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Mechanical and physical response of recycled aggregates high-strength concrete at elevated temperatures

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A B S T R A C T

The advances in concrete technology have enabled construction industry with the possibility to produce high-strength concrete (HSC) incorporating recycled aggregates. The envisaged structural applications of recycled aggregates high-strength concrete (RA-HSC) necessitates characterizing its behavior under different service conditions. Fire is among major hazards to which structures are susceptible during their service life. Therefore, characterization of the mechanical and material performance of RA-HSC at elevated temperatures is desirable. In this study, properties of HSC produced using recycled coarse aggregate (RCA) were investigated at high temperatures from 23 to 800 °C. Mechanical properties comprising compressive and splitting tensile strength, elastic modulus, and stress-strain response were investigated under different heating and test conditions. Additionally, visual observations and microstructural analysis were performed to illustrate the comparative high temperature damage to RA-HSC and natural aggregates high-strength concrete (NA-HSC). Results exhibit that the rate of drop in compressive and splitting tensile strength was lower in the case of RA-HSC compared to that of NA-HSC. Changes in the stress-strain response with an increase in temperature show that RA-HSC exhibits comparatively higher axial strains compared to NA-HSC above 400 °C. Visual investigations after exposure to elevated temperatures show that RA-HSC exhibits lower thermal cracking and fewer color changes compared to that of NA-HSC. For analytical fire resistance calculations, data obtained from high temperature material property tests was used to develop simplified equations for expressing mechanical properties of RA-HSC as a function of temperature.

1. Introduction

Sustainable development and environmental awareness have been recognized as key attributes for societal growth. Sustainability in the built environment is being achieved through conservation of natural resources, energy saving, and sustenance of construction materials. Concrete is a composite material composed of various constituents and each constituent has some contributing impact on the environment. Aggregates which are about 70% to 80% of concrete volume add significant disturbances to the ecological system due to its procurement and transportation. With the increased amount of concrete used in the construction industry, main challenges being faced are depletion of natural coarse aggregate (NCA) resources and high consumption of portland cement with its associated carbon footprint. A substantial amount of demolition waste is produced from old and damaged concrete structures that are being replaced. Construction and demolition (C&D) waste, is one of the biggest environmental issues in many developed countries, which renders recycling of concrete as a necessity. A certain percentage of concrete (between 1% and 2%) produced by the ready-mix plants is usually rejected mainly due to workability issues, construction delays, and over-estimated quantities [1]. It is estimated that about 850 million tons of construction and demolition waste is generated in Europe every year, which represents 31% of the total waste generation [1]. The usual method to manage C&D waste in the recent past was to dispose it off in the landfill sites. This has led to huge landfills of C&D waste, occupying the useful land and presenting an environmental problem [2].

Keeping in view the environmental issues, sustainability of natural resources, and voluminous increase in concrete construction, the necessity and importance of recycling C&D waste is accentuated. Recycling concrete to produce recycled coarse aggregate (RCA) is one of the leading approaches to sustainability in the construction sector. The use of recycled aggregate concrete (RAC) is encouraged as it is one of the well-recognized means for achieving environmental friendly concrete, which preserves natural resources, decreases landfill, and supports

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sustainability. Numerous studies have been conducted on RAC to ensure the effective usage of aggregates produced from the recycling of concrete by studying different parameters both in fresh and hardened states. The main properties include replacement percentage, thermal and mechanical properties, shrinkage and creep, cracking resistance, rheology, permeability/transport, and fire damage investigated mostly at ambient conditions.

Dosho [3] replaced 30% and 50% of NCA with that of RCA and obtained compressive strength between 32.6 and 35.8 MPa after 28 days with standard curing conditions. The author concluded that RAC with appropriate mixture design and replacement technique can lead to sufficient quality as structural concrete. Tabsh and Abdelfatah [4] investigated RAC for the structural use and observed the effect of source variation of RCA on the strength of resulting RAC. It was reported by the authors that the improvements in compressive and splitting tensile strength of RAC depend on the mixture proportion. RAC was found 10% and 25% lower in strength compared to concrete based on natural aggregates having similar mixture proportions.

Zega and Di Maio [5] studied the effect of high temperature on conventional normal strength concrete (NSC) made with NCA having different water to cement (w/c) ratios and compared performance with RAC containing 75% of recycled aggregates by volume. The author observed that static modulus of elasticity and compressive strength in all cases in RAC exposed to high temperatures were lower than natural aggregate concrete produced with similar concrete mix characteristics. Laneyrie, et al. [6] studied three types of RCA, namely silica-calcareous coarse aggregate (as reference concrete), laboratory RCA, and industrial RCA. Normal and high-strength concrete (HSC) were prepared using w/c ratio of 0.6 and 0.3 respectively. Specimens were subjected to temperatures ranging from 20 to 750 °C. Different tests were performed to determine the compressive and tensile strength, dynamic elastic modulus, porosity and thermal properties under residual test conditions. No spalling was observed in any concrete specimens at low exposure temperatures. However, a higher mass loss was observed in RCA concrete and it was attributed to extra water retention in RAC. The response of RAC in terms of mechanical properties, mass loss and porosity under residual test conditions was observed to be inferior to that of control samples.

The review of various studies on utilization of RCA as replacement of natural aggregates indicates satisfactory performance in terms of physical and mechanical properties. The use of RCA in conventional concrete mixes is on the rise due to the recent research and development in concrete technology [7–9]. As a result, obtaining higher strength in RAC has become possible due to technological advancements, which also warrants its structural use. For the preservation of natural resources, the use of RAC is thus gaining acceptance in reinforced concrete (RC) structures. Concrete, because of its heterogeneous nature, exhibits complex and unpredictable behavior under fire conditions. This mainly depends on chemical and physical properties of constituent materials, proportioning of ingredients, and curing conditions [10]. Structural members made of normal strength concrete (NSC) usually exhibit reasonable fire resistance performance due to its lower thermal conductivity and high specific heat [11–13]. It has been reported by various experimental studies that HSC members show lower fire endurance compared to that of NSC [14,15]. The inferior high temperature performance of HSC members is attributed to faster strength degradation and fire induced spalling in HSC [16,17]. The envisaged use of recycled aggregate high-strength concrete (RA-HSC) in structural members, therefore, demands characterization of its fire resistance performance.

The temperature induced variations in the physical and chemical properties of concrete not only depend on its material constituents but also on its moisture and porosity [18]. High temperature exposure due to fire affects concrete in many ways, such as color change, loss of compressive strength and modulus of elasticity, mass loss, micro-cracking and surface crazing [19]. Concrete exhibits color changes after exposure to high temperatures, which is largely attributed to the type/source of aggregates used in concrete [20]. Concrete made with siliceous and limestone aggregates usually exhibits changes in color from pink (from 300 to 600 °C), to gray (from 600 to 900 °C) and to buff color (above 900 °C) [21]. The color of concrete after fire exposure becomes a convenience to estimate the fire temperatures to which it has been exposed and thus helps to predict residual strength and serviceability of concrete members. Limited studies have been carried out to establish the fire behavior of NSC made with recycled aggregates from industrial waste products, and these mainly comprise of post-fire (residual) mechanical properties of RCA under residual conditions [22,23]. However, not much literature is available on fire properties of HSC made of RCA under unstressed and residual test conditions.

In unstressed test method, a specimen is heated to target temperature without any preload/stress. Once thermal equilibrium conditions are met during heating and the target temperature is reached, the specimen is loaded (stressed) till failure. In the case of the residual test method, a test specimen is heated to a target temperature until the time of attaining steady-state condition and then allowed to gradually cool down to room temperature. The specimen is then loaded until it fails to obtain the residual strength of concrete. As thermal and mechanical properties of concrete are related to the type of aggregates used, a significantly different high temperature behavior of RA-HSC is envisaged. In this study, the effect of high temperature on mechanical properties namely, compressive and splitting tensile strength, stress-strain response, elastic modulus, and physical properties namely mass loss, thermal cracking response, and microstructure of RA-HSC are evaluated and compared with the natural aggregates high-strength concrete (NA-HSC) under unstressed (hot state) and post-fire residual (cold state) test conditions.

2. Experimental program

2.1. Materials and mixture proportions

Two concrete mix batches namely RA-HSC and NA-HSC were prepared using Type-I, ordinary portland cement (OPC) (BS CEM-I Grade 42.5-N) conforming to ASTM [24]. The OPC comprised of 79% CaO, 13.82% Al_2O_3, and 5.8% SiO_2 as major compounds. Natural sand was used as fine aggregates having fineness modulus of 2.79. Limestone-based natural coarse aggregates and recycled coarse aggregates prepared from lab tested large concrete specimens, with a maximum size of 12.5 mm were used. Both fine and coarse aggregates were used in saturated surface dry (SSD) conditions in the mixtures. The physical properties of aggregates are shown in Table 1. Densified silica fume with a higher silica (SiO_2) content of 96.98% and having bulk specific gravity (BSG) of 2.2 was used as a mineral admixture to achieve high-strength in RAC. Potable water was used for mixing and curing of concrete. For both RA-HSC and NA-HSC concrete mixtures, a constant water to cement (w/c) ratio of 0.32 was used. Owing to lower w/c ratio, naphthalene based second generation high range water reducer having BSG of 1.22 was used as superplasticizer to increase workability. This helped to achieve slump between 85 mm and 110 mm range. Mixture proportion was finalized based on trial batches in the laboratory as per ACI concrete mixture design [25]. The details of the mixture proportions are given in Table 2.

2.2. Test specimens

Cylindrical specimens of 200 mm height and 100 mm diameter were prepared for each batch of concrete. The specimens were de-molded after 24 h and water cured for 28 days at 23 °C average temperature. For compression and stress-strain tests, concrete specimens were ground at the ends to smoothen the surface and to meet the end tolerance as per ASTM [26]. Compressive strength tests were performed on concrete specimens at 7, 14, and 28 days as per ASTM [27] to monitor strength progression. Splitting tensile strength tests were performed as per ASTM [28] at 28 days. Results of room temperature compressive strength for