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Residual stress-strain relationship for thermal insulation concrete with recycled aggregate after high temperature exposure

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HIGHLIGHTS

- The critical temperature for RATIC is 400 °C due to combined actions of aggregates.
- The residual strength and elastic modulus of RATIC are higher than those of NC.
- RCA ratio has little effect on the post-fire stress-strain relationship of RATIC.
- Equations are proposed to predict the post-fire mechanical performances of RATIC.

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ABSTRACT

Containing recycled coarse aggregates and insulation aggregates, the thermal insulation concrete with recycled aggregates (RATIC) was developed to alleviate the environmental impact and improve the energy efficiency in buildings. This paper presents the experimental results of the residual mechanical performance and the complete compressive stress-strain relationship of RATIC after a high temperature exposure of 20–800 ◦C. In the experiments, three different concrete compositions were designed by substituting natural coarse aggregates with recycled coarse aggregates at the replacement ratios of 0%, 30% and 50%. The results show that the residual compressive strength of heated concrete decreases significantly when the temperature exceeds 400 °C and the elastic modulus deteriorates faster than the strength. However, both the residual strength and the elastic modulus of RATIC are apparently larger than those of the normal concrete. Higher RCA percentage results in higher relative ultimate strain but appears not having much influence on the failure modes, residual strength, elastic modulus, and peak strain of RATIC. Based on the experimental results, the equations for predicting the residual strength, peak strain, and ultimate strain, and elastic modulus of the RATIC after high temperature exposure are proposed along with the compressive stress-strain constitutive relationship.

1. Introduction

Aggregate is known as the major constituent of concrete. Therefore, the selection of aggregates is a very important task of innovative concrete production. In recent years, recycled aggregates have been widely utilized due to the increasing shortage of natural aggregate resources and the change in climate. The thermal insulation concrete with recycled aggregates (RATIC) is an innovative material in which both recycled coarse aggregates and a substantial percentage of insulation aggregates are used to alleviate the environmental impact and help improve the energy efficiency in buildings [1]. Research has shown that an optimal mix proportion designs for RATIC can result in the mechanical properties and seismic performance comparable to the normal concrete (NC) [2–4]. Therefore, RATIC may be deemed as a functional recycled aggregate concrete (RAC) or a structural concrete satisfying the load-bearing requirements.

Despite of the reasonable performance under room temperature, the mechanical properties of RATIC in high temperature environment could be deteriorated due to the expansion of aggregates, shrinkage of cement, spalling, and cracking [5]. The extent of such deterioration remains unclear and deserves a further research for helping make an appropriate decision on repairing or demolishing [6].

As a structural concrete, the characteristics of RATIC properties may be evaluated and compared against the NC and the RAC. The

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NC at high temperatures has been thoroughly studied and concluded that its physical and mechanical properties are adversely affected by high temperatures [7]. In general, the NC experiences 15–40% reduction in compressive strength when the temperature is in the range of 200–300 °C [8], in which 300 °C is considered as a critical temperature as the loss of strength is relatively low and may be recovered by re-hydration below that temperature. To the contrary, the strength degradation would be considerable and irretrievable when the NC is heated above 300 °C. This strength loss would be 50% at 600 °C and more than 80% at 800 °C, leading to a structural failure [9]. Previous research [10] indicates that the elastic modulus of NC decreases more rapidly than the strength and proposes the residual stress-strain relationship for the NC under different temperatures.

Few studies have been conducted on the residual mechanical performance of RAC exposed to high temperature. It is generally believed that the mechanical property of recycled concrete will decrease significantly at high temperatures, similarly to the NC. However, inconsistent conclusions about the damage level of the recycled aggregate on the concrete seem to have been made by various researchers. For instance, Zega and Di Maio [11,12] showed that the deterioration of the mechanical properties of RCA at high temperatures was not as severe as compared to the NC. This is due to the fact that the thermal expansion coefficients of mortar and recycled aggregate are very similar, resulting in a beneficial factor to reduce the micro-cracking in the interfacial transition zone (ITZ). They also reported that the recycled concrete with a low water/cement (w/c) ratio performed better than the NC when exposed to 500 °C for 1 h. The positive influences of RCA were also reported by other researchers [13,14]. Through an experimental study on RAC designed by substituting natural coarse aggregates with recycled coarse aggregates at different replacement ratios, Xiao [14] stated that the replacement ratio was the factor determining the residual mechanical performance of recycled concrete after a high temperature and that a higher replacement ratio ($\geqslant$50%) would lead to a higher residual compressive strength of the concrete. On the contrary, Chen [15] reported that the RAC experienced more strength loss after fire because of the more porous inner structure of RCA. Unlike the others, Vieira et al. [16] stated that there was no significant difference in residual mechanical properties between RAC and NC, including compressive strength, tensile strength, and elastic modulus. In addition to the inconsistent results, studies on the stress-strain relationships of RAC at high temperatures and on the fire performance of the RAC are rather limited.

Due to the variability of the available origins of demolished concrete and the physical performance of aggregates, it is difficult to compare the results and quantify the residual mechanics of RAC. Nevertheless, it is generally believed that both the inner structure of the concrete and the environmental factors could affect the physicochemical changes and the deterioration of mechanical properties. The inner structure is related to the cementitious material, aggregate properties, and mix proportion [17]. During the heating process, the free water in aggregates could evaporate below 100 °C. In the 300–500 °C stage, both the siliceous and calcareous natural aggregates remain stable. The quartz in aggregates expands by about 5.7% in volume above 570 °C. In the 600–800 °C stage, the carbonate aggregate undergoes a de-carbonation reaction [17].

With both recycled coarse and insulation aggregates, the residual strength and stress-strain relationship of RATIC at high temperatures will be affected by the aggregate type, physical property, and chemical property of aggregates. Additionally, for recycled aggregates with mortar paste, the ITZs in RAC would be doubled, affecting the mechanical performance of concrete significantly. Therefore, RATIC may experience different changes because of the RCA paste and aggregate content. Further study on the residual mechanical property of RATIC is thus warranted.

The purpose of this paper is to establish a database of the mechanical properties of the relatively new RAC after heating to 800 °C. Since there is very little research work available on the stress-strain relationship of concrete with RCA, which is very important to the structural analysis and design, this study attempts to make up such insufficient knowledge by focusing on the residual elastic modulus and complete stress–strain curve. The compression tests were carried out to evaluate the deterioration of the mechanical properties of RATIC exposed to high temperatures. The effects of temperatures (varying from 20 to 800 °C) and the percentage of RCA (0%, 30%, and 50%) on the residual strength, corresponding strain, elastic modulus, and stress–strain curve of RATIC are investigated. The equations for predicting the strength and elastic modulus applicable to unheated and heated concrete are proposed through a regression analysis along with the complete stress-strain curve, which may be used to understand the behavior of structure during the entire damage process.

2. Experimental program

2.1. Materials

RATIC constitutes ordinary Portland cement, silica fume (SF), and Nano-SiO_2 (NS) as the cementitious materials. The ordinary Portland cement used in this study has the 28-day compression strength of 42.5 MPa and the fineness modulus of 0.63. The average particle diameter of silica fume is 180 nm. The properties and constituents of cementitious materials are listed in Table 1.

The aggregates in the concrete mix include natural coarse aggregate (NCA), natural fine aggregate (FA), recycled coarse aggregate (RCA), and thermal insulation aggregate. The natural coarse aggregate was made of the crushed limestone with the particle size of 5–20 mm and the fine aggregate was composed of the quartz sand with a fineness modulus of 2.5. The RCA was produced by crushing, screening, and cleaning the waste concrete of a demolished building in Beijing, China. To obtain the high-quality RCAs to meet the quality requirement specified in the Chinese standard "*Recycled coarse aggregate for concrete*" (GB/T25177), the concrete debris was crushed into particles with a diameter of less than 40 mm at a plant and separated into coarse aggregates and fine aggregates with a wet triturator. The coarse aggregates obtained were crushed once again in a jaw crusher, and then shaped and strengthened at a strengthening facility. The recycled aggregate is composed of 95.3% of concrete pieces, 2.3% of brick pieces, and remaining 2.4% of other debris.

A series of tests on aggregates were carried out on both ~~the~~ natural coarse aggregates (NCA) and recycled coarse aggregates (RCA) according to the Chinese standard "*Standard for technical requirement and test method of sand and crushed stone for ordinary concrete*" (JGJ52) and "*Recycled coarse aggregate for concrete*" (GB/T25177) respectively, including size grading analysis, particle density, content of fine powder and sediment, crushing index, soundness (mass loss), and water absorption. Besides, for comparison with the results of other researchers, the shape index was measured according to the European standard EN933-4. The physical properties of NCA, FA, and RCA are summarized in Table 2.

As seen in Table 2, RCA's shape index is about 24% higher than that of the NCA, meaning that the RCAs considered in this study are sharper than the NCAs. They are smoother than those considered previously [16] though, which is believed to have a beneficial effect on the water absorption of RCAs.

Due to the higher porosity and lower resistance of the adhered mortar, the RCA has lower densities and higher mass loss than