



Properties of autoclaved aerated concrete incorporating rice husk ash as partial replacement for fine aggregate



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ABSTRACT

This study examines the effects of rice husk ash (RHA) on the physical, mechanical and microstructural properties of autoclaved aerated concrete (AAC) produced at a temperature of 180 °C for 8 h and 18 h. The RHA was used as an aggregate at various replacement ratios. The results demonstrated that RHA substitution for sand reduces compressive strength and unit weight. In terms of the microstructure, the highly reactive silica in RHA strongly affected the tobermorite transformation. At 8 h of autoclaving time, the lath-like and plate-like tobermorite formed in mixtures containing up to 50% RHA was replaced by a glass-like, silica-rich CSH structure at increased replacement ratios. However, extended processing had no significant effect on these properties, which indicates that the substitution of RHA for sand has a tendency to reduce the autoclaving time or autoclaving temperature required.

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1. Introduction

Rice husk is an agricultural by-product obtained from the milling of paddy [1]. Approximately 5 million tons of rice husks are generated each year. Most of the husk is used as fuel in biomass power plants or in the boilers of various industrial sectors to produce steam [2–4]. Although the residues obtained from these processes contain approximately 90% silica by mass, the reactivity of the silica is relatively poor, and the colour of the residues varies from white to black, thus preventing the widespread use of this material. However, these by-products and residues are produced in an increasing amount each year, and there is, therefore, great interest in incorporating these solid wastes into construction materials as an environmentally friendly method of resource conservation.

Autoclaved aerated concrete (AAC) is a lightweight concrete that has been widely used in building applications. Compared with conventional construction materials, AAC offers lower density, lower thermal conductivity, lower shrinkage, greater fire resistance and ease of use in construction [5–8]. AAC is normally produced by a hydrothermal treatment of a mixture of finely ground

quartz sand, lime cement and a small amount of aluminium powder as a pore-forming agent under high-pressure steam curing at a temperature typically between 180 °C and 200 °C [9]. During the slurry phase, the metallic aluminium reacts with calcium hydroxide or alkali to form hydrogen gas bubbles, which contribute to the high porosity of the aerated concrete.

As a product of the hydrothermal reaction during autoclaving, the crystalline phase of calcium silicate hydrate, namely, tobermorite ($\text{Ca}_5\text{Si}_6\text{O}_{16}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$), is formed [9]. Previous studies have reported that the reactivity of the silica source, the amount of Al added and the presence of alkali compounds strongly affected the formation of tobermorite [10,11]. Crystalline tobermorite is rapidly formed during the early stage of the autoclave process when reactive quartz is used as the silica source; however, the quantity of tobermorite formed is lower than in the less-reactive quartz system. The introduction of Al in the form of $\gamma\text{-Al}_2\text{O}_3$ has also been reported to have a significant effect on tobermorite formation via CSH and katoite pathways but not to affect the dissolution rate of quartz. In addition, the types of hydration products formed were found to be affected by lime content. In the high-lime mixes containing up to 30% air-cooled slag (AS), the fibrous, calcium-rich CSH that initially formed was subsequently transformed into needle-like and lath-like tobermorite; however, glass-like, silica-rich CSH appeared in low-lime mixes [12].

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The application of industrial by-products or waste residues in AAC has been investigated for many years [13–17]. These by-products include pulverised fuel ash, coal bottom ash, wheat straw ash and air-cooled slag. Some of these materials are used as cement replacement material or as partial replacements for fine aggregates. Although extensive studies of the use of by-products or residues in AAC have been reported, the substitution of rice husk ash (RHA) for ground quartz sand as a silica source has not been investigated. Thus, the purpose of this study was to investigate the physicochemical and microstructural properties of AAC incorporating reactive silica prepared from rice husk.

2. Materials and experiment

2.1. Materials

The mixture of aerated concrete with RHA, called RHC, was produced from ordinary Portland cement (OPC), quick lime, quartz sand, RHA and water. The RHA used in this study was synthesised in a laboratory using an electric furnace at a temperature of 650 °C for 1 h. It was then ground before being passed through sieve No. 325, with less than 34% by weight being retained, in accordance with ASTM C618 [18]. Quartz sand was also ground to an average particle size of approximately 100 µm. Aluminium powder was provided by the Super Block Company, Limited. The chemical compositions of the materials used in this study were determined using X-ray fluorescence (XRF; WDXRF PW2400) analysis, and the results are provided in Table 1. The physical properties of these materials are listed in Table 2. The particle size distribution of RHA and quartz sand were conducted by Lazer particle size distribution (Malvern Mastersizer S Particle Size Analyser), and is given in Fig. 1. The crystalline phase of the RHA was analysed by X-ray diffraction (XRD; Miniflex using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) at a voltage of 40 kV and 40 mA), and the XRD spectrum is presented in Fig. 2. A broad peak characteristic of amorphous SiO₂ is observed at $\approx 23^\circ$ (2θ) in the spectrum.

2.2. Experimental program

The reference mix was composed of 45% OPC, 5% quick lime and 50% sand; the sand was replaced by RHA at levels of 25%, 50%, 75% and 100% to produce RHC25, RHC50, RHC75 and RHC100, respectively. Aluminium powder was added at 0.5% by weight of the binder (OPC + quick lime), and the water/binder ratio was determined by the flow table method to obtain a flow of $110 \pm 5\%$ in accordance with ASTM C109 [19]. These mix proportions are summarised in Table 3. The solid components were mixed in a Hobart mixer for 1 min. Water was then added to the solid components, and the mixing was repeated for 1 min and 30 s. This slurry was poured into 5 cm cubic steel moulds. After casting, the samples were pre-heated in an oven at 40 °C for 3 h to achieve the desired setting and volume stability. Autoclave curing was conducted at 180 °C for 8 h and 18 h.

Table 1
Chemical compositions of OPC, rice husk ash and quick lime.

Oxide	OPC	RHA	Quick lime
CaO	66.20	0.70	94.7
SiO ₂	18.80	92.80	0.89
Al ₂ O ₃	4.65	0.15	0.11
Na ₂ O	0.20	0.08	–
Fe ₂ O ₃	3.22	0.17	0.10
MgO	0.79	0.77	2.61
P ₂ O ₅	0.07	1.07	0.02
K ₂ O	0.75	3.35	0.01

After curing, the samples for which compressive strength was to be tested were dried in the oven at 40 °C for 24 h, after which they contained 5–15% moisture content by mass in accordance with ASTM C1368 [20]. The remaining samples were dried at 105 °C for 24 h to determine their unit weights. For each mix proportion, a set of five samples was used to determine the compressive strength and the unit weight, and the average compressive strength of the samples was reported to the nearest 10 psi (0.1 MPa), in accordance with ASTM C109 [19]. The microstructures of the samples were investigated using XRD and scanning electron microscopy (SEM, JEOL-JSM-6400). Thermal conductivity was determined on $30 \times 30 \times 5 \text{ cm}^3$ RHC samples during autoclave curing for 8 h in accordance with the ASTM C518 [21] Heat Flow Meter Method using the Thermal Conductivity of Building and Insulating Materials Unit B480.

3. Results and discussion

3.1. Unit weight

The unit weights of the RHC samples, cured for 8 and 18 h, are indicated in Fig. 3. The unit weight of aerated concrete with RHA is reduced as RHA is introduced; however, the unit weight was stable or only slightly changed for the different autoclaving times. This result indicates that the unit weight reduction in RHC resulted from the relatively low specific gravity (2.13) and higher pore structure of RHA compared with quartz sand (2.59). The unit weight loss of the RHC samples compared with the control samples was in the range of 16–45% for the samples that were subject to 8 h and 18 h of autoclave curing.

A slight increase in the unit weight of some of the mixtures (RHC25, RHC75 and RHC100) was observed when the duration of the autoclaving step was extended to 18 h, and this might be due to the formation of more solid hydration products in the concrete. Considerable phase evolution occurred during the AAC processing; the cement phases, mainly alite (C₃S) and belite (C₂S), were transformed into CSH phases and Ca(OH)₂ during the moulding process. Under high steam pressure, the silica in the quartz is dissolved and rapidly reacts with CSH and Ca(OH)₂ to form tobermorite or other products, such as xonotile (C₆S₆H) or α -dicalcium silicate hydrate, depending on the starting materials and the duration and temperature of the autoclaving step. At this stage, the hydration products form as autoclaving progresses. In addition, an earlier study performed by Taylor [9] demonstrated that the unit weight of the hydration products was in the range of 2200–2500 kg/m³ (for example, CSH = 2250 kg/m³ and 1.1 nm tobermorite = 2481 kg/m³). This result indicated that autoclaving for a longer time leads to a decrease in the porosity and increase in unit weight of the AAC produced [22].

3.2. Mechanical properties

The compressive strength test results of the RHC samples are presented in Fig. 4. The compressive strength of RHC decreased with increasing replacement of quartz sand with RHA, but it remained constant or only slightly changed with the variation in autoclaving time. The compressive strength decrease observed in the RHC samples depends on many factors, for example, the water/binder (W/B) ratio, curing time, curing conditions, types of raw materials and mix proportions. In terms of the W/B ratio, a higher ratio leads to reduce strength because water that is not consumed by the hydration reaction may leave the concrete as it hardens, resulting in the formation of microscopic pores that will reduce the final strength of the concrete [23]. In this research, the W/B ratio increased with increasing RHA content, as indicated

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