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Thermal and mechanical properties of alkali-activated slag paste, mortar and concrete utilising seawater and sea sand

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HIGHLIGHTS

- Tests on seawater and sea sand concrete (SWSSC) under elevated temperatures.
- Temperature gradient, mass loss and thermal strain of SWSSC were measured.
- Mechanical properties of SWSSC at elevated temperatures were measured.
- X-ray CT scanning and SEM were used to explain failure mechanism of SWSSC.

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ABSTRACT

This paper presents an experimental study on the thermal properties of alkali-activated slag paste, mortar and concrete utilising seawater and sea sand exposed to elevated temperature. The thermal properties of paste and concrete utilising cement, fresh water and river sand were also investigated for comparison purpose. The samples were heated to different target temperatures up to 1000 °C at a heating rate of 5 °C/min, and tested both under hot and cooled conditions. The thermal properties, including temperature gradient, visual observation, mass loss, thermal strain and mechanical properties (i.e. strength, Young's modulus and stress-strain curve) were investigated. X-ray CT scanning and scanning electron microscopy (SEM) were conducted to understand the macro/microscopic changes of the paste and concrete in response to heating. Degradation in mechanical properties of slag paste is attributed mainly to the cracks induced by temperature gradient, pore pressure and phase change. The degradation of concrete is caused by thermal mismatch between paste matrix and aggregates regardless of the use of cement or slag, fresh-water or seawater, and river sand or sea sand.

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1. Introduction

As the most widely used construction material, concrete has the advantages of low cost, easy maintenance, flexible workability and good fire resistance. The binding phase which provides strength to a concrete is usually based on ordinary Portland cement (OPC). The rapidly increasing demand of concrete generates significant environmental issues. About 0.8 tonnes of CO₂ is emitted to produce 1 tonne of Portland cement, i.e., from the combustion of fossil fuels and the conversion of calcium carbonate to oxide [1]. Besides, large quantities of fresh water and river sand are also consumed in the concrete industry, which exacerbate the resource shortage. In recent decades, an alternative

cement-like binder called 'alkali-activated material (AAM)', which is formed by the interaction between aluminosilicate precursors (which are generally industrial by-products) and alkaline activators, was proposed and extensively investigated [2–5]. AAMs are also called geopolymers in some literatures. To avoid the high consumption of fresh water and river sand in concrete industry, seawater and sea sand have attracted the researchers' attention as potential candidates for construction industry [6–11]. Research on hybrid construction system utilising seawater, sea sand and fiber reinforced polymer is being carried out at Monash University in collaboration with The Hong Kong Polytechnic University and Southeast University, China. Earlier work out of this exercise concerns to the structural behaviour of FRP confined seawater and sea sand concrete [12,13] and the durability of FRP bars in seawater and sea sand concrete environment [14,15].

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The most common precursors used in AAM are ground granulated blast furnace slag (GGBFS), fly ash and metakaolin, among which slag has much higher calcium content. The alkaline activation requires the addition of activator (e.g. sodium hydroxide, sodium silicate and potassium hydroxide in solution or dry forms), which is the major difference to Portland cement. Generally, the reaction mechanism involved in alkaline activation includes dissolution, rearrangement, condensation and re-solidification [3,4,16,17]. Calcium aluminium silicate hydrate (C-A-S-H) gel with a disordered tobermorite-like structure is the main reaction product in alkali-activated slag [1].

The behaviour of concrete at elevated temperatures or in fire is one of the major concerns when considering durability of concrete structures. In comparison to steel and timber, concrete has the advantages of low thermal diffusivity and incombustibility in fire. However, the concrete at elevated temperature exhibits mechanical properties deterioration due to the physicochemical changes in paste and aggregate and the thermal incompatibility between paste and aggregate [18–20]. The studies on Portland cement concrete [19,21,22] find the decomposition temperatures of calcium hydroxide and calcium carbonate to be 300–500 °C and 700–1000 °C respectively, and their melting starts at 1000–1300 °C. Other changes like crystallisation and phase changes have been observed in alkali-activated materials exposed to elevated temperature [23]. The morphology of the geopolymer paste can be altered by manipulating the schedules of sintering, crystallisation and melting, whilst dehydration and densification can affect the size and distribution of the pore structure [24].

Different properties of geopolymers and geopolymer composites (mortar and concrete) exposed to elevated temperature have been investigated by several research groups, e.g., the effects of ductility and transit creep on residual strength [25–27], the residual strength of alkali-activated slag concrete [28], the spalling behaviour of geopolymer and Portland cement concrete in simulated fire [29], the effects of specimen size, aggregate size, aggregate type, precursors, and activators on the thermal properties [30–32]. Also, the thermal properties of alkali-activated slag paste and mortar are reported [24,33–36]. Recently, Aslani [37] summarized the reported researches on the mechanical properties of geopolymers exposed to elevated temperature, and proposed constitutive models for strength and modulus. Besides the mechanical properties, morphology, phase changes and pore structures of geopolymers and geopolymer composites are investigated by means of scanning electron microscope (SEM), X-ray diffraction analysis (XRD), thermogravimetric and derivative thermogravimetric analysis (TGA/DTG), Differential thermal analysis (DTA), FTIR spectroscopy, and mercury intrusion porosimetry [34,35,38], which are helpful explaining the strength change. In general, the strength change is a resultant of phase transformation, thermal incompatibility and pore structure effects.

Up to now, no studies have been conducted on the behaviour of alkali-activated concrete using seawater and sea sand exposed to elevated temperature or fire [11], which may limit further application of this 'environment-friendly' concrete. The research in this paper aims to fill up this knowledge gap. This paper focuses on the thermal properties of alkali-activated slag paste, mortar and concrete that was prepared using seawater and sea sand, and then exposed to elevated temperature. The ordinary Portland cement paste and concrete were also investigated for comparison purpose. The temperature gradient, mass loss, thermal strain and mechanical properties, such as residual strength, hot strength, Young's modulus, stress-strain curve, were studied for paste, mortar and concrete. The X-ray CT scanning and SEM are conducted to characterize the macro/microstructures of paste and concrete after high temperature exposure.

2. Experimental investigation

2.1. Materials

The ground granulated blast furnace slag (GGBFS, called 'slag' in short throughout this paper), which is a by-product of steel-making, was adopted as cementitious material in this research. The chemical composition of slag was determined by X-ray fluorescence (XRF) and is listed in Table 1. Its chemical composition is consistent with most of the existing researches [5], with Si-to-Al ratio of 2.19. The calcium oxide (CaO) content in slag is much higher compared to that in fly ash or metakaolin and less in Portland cement.

The powdered sodium meta-silicate with modulus ratio of 1.35 was used as an activator in this research. The chemical composition of sodium meta-silicate is shown in Table 1. Following the suggestions made by Collins [39] and Cheng and Sarkar [40] on how to improve the workability, 1% (weight percentage of slag) hydrated lime slurry, which consisted of 1/4 lime and 3/4 water by weight, was added to the mixture. The slump of SWSSC (with hydrated lime slurry, 14 mm coarse aggregate) is about 140 mm.

The sea sand and seawater were obtained in the coastal beach near Melbourne. Sieve analysis was carried out according to AS 1141.11.1 [41] to determine the particle size distribution (PSD) of sea sand. The PSD of sea sand is compared in Fig. 1 with the river sand used in this research. 51.7% and 13.3% of the sea sand could respectively pass the sieves with the apertures of 0.6 mm and 0.3 mm, whilst the corresponding percentages for river sand are 79.4% and 36.8% respectively. The fineness modulus of sea sand is 2.39 and that of river sand is 1.86, indicating the sea sand is slightly coarser than the river sand. The chemical composition of sea sand is listed in Table 1, in which the weight percentage of Cl ions is 0.13%. The chemical composition of seawater used in this research is shown in Table 2, where the concentration of NaCl is about 30 g/l.

Two kinds of coarse aggregate were adopted in this study: basalt with maximum size of 7 mm and basalt with maximum size of 14 mm. The ordinary Portland cement (OPC) is a general purpose cement produced in Australia. The tap water provided in the laboratory is adopted as fresh water.

2.2. Sample preparation

A total of eight mixtures, including three kinds of paste (SWP - slag paste using seawater; FWP - slag paste using freshwater; OPCP - ordinary Portland cement paste using freshwater), one kind of mortar (SWSSM - slag based seawater and sea sand mortar), and four kinds of concrete (SWSSC - slag based seawater and sea sand concrete; FWRSC - slag based freshwater and river sand concrete; OPCC - ordinary Portland cement based freshwater and river sand concrete; SWSSC2 - slag based seawater and sea sand concrete utilising coarse aggregate with larger size (~14 mm)), were investigated in this paper. The water-to-binder (slag or OPC) ratio is fixed as 0.53 and the fine-to-coarse aggregate ratio is 0.73. The mix proportions are summarized in Table 3.

The activator (i.e. sodium meta-silicate) was pre-blended with slag in dry state before mixing. The mixing sequence for mortar and concrete is: premixing the aggregates with 1/3 water for 30 s, adding binder (slag pre-blended with activator or OPC), mixing for 2 min during which adding the rest of water and lime slurry simultaneously (if applicable), resting for 2 min, and mixing for another 2 min. The step of premixing aggregates was skipped when mixing the paste. The mixtures were poured into the moulds in three equal layers, with mechanical vibration for each layer for about 30 s to achieve compaction in each layer. All the samples

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