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Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures

Shi Cong Kou [a,b], Chi Sun Poon [a,*], Miren Etxeberria [c]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University, China
[c] Department of Construction Engineering, Faculty of Civil Engineering, Barcelona 08034, Spain

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A B S T R A C T

In this paper, the effects of high temperature exposure of recycled aggregate concretes in terms of residual strengths, capillary water absorption capacity and pore size distribution are discussed. Two mineral admixtures, fly ash (FA) and ground granulated blast furnace (GGBS) were used in the experiment to partially replace ordinary Portland cement for concrete production. The water to cementitious materials ratio was maintained at 0.50 for all the concrete mixes. The replacement levels of natural aggregates by recycled aggregates were at 0%, 50% and 100%. The concretes were exposed separately to 300 °C, 500 °C and 800 °C, and the compressive and splitting tensile strength, capillary water coefficient, porosity and pore size distribution were determined before and after the exposure to the high temperatures. The results show that the concretes made with recycled aggregates suffered less deteriorations in mechanical and durability properties than the concrete made with natural aggregates after the high temperature exposures.

1. Introduction

There is an increasing interest in exploring the possible use of recycled aggregate concrete (RAC) as a construction material. However, due to the limited knowledge on its durability performance, including high temperature performance, the use of RAC is still limited. The mechanical properties of RAC have been extensively studied [1–20] over the years, and it has been observed that when the recycled concrete aggregates (RA) percentage increases and the effective water–cement ratio of concrete is maintained at the same level, the properties of RAC deteriorates. This is because of the inferior characteristics of RA when compared to natural aggregates due primarily to the presence of attached old cement mortar in the RA. It has been found that reducing the effective water–cement ratio or by the addition of fly ash (FA) or ground granulated blast furnace slag (GGBS) as additional binder materials could improve the physical and mechanical properties of the RAC [21,22].

Information on the durability properties of RAC however is still limited, in particular its performance when subjected to a fire. Generally, concrete is thought to have good fire resistance [23–25]. It is now commonly recognised that the behaviour of concrete when exposed to high temperatures is affected by many factors, including both environmental and constituent materials. Among the environmental factors, the heating rate and the peak temperature are the two main factors. The dehydration of calcium silicate hydrates (C–S–H) gel, the thermal incompatibility between the aggregates and the cement paste and the build up of vapour pressure within the pore system are the main constituent materials factors [26–28].

According to Poon et al. [29], when compared to silica fume (SF) or plain Portland cement (C) concretes, the incorporation of fly ash (FA) or blast furnace slag in concrete improved its performance at elevated temperatures by retaining higher relative residual strength and forming relatively finer cracks. However, this improvement was significant only at temperatures below 600 °C. After exposure to 900 °C the GGBS concrete showed the best performance followed by FA and SF concretes. Mercury intrusion porosimetry (MIP) test results clearly indicated an increase in porosity and average pore diameter with the increase in temperature. The effect can be regarded as the coarsening of the pore structure [30–32] and was responsible for strength loss and increased permeability. In both high strength and normal strength concretes, a significant decrease in porosity and average pore diameter was observed by the addition of pozzolans as compared to the plain Portland cement concretes even at elevated

* Corresponding author. Tel.: +852 2766 6024.
E-mail address: cecspoon@polyu.edu.hk (C.S. Poon).

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temperatures. But concrete produced with 10% SF suffered severe internal cracking due to its the very dense internal structure. With the increase in temperature, this dense structure suffered more damage particularly due to the internal cracking produced by the high vapour pressure.

Xu et al. [33] reported that the inclusion of FA in concrete would raise the concretes' damage temperature to 450 °C. The compressive strength decrease was lower than that of ordinary Portland cement concretes. The beneficial influence of FA can be attributed to the pozzolanic reaction consuming $Ca(OH)_2$ in the hydrated cement matrix.

A limited number of researchers have investigated the fire resistance behaviour of recycled materials in concrete. According to Zega and Di Maio [34,35] high temperature performance of RAC prepared with low w/c ratios were better than that of conventional concretes. The coefficient of Thermal Expansion (CTE) of the old/new mortar interface was perceived to be comparable and its compatibility reduced micro/macro cracking of the cement mortars. Eguchi et al. [36] investigated the spalling behaviour of RA concrete from concrete blocks in replacement ratios of 0–100% by volume. The specimens were heated according to the Japanese standard JIS A 1304 "Method of Fire Resistance Test for Structural Parts of Building". Spalling was not observed on either the RAC or the control samples. The authors considered that the elevated temperature behaviour of RAC concrete was comparable to that of conventional concrete. However, the residual compressive strength of the RAC concrete was not reported. The same conclusions were obtained by Xiao and Zang [37]. Vieira et al. [38], who did not find a correlation of residual mechanical properties with replacement ratios of coarse RA in concretes, reported that after the exposure to 400 °C, 600 °C, and 800 °C, the compressive strength of conventional concrete and concrete made with 100% RCA decreased with the same magnitude. According to Cree et al. [39], coarse RCA in concrete had a better residual strength than that of the conventional concrete for temperatures ranging from 500 °C to 700 °C.

It is generally known that hydrated ordinary Portland cement paste and most aggregates change their structure as temperature increases. With respect to the hydrated cement paste, the unhydrated cement particles and CSH gel are not affected when the temperature increases up to 300 °C [40], concrete heated below 300 °C does not lose significant amount of strength and the strength loss can be recovered through re-hydration. From 350 °C to 550 °C the CH decomposes into lime and water [31], and the CSH gel completely dehydrates and decomposes when the temperature rises to above 700 °C. With respect to the aggregates, common aggregates remain stable up 500 °C. Quartz expands by approximately 5.7% in volume at 570 °C [41,42] and limestone decomposes at 600–900 °C [43].

The objective of this research paper is to present the results of a systematic study on the effect of high temperatures exposures on the mechanical and durability-related properties of RAC.

2. Experimental details

2.1. Materials

The cementitious materials used in this study were ordinary Portland cement (PC) equivalent to ASTM Type I, ASTM Class-F fly ash (FA) obtained from a power plant in Hong Kong and ground granulated blast furnace slag (GGBS) obtained from mainland China. The chemical compositions and physical properties of the cement, FA and GGBS are listed in Table 1.

Natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. Crushed natural granite was used as the natural aggregate and recycled aggregate (with >90% recycled concrete aggregate, approximately 8% of natural stone, 1% of clay masonry and 1% of others) sourced from a recycling facility in Hong Kong was used. The nominal sizes of the natural and recycled coarse aggregates were 20 and 10 mm and their particle size distributions conformed to the requirements of BS 882 (1985). The physical and mechanical properties of the coarse aggregate are shown in Table 2. The porosity of the aggregates was determined by using MIP. River sand was used as the fine aggregate in the concrete mixtures.

Table 1
Physical and chemical properties of cement, fly ash and GGBS.

Contents	Cement	Fly ash	GGBS
SiO_2	21.0	56.79	44.6
Al_2O_3	5.9	28.21	13.3
Fe_2O_3	3.4	5.31	0.9
CaO	64.7	<3	33.8
MgO	0.9	5.21	4.8
Na_2O	–	–	1.0
K_2O	–	–	–
TiO_2	–	–	–
SO_3	2.6	0.68	1.3
Loss on ignition (%)	1.2	3.90	0.2
Specific gravity (g/cm^3)	3.15	2.31	2.98
Fineness (>45 μm)	–	–	–
Specific surface (cm^2/g)	3520	3960	5350

2.2. Test specimen preparation

Three series of concrete mixtures were prepared in the laboratory using a pan concrete mixer. The absolute volume method was used in calculating the mixture proportions. FA and GGBS were used as cement replacements on a weight basis. In all concrete mixtures, a constant water/binder ratio at 0.50 was used. The replacement level of FA and GGBS were kept at 35% (FA35) and 55% (GGBS55), respectively. The replacement levels of natural aggregates by the recycled coarse aggregates were 0% (control-C), 50% (RA50%) and 100% (RA100) and, sand was used for approximately 40% of the total weight of aggregates. The mixture proportions of the concrete are presented in Table 3.

The test specimens were produced, in accordance with ASTM C192-88, to determine the compressive and splitting tensile strength and water absorption coefficient. After casting, all the concrete specimens were first cured for 24 h in laboratory conditions (23 °C ± 2 °C, 65% humidity). Plastic sheets were used to cover the specimens to prevent water evaporation. After 24 h, the specimens were demolded and placed in a water curing tank at 27 ± 2 °C until the test ages.

2.3. Heating and cooling regimes

After 90 days of water curing, the specimens were dried in the oven at 105 °C for 24 h before being heated in an electric furnace. In order to evaluate the behaviour of different materials with respect to the temperatures applied, in this research work the specimens were heated in an electric furnace to 300 °C, 500 °C and 800 °C separately. The heating rate was set at 5 °C per minute. The respective maximum temperature was maintained for 4 h. After that, the specimens were allowed to cool naturally to room temperature, by turning off the furnace and allowing for natural cooling.

2.4. Testing

2.4.1. Compressive and splitting tensile strength

The 100 mm cubes and concrete cylinders with 100 mm (diameter) by 200 mm (height) were used for the determining of the