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Effect of alkali-activator and rice husk ash content on strength development of fly ash and residual rice husk ash-based geopolymers

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HIGHLIGHTS

- A mixture of fly ash and residual rice husk ash is introduced as new binder material.
- The alkali-activator and rice husk ash affects the strength development significantly.
- The strength peaked at an optimum activator concentration and rice husk ash content.
- The compressive strength of all geopolymers increased with ageing time.
- The geopolymer system included an amorphous gel phase and a crystalline zeolite phase.

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ABSTRACT

This study combines various proportions of class-F fly ash (FA) and residual rice husk ash (RHA) with an alkaline solution to produce geopolymers. All of the geopolymer samples were cured at 35 °C and at 50% relative humidity until the required testing ages. The effects of the RHA content (0–50%) and of the concentration of the sodium hydroxide (NaOH) solution (8–14 M) on the compressive strength development of the samples were then investigated. X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) were used to examine the microstructural properties of the samples. Further, scanning electron microscopy (SEM) coupled with energy dispersive spectrometer (EDS) was used to characterize sample surface morphologies and compositions. Results found that the samples prepared with a NaOH concentration of 10 M and a RHA content of 35% exhibited the highest compressive strength and that increasing the NaOH concentration and RHA content beyond these values exhibited decreasing compressive strength. Chemical analysis showed that the major crystalline phases presented in the resultant geopolymer were quartz, mullite, and cristobalite. Furthermore, minor zeolite phases were detected in all of the geopolymer samples. The results of the present study support FA and RHA as promising solid waste materials for use in the production of geopolymers.

1. Introduction

Manufacturing ordinary Portland cement (OPC) is an energy-intensive process that releases significant quantities of greenhouse gases into the atmosphere [1]. To reduce the carbon footprint of the cement manufacturing industry, researchers have focused increasing attention on the potential for pozzolanic materials to be used as a partial replacement for OPC and on the development of alternative cementitious materials. "Geopolymer", an aluminosilicate material first introduced by Davidovits in the mid-1970s [2,3], is currently one of the most promising of these alternative materials.

Researchers have recently studied the potential for using geopolymerization technology to produce geopolymers. Geopolymerization uses the natural chemical reaction that occurs between amorphous silica and alumina-rich solids in highly concentrated hydroxide or silicate solutions at ambient or slightly elevated temperatures to form a highly stable material that has an amorphous polymeric structure with interconnected Si–O–Al–O–Si bonds [3–5]. The geopolymerization process includes: the dissolution of solid aluminosilicate materials in a strong alkaline solution, the formation of silica–alumina oligomers, the polycondensation of the oligomeric species to form inorganic polymeric material, and the bonding of the un-dissolved solid particles in the final

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geopolymeric structure [6]. Geopolymers have demonstrated good performance in practical applications. Moreover, this material provides many advantages, including the widespread availability of raw material inputs, rapid development of mechanical strength, good durability, high resistance to acids, excellent adherence to aggregates, the ability to immobilize contaminants, and significantly reduced energy consumption and greenhouse gas emissions during production [4,6].

Fly ash (FA) is an industrial waste with pozzolanic properties that is widely obtained from thermal power plants. Millions of tons of FA are generated each year globally [2]. FA contains high levels of amorphous silica and alumina, which are frequently removed using an alkaline solution. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) are the most commonly used alkali-activators [2,7]. In the synthesis of geopolymers, NaOH has been found to affect both the compressive strength and the structure of geopolymers significantly [7]. FA may be used as a source material in the production of geopolymers because geopolymerization is based on the alumina–silica chain. Previous studies have concluded that class-F FA is a good source of geopolymers and that NaOH is the best of several potential FA activators for producing geopolymers. Additionally, when NaOH is used together with sodium silicate (Na_2SiO_3), the compressive strength of the geopolymer material is higher than when only NaOH is used [8].

Rice husk ash (RHA) is an industrial waste that is generated as a by-product of burning rice husks (RH) for power or for other purposes. RH is an abundantly available by-product of rice milling. The annual worldwide production of RH is about 70 million tons [9]. In Vietnam, RH, which currently has no commercial use, is most often dumped into rivers where it is a source of serious environmental pollution [10]. The residual ash from burning RH is known as RHA, which consists of highly porous particles that present a low bulk unit weight and a very large external surface area. Burning conditions (temperature and duration) affect both the silica content and mineral phases of the RHA significantly. Depending on the burning conditions of RH, the silica content in the RHA varies from 90 to 95 wt.%, which exists predominantly in an amorphous phase and partly in a crystalline phase [16]. The amorphous silica in RHA is reactive and may be used as a pozzolana [11]. Previous studies have indicated that RHA may be an effective additive in geopolymers when used in appropriate quantities [9].

Because RHA and FA contain significant quantities of silica and alumina, these materials are suitable for producing geopolymers [1,11]. Furthermore, the alkali-activator solution plays an important role in the dissolution of Si and Al atoms to form geopolymer precursors and the final aluminosilicate material. The concentration level of the activator significantly affects the compressive strength of the resultant geopolymer material, with the ideal concentration maximizing the strength of that material [8]. Therefore, the main objective of the present study is to investigate the potential use of FA and RHA as raw materials for producing geopolymer using geopolymerization technology in order to address the gap in the literature regarding this important issue. The effect of the alkali-activator and of the RHA content on the compressive strength development of geopolymers is investigated comprehensively. Additionally, SEM/EDS, XRD, and FTIR are performed to characterize the composition and microstructure properties of the resulting geopolymers.

2. Materials and experimental methods

2.1. Materials

FA and RHA were used to prepare the geopolymers in this study. The FA sourced from a power plant in Taichung, Taiwan, whereas the RHA was collected from Saigon Ve Wong Co., Ltd., Ho Chi Minh City, Vietnam. The RHA powder was prepared by grinding the unground rice husk ash (URHA) in a ceramic ball mill for 2 h in order to obtain a significant small particle size of the RHA. The URHA used for the preparation of RHA was a residual of steam generation process, where rice husk pellets were burnt in a steam boiler at the temperatures of 700–900 °C. Particle size distributions, XRD patterns, and SEM images of raw materials are given in Figs. 1–3, respectively. The physical and chemical characteristics, determined by X-ray fluorescence analysis of these ashes, are given in Table 1. The FA was composed mainly of SiO_2 (63.9%) and Al_2O_3 (20.0%) and that the main constituent of RHA was SiO_2 (95.6%). As observed from XRD patterns (Fig. 2) and SEM images (Fig. 3), the FA contained mainly stable crystals of mullite and quartz and the FA particles were mostly smooth and spherical. Further, the RHA contained mainly stable crystals of cristobalite and RHA particles were irregular in shape. Moreover, the RHA particles were significantly smaller than the FA particles (Fig. 1).

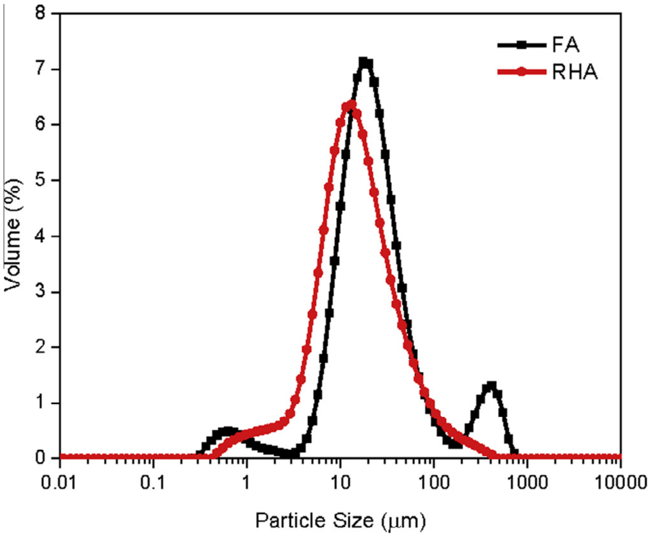

Fig. 1. Particle size distributions of FA and RHA.

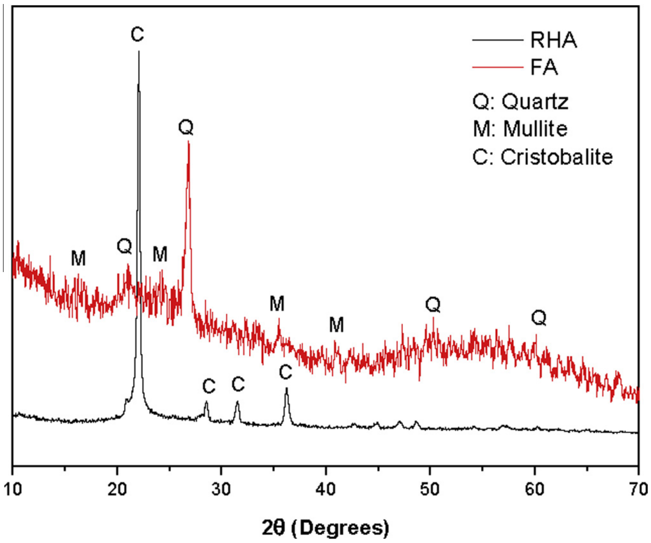

Fig. 2. XRD patterns of FA and RHA.

A solution of NaOH and Na_2SiO_3 was used as the alkali-activator solution. The NaOH used was commercial grade and supplied by Formosa Plastics Corporation in white flake forms at 98% purity. The NaOH solution was prepared by dissolving the NaOH flakes in water at an appropriate concentration. The Na_2SiO_3 liquid used was commercial grade and supplied by Pinnacle Industrial Co., Ltd., with an approximate 34% solid content (25.7% SiO_2, 8.26% Na_2O, 66.04% H_2O, and $SiO_2/Na_2O = 3.11$) and a specific gravity of 1.34 g/cm^3. The liquid was gray in color and highly viscous. The mixing water used was local tap water. All of the materials used in the present study conform to the relevant ASTM standards.

2.2. Sample preparation

The NaOH solutions were initially prepared by dissolving the NaOH flakes in water in concentrations of 8–14 M. The solutions were then mixed with the Na_2SiO_3 solution and allowed to cool to room temperature. The solutions with NaOH con-