms of the specific heat as a function of temperature, with results of Laneyrie [21] and the models specified in Eurocode 2

[32] and ASCE (Siliceous) [33]. Comparative analysis shows that there are some discrepancies between the results of different studies. The reasons for these discrepancies of the high-temperature specific heat are similar to those of high-temperature thermal conductivity, which is mainly attributed to the variabilities in moisture content, materials and measurement techniques. Research results show that the moisture content has an important influence on the specific heat of concrete at lower temperatures. Below 200 °C moist concrete presents an apparent specific heat about twice of oven-dried concrete because of the higher specific heat of water [35]. The endothermic peak on DSC curves appearing about 750 °C has been observed in carbonate concrete, which is due to the decomposition of carbonate [34]. Results in carbonate aggregate concrete measurements also show that the peak areas in the DSC curves increase with a decrease in heating rate [38]. The moisture content and measurement technique are not taken into consideration in Eurocode 2 and ASCE models. The ASCE provides different specific heat models for siliceous and carbonate aggregate concrete, respectively.

Taking into account the test result scatter in the present study and the large discrepancies from different researches, a unified regression equation is proposed for specific heat of coarse RCA concrete with 0%, 50% and 100% replacement percentages, as presented in Eq. (7).

0%, 50% and 100% coarse RCA concrete

$$C_{\mathrm{p}} = \begin{cases} 0.0024T + 1.08 & 25℃ \le T \le 200℃ \\ -0.0015T + 1.86 & 200℃ \le T \le 400℃ \\ 1.26 & 400℃ \le T \le 500℃ \\ 0.0054T - 1.44 & 500℃ \le T \le 550℃ \\ -0.0021T + 2.68 & 550℃ \le T \le 650℃ \\ 0.0018T + 0.15 & 650℃ \le T \le 750℃ \\ -0.0024T + 3.30 & 750℃ \le T \le 800℃ \end{cases} \tag{7}$$

where C_{p} is the specific heat of coarse RCA concrete at elevated temperatures in J/gK, T is the specimen's temperature in $^{\mathrm{o}}$C. As shown in Fig. 8(b), the proposed Eq. (7) well corresponds to the experimental results.

3.4. Thermal expansion

Fig. 9(a) shows the thermal expansion of coarse RCA concrete as temperature was increased from 20 to 800 °C. For concrete incorporated with different coarse RCA content, thermal expansion increases with increasing temperature up to 800 °C, which mainly resulted from the thermal expansion of aggregate and cement paste [30, 39]. The steep increase between 500 and 600 °C is related to the quartz transformation in siliceous aggregates [30, 36].

The effect of coarse RCA replacement percentage on the thermal expansion at elevated temperatures is presented in Fig. 9(b). The thermal expansion of concrete is marginally influenced by the replacement percentage of coarse RCA within the 500 °C temperature range. Beyond 500 °C, the largest value of thermal expansion occurred in the 50% replacement specimen as compared to 0% and 100% coarse RCA concrete. The higher thermal expansion for 50% replacement specimens may be attributed to the microcracking caused by the nonuniform thermal stresses between coarse NA and RCA. Similar thermal expansion was observed between 0% and 100% coarse RCA concrete.

Fig. 10(a) compares this experimental result of thermal expansion with the reference values suggested in Eurocode 2 (Siliceous) [32] and ASCE [33]. There are also large discrepancies between the results from different studies. As observed in Fig. 10(a), the test results of thermal expansion for coarse RCA concrete are basically located between the curves suggested in Eurocode 2 [32] and ASCE [33].

Given some influence of the coarse RCA content on the thermal expansion in the 500-800 °C range, two separate regression expressions are proposed for thermal expansion of concrete with 0%, 50% and 100% coarse RCA, as shown in Eqs. (8)-(9).

0% and 100% coarse RCA concrete

$$\varepsilon_{\mathrm{th}} = \begin{cases} -0.015 + 0.00075T & 20℃ \le T \le 500℃ \\ -0.84 + 0.0024T & 500℃ \le T \le 600℃ \\ 0.12 + 0.0008T & 600℃ \le T \le 800℃ \end{cases} \tag{8}$$

50% coarse RCA concrete

$$\varepsilon_{\mathrm{th}} = \begin{cases} -0.0175 + 0.000875T & 20^{\circ}\mathrm{C} \leq T \leq 500^{\circ}\mathrm{C} \\ -0.93 + 0.0027T & 500^{\circ}\mathrm{C} \leq T \leq 600^{\circ}\mathrm{C} \\ 0.15 + 0.0009T & 600^{\circ}\mathrm{C} \leq T \leq 800^{\circ}\mathrm{C} \end{cases} \quad (9)$$

where ε_{th} is the thermal strain of coarse RCA concrete at elevated temperatures in %, T is the specimen's temperature in ^{o}C. As shown in Fig. 10(b), the proposed Eq. (8) and (9) fit the test results well.

4. Conclusions

This study investigated the thermal properties (thermal conductivity, specific heat and thermal expansion) of coarse RCA concrete for temperatures up to 800 °C. The following conclusions were drawn from the results of this study:

The thermal conductivity of coarse RCA concrete at room temperature and elevated temperatures decreases with the increase of coarse RCA replacement percentage. As the specimen's temperature is increased, the thermal conductivity of coarse RCA concrete decreases.

There are two major peaks of specific heat for coarse RCA concrete in 25-800 °C range. The coarse RCA content has no regular influence on the specific heat of concrete at elevated temperatures.

The thermal expansion of coarse RCA concrete increases with temperatures from 20 to 800 °C. Above 500 °C, concrete at 50% replacement has a larger thermal expansion than 0% and 100% coarse RCA concrete.

The suggested relationships to model the elevated-temperature thermal properties of coarse RCA concrete can be used to evaluate the behavior of structures made with coarse RCA concrete under fire exposure.

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References

[1] C.H. Wang, J.Z. Xiao, G.Z. Zhang, L. Li, Interfacial properties of modeled recycled aggregate concrete modified by carbonation, Constr. Build. Mater. 105 (2016) 307-320.

[2] R.O. Neto, P.G. Gastineau, B.G. Cazacliu, L.L. Guen, R.S. Paranhos, C.O. Petter, An economic analysis of the processing technologies in CDW recycling platforms, Waste Manage. 60 (2017) 277-289.

[3] J.Z. Xiao, W.G. Li, Y.H. Fan, X Huang, An overview of study on recycled aggregate concrete in China (1996-2011), Constr. Build. Mater. 31 (2012) 364-383.

[4] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review, Constr. Build. Mater. 68 (2014) 501-516.

[5] K.E. Hassan, J.J. Brooks, M. Erdman, The use of reclaimed asphalt pavement (RAP) aggregates in concrete, Waste Manage. 1 (2000) 121-128.

[6] C.S. Poon, S. Azhar, S.C. Kou, Recycled aggregates for concrete applications. In Proceeding of the Materials Science and Technology in Engineering Conference—Now, New and Next, 2003.

[7] Y. Geng, Y.Y. Wang, J. Chen, Creep behaviour of concrete using recycled coarse aggregates obtained from source concrete with different strengths, Constr. Build Mater. 128 (2016) 199-213.

[8] H. Zhao, Y.Y. Wang, F.Q. Liu, Stress-strain relationship of coarse RCA concrete exposed to elevated temperatures, Mag. Concr. Res. 69 (2017) 649-664.

[9] Y.Y. Wang, J. Chen, Y. Geng, Testing and analysis of axially loaded normal-strength recycled aggregate concrete filled steel tubular stub columns, Eng. Struct. 86 (2015) 192-212.

[10] Y. Geng, Y.Y. Wang, J. Chen, Time-Dependent behavior of recycled aggregate concrete-filled steel tubular columns, J. Struct. Eng. 141 (2015) 1-12.

[11] Y.Y. Wang, Q.H. Wang, Y. Geng, G. Ranzi, Long-term behaviour of simply supported composite slabs with recycled coarse aggregate, Mag. Concr. Res. 68(2016) 1278-1293.

[12] Q.H. Wang, G. Ranzi, Y.Y. Wang, Y. Geng, Long-term behaviour of simply-supported

steel-bars truss slabs with recycled coarse aggregate, Constr. Build. Mater. 116 (2016) 335-346.

[13] Y. Geng, Y.Y. Wang, J. Chen, Time-Dependent behavior of steel tubular columns filled with recycled coarse aggregate concrete, J. Constr. Steel Res. 122 (2016) 455-468.

[14] J. Chen, Y.Y. Wang, C.W. Roeder, J. Ma, Behavior of normal-strength recycled aggregate concrete filled steel tubes under combined loading, Eng. Struct. 130 (2017) 23-40.

[15] W.C. Choi, H.D. Yun, Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate, Mater. Des. 51 (2013) 742-750.

[16] M. Arezoumandi, A. Smith, J.S. Volz, K.H. Khayat, An experimental study on flexural strength of reinforced concrete beams with 100% recycled concrete aggregate, Eng. Struct. 88 (2015) 154-162.

[17] W.C. Choi, H.D. Yun, Compressive behavior of reinforced concrete columns with recycled aggregate under uniaxial loading, Eng. Struct. 41 (2012) 285-293.

[18] V. Corinaldesi, V. Letelier, G. Moriconi, Behaviour of beam-column joints made of recycled-aggregate concrete under cyclic loading, Constr. Build Mater. 25 (2011) 1877-1882.

[19] Z. Xing, A.L. Beaucour, R. Hebert, A. Noumowe, B. Ledesert, Aggregate's influence on thermophysical concrete properties at elevated temperature, Constr. Build. Mater. 95 (2015) 18-28.

[20] V.K.R. Kodur, M.A. Sultan, Effect of temperature on thermal properties of high-strength concrete, J. Mater. Civ. Eng. 15 (2003): 101-107.

[21] C. Laneyrie, A.L. Beaucour, M.F. Green, R.L. Hebert, B. Ledesert, A. Noumowe, Influence of recycled coarse aggregates on normal and high performance concrete subjected to elevated temperatures, Constr. Build. Mater. 111 (2016) 368-378.

[22] ISO 834-1:1999, Fire-resistance Tests – Elements of Building Construction – Part 1: General Requirements, International Organization for Standardization, Switzerland.

[23] GB 50368-2005, Residential Building Code (in Chinese).

[24] JGJ-52-2006, Standard for Technical Requirements and Test Method of Sand and Crushed Stone (or Gravel) for Ordinary Concrete (in Chinese).

[25] GB/T 10297-2015, Test Method for Thermal Conductivity of Nonmetal Solid

Materials-Hot-Wire Method (in Chinese).

[26] A. Franco, An apparatus for the routine measurement of thermal conductivity of materials for building application based on a transient hot-wire method, Appl. Therm. Eng. 27 (2007) 2495-2504.

[27] ASTM E1269-11, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry, ASTM International.

[28] GB/T 7320-2008, Refractories-Determination of thermal expansion (in Chinese).

[29] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (2007) 735-742.

[30] V. Kodur, F. ASCE, W. Khaliq, Effect of temperature on thermal properties of different types of high-strength concrete, J. Mater. Civ. Eng. 23 (2011): 793-801.

[31] K.Y. Shin, S.B. Kim, J.H. Kim, M. Chung, P.S. Jung, Thermo-physical properties and transient heat transfer of concrete at elevated temperatures, Nucl. Eng. Des. 212 (2002): 233-241.

[32] BS EN 1992-1-2:2004, Eurocode 2: Design of Concrete Structures-Part 1-2: General Rules-Structural Fire Design, British Standards.

[33] ASCE, Structural Fire Protection, ASCE Committee on Fire Protection, Manual No. 78, 1992.

[34] D.R. Flynn, Response of high performance concrete to fire conditions: review of thermal property data and measurement techniques, NIST GCR, 1999.

[35] D.J. Naus, A compilation of elevated temperature concrete material property data and information for use in assessment of nuclear power plant reinforced concrete structures, US-NRC, NUREG/CR-7031, 2010.

[36] R.N. Razafinjato, A.L. Beaucour, R.L. Hebert, B. Ledesert, R. Bodet, A. Noumowe, High temperature behavior of a wide petrographic range of siliceous and calcareous aggregates for concretes, Constr. Build. Mater. 123 (2016) 261-273.

[37] T.T. Lie, V.K.R. Kodur, Thermal and mechanical properties of steel-fibre-reinforced concrete at elevated temperatures, J. Mater. Civ. Eng. 23 (1996) 511-517.

[38] X.F. Hu, T.T. Lie, G.M. Polomark, J.W. MacLaurin, Thermal properties of building materials at elevated temperatures, Internal Report No. 643, National Research Council of Canada, Ottawa; 1993.

[39] T.F. Uygunoğlu, İ.B. Topçu, Thermal expansion of self-consolidating normal and lightweight aggregate concrete at elevated temperature, Constr. Build. Mater. 23 (2009) 3063-3069.

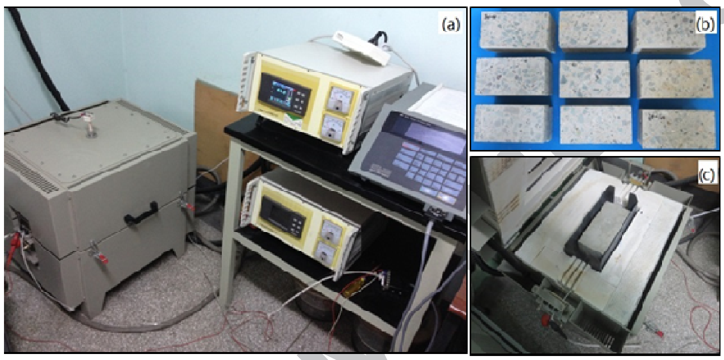


Fig. 1. Measurement of thermal conductivity of coarse RCA concrete at elevated temperatures, (a) Transient hot-wire device, (b) Concrete specimens, (c) Concrete specimen ready for thermal conductivity tests.

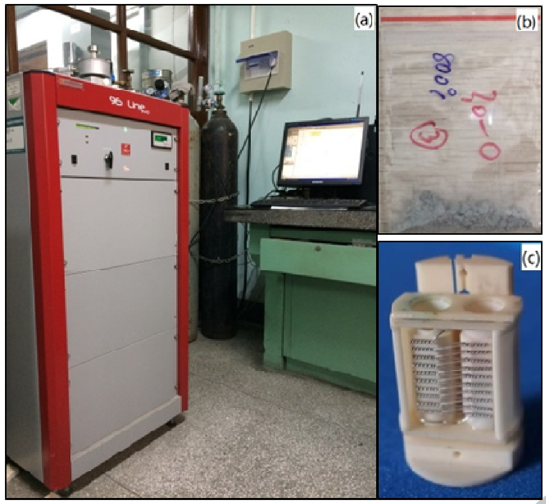


Fig. 2. Measurement of specific heat of coarse RCA concrete at elevated temperatures, (a) MHTC 96 Differential Scanning Calorimeter, (b) Concrete specimens, (c) Cell used for specific heat tests.

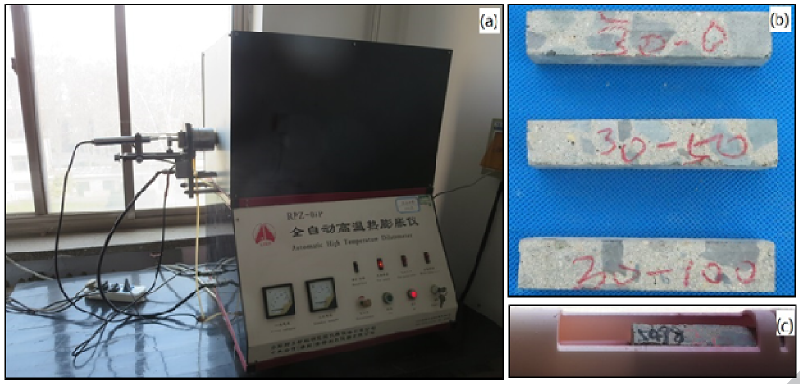


Fig. 3. Measurement of thermal expansion of coarse RCA concrete at elevated temperatures, (a) RPZ-03P Automatic High Temperature Dilatometer, (b) Concrete specimens, (c) Concrete specimen ready for thermal expansion tests.

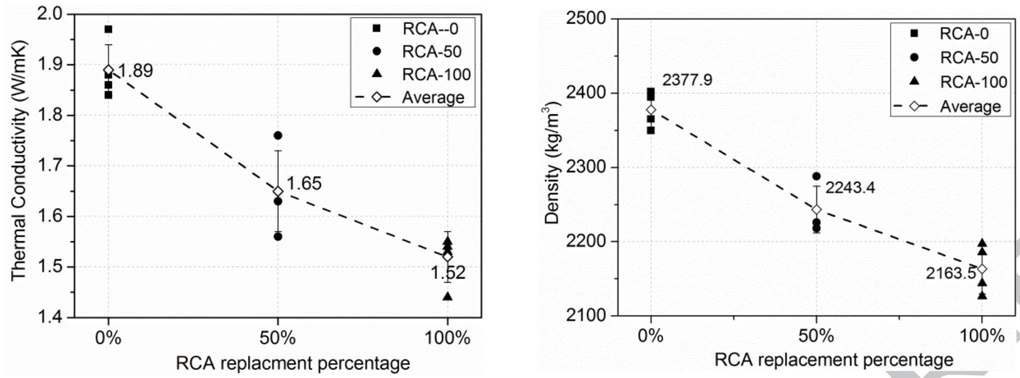


Fig. 4. Effect of coarse RCA replacement percentage on the thermal conductivity and density of coarse RCA concrete at room temperature.

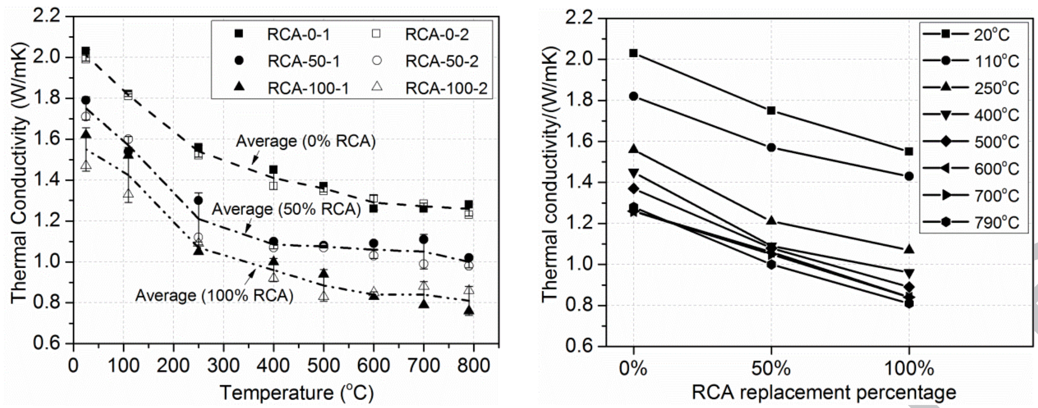


Fig. 5. Thermal conductivity of coarse RCA concrete at elevated temperatures, (a) thermal conductivity versus temperature, (b) thermal conductivity versus coarse RCA replacement percentage.

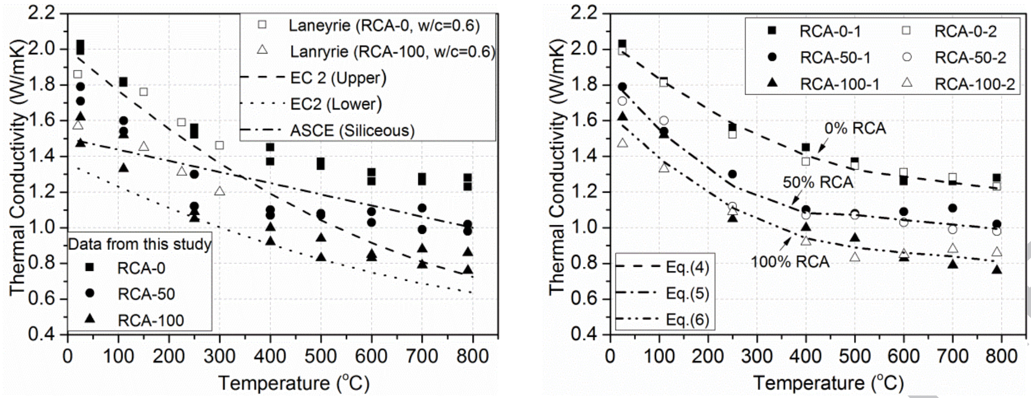


Fig.6. Comparisons of the thermal conductivity of concrete specimens at elevated temperatures, (a) test results of this study and Laneyrie, models of EC2 and ASCE, (b) test results of this study and corresponding regression expressions.

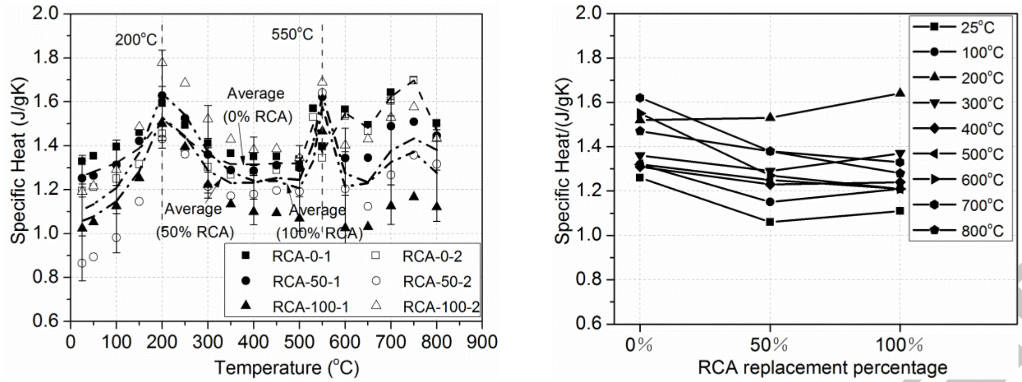


Fig. 7. Specific heat of coarse RCA concrete at elevated temperatures, (a) specific heat versus temperature, (b) specific heat versus coarse RCA replacement percentage.

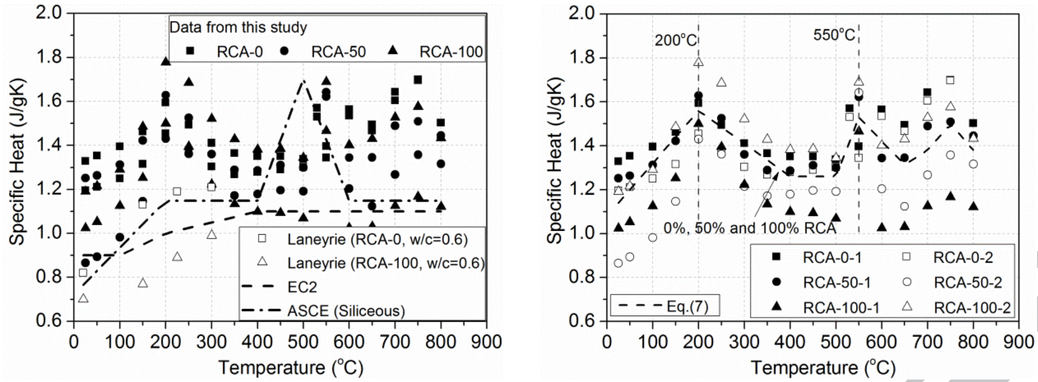
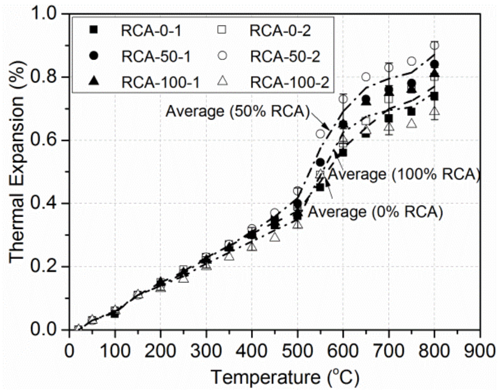


Fig.8. Comparisons of the specific heat of concrete specimens at elevated temperatures, (a) test results of this study and Laneyrie, models of EC2 and ASCE, (b) test results of this study and corresponding regression expressions.



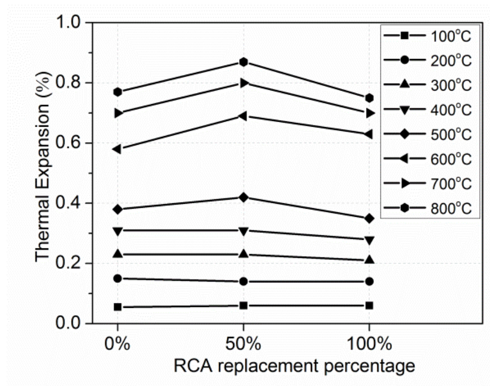


Fig. 9. Thermal expansion of coarse RCA concrete at elevated temperatures, (a) thermal expansion versus temperature, (b) thermal expansion versus coarse RCA replacement percentage.

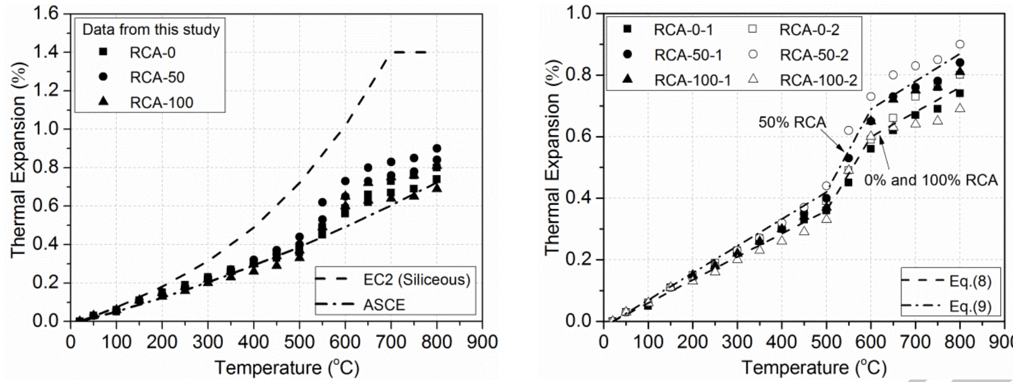


Fig.10. Comparisons of the thermal expansion of concrete specimens at elevated temperatures, (a) test results of this study, models of EC2 and ASCE, (b) test results of this study and corresponding regression expressions.

Table 1 Gradation of coarse aggregates

Sieve size (mm)	Cumulative passing by weight(%)
26.5	100
19.0	62
16.0	43
9.5	14
4.75	0

Table 2 Basic properties of coarse NA and RCA

Properties	NA	RCA
Grading (mm)	4.75-26.5	4.75-26.5
Dry density(kg/m^3)	2780	2500
Water absorption(%)	0.49	4.40
Index of crushing(%)	3.7	12.0

Table 3 Mix proportions of coarse RCA concrete

No.	*r* (%)	w/c ratio	Materials (kg/m^3)					
			C	W	S	Coarse aggregate		SP
						NA	RCA	
RCA-0	0	0.45	400	180	667	1186	0	2
RCA-50	50	0.45	400	180	645	573	573	2
RCA-100	100	0.45	400	180	624	0	1108	2

Note:

r is the coarse RCA replacement percentage, C is the cement, W is the water, S is the sand, and SP is the superplasticizer.

Table 4 Compressive strengths of coarse RCA concrete

Age of concrete (days)	Compressive strength (MPa)		
	RCA-0	RCA-50	RCA-100
28	48.2	46.2	43.5
90	60.8	53.2	45.3