Journal of Cleaner Production 119 (2016) 128–134

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A sustainable calcined water treatment sludge and rice husk ash geopolymer

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ARTICLE INFO

Article history:
Received 27 June 2015
Received in revised form
17 December 2015
Accepted 22 January 2016
Available online 30 January 2016

Keywords:
Geopolymer
Water treatment sludge
Rice husk ash
Sustainability
Alternative cement

ABSTRACT

Geopolymer is an environmentally friendly cementing agent and is an alternative to Ordinary Portland Cement (OPC). Calcined Water Treatment Sludge (WTS) and Rice Husk Ash (RHA) blends are used as a sustainable precursor for developing a lightweight geopolymer binder in this research. The alkali activator is a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The effects of the SiO_2/Al_2O_3 ratio, which reflects the characteristics of chemical compositions of WTS and RHA, and the heat-curing temperature (at room temperature and 60 °C) on density, setting time and Unconfined Compressive Strength (UCS) are investigated. It is evident from this study that the density of WTS–RHA geopolymers at various SiO_2/Al_2O_3 ratios and temperatures is essentially the same and is approximately 3 times lower than that of OPC (of 3.15 g/cm^3). The SiO_2/Al_2O_3 ratio and temperature significantly affect the setting time and UCS. A higher SiO_2/Al_2O_3 ratio results in longer initial and final setting times as the condensation rate between silicate and aluminate species is faster than that between silicate and silicate species. The optimum SiO_2/Al_2O_3 ratio providing the highest strength is found at approximately 4.9 and 5.9 for room temperature and 60 °C curing conditions. At these optimum SiO_2/Al_2O_3 ratios, the UCSs of geopolymers meet the minimum requirement for OPC of 19 MPa. This research will enable WTS and RHA traditionally destined for landfills to be used in a sustainable manner as a precursor in geopolymer binders. This sustainably, in terms of economic and environmental perspectives, is also analyzed and discussed in this paper.

1. Introduction

Ordinary Portland Cement (OPC) is widely used for construction works human society. However, OPC has negative environment impacts because the production of OPC requires high energy consumption and emits high quantities of carbon dioxide gas (Gartner, 2004; Habert et al., 2011; Turner and Collins, 2013), thereby contributing to the global warming. Geopolymers have recently been investigated by several researchers as an alternative cementing agent to OPC (Chindaprasirt and Chalee, 2014; Sun et al., 2013).

A geopolymer is an inorganic polymer technology (Cheng and Chiu, 2003; He et al., 2012; Komnitsas and Zaharaki, 2007; Lemougna et al., 2013) and is synthesized by the aluminosilicate compound materials with alkali hydroxide and/or alkali silicate (He et al., 2013; Zhang, 2013). Geopolymers have been the subject of intense study because they are an environmentally friendly cementing agent, with low energy consumption and low toxicity, are stable at high temperature and have high durability (Pacheco-Torgal et al., 2012). Previous studies (Sukmak et al., 2013a, 2013b, 2015) have investigated the strength and durability of clay–fly ash geopolymers as masonry bearing units. The durability against

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http://dx.doi.org/10.1016/j.jclepro.2016.01.060
0959-6526/

sulfate attack of clay–fly ash geopolymers is superior to that of clay–cement; i.e., there is no major change in the microstructure and pH of clay–fly ash geopolymers when exposed to sulfate solutions.

Geopolymers can be synthesized from a variety of silica and alumina rich materials (Gouny et al., 2012; Palamo et al., 2007), such as clay or kaolin (Buchwald and Kaps, 2002), fly ash, and bottom ash (Davidovits, 1999). Fly ash derived from coal-fired electricity generation provides the greatest opportunity for commercial utilization of this technology due to the plentiful worldwide raw material supply (Mohapatra and Rao, 2001; Van Jaarsveld et al., 1998). High quality fly ash is a highly desirable commodity in the construction industry. The recycled waste silica and alumina rich materials are thus of interest for sustainability research and practice.

Water Treatment Sludge (WTS) is a waste by-product from the water treatment process in the production of tap water and drinking water as it is extracted from raw water by coagulation techniques (Keeley et al., 2012). The increasing demand of treated water has resulted in increasing quantities of sludge by-products generated annually (Rodríguez et al., 2010; Teixeira et al., 2011). Environmentalists have proposed effective ways to solve the problem of WTS by re-using or processing it into usable products (Kyncl, 2008; Mery et al., 2014). The important chemical compositions of WTS are Al_2O_3 and SiO_2 (Suksiripattanapong et al., 2015b), which are the essential components of the geopolymer structure.

At the Metropolitan Waterworks Authority (MWA) of Thailand, the WTS is generated with the maximum capacity of 300 tons per day in the dry season and approximately 700 tons per day in the wet season. With continuous increases in water demand due to a rapidly growing population, the quantity of WTS is subsequently and perpetually increasing and has been mainly disposed of in landfills. There has been a recent initiative by MWA to study the usage of WTS as construction and building materials according to the zero-waste directive. WTS has been successfully used as aggregates to manufacture sustainable geopolymer bearing units (Horpibulsuk et al., 2015; Suksiripattanapong et al., 2015b) and geopolymer lightweight blocks (Suksiripattanapong et al., 2015a). The liquid alkali activator was a mixture of Na_2SiO_3 and NaOH and the precursor was a high calcium fly ash. In addition to aggregates, silica- and alumina-rich WTS can be also used as precursors after being calcined.

Waijarean et al. (2014) showed that the calcined WTS could be used as a precursor, but the strength was low due to an unsuitable SiO_2/Al_2O_3 ratio. Khater et al. (2012) reported that the strength development of a geopolymer matrix depended on the type of precursor and the SiO_2/Al_2O_3 ratio. The quality of the calcined WTS as a precursor can be improved by the modification of the intrinsic SiO_2/Al_2O_3 ratio. A cost-effective means is blending calcined WTS with a SiO_2/Al_2O_3 rich waste material. Rice Husk Ash (RHA) is considered to be a potential waste material of a biomass power generation and the rice drying process. Typically, RHA is composed of SiO_2 by more than 80 wt% (Sua-Iam and Makul, 2015). It is a reactive silica material (Billong et al., 2011; Bui et al., 2012) that is abundant in rice producing countries, including Thailand. This blended precursor (WTS and RHA) is a sustainable alternative to quality fly ash.

The present paper aims to develop a geopolymer binder using calcined WTS and RHA blends as a sustainable precursor. The effect of WTS/RHA ratios and heat-curing conditions (room temperature and 60 °C) on the density, setting time, and Unconfined Compressive Strength (UCS) of the WTS–RHA geopolymer are examined and analyzed. This research will enable WTS and RHA traditionally destined for landfills to be used in a sustainable manner as a precursor in geopolymer binders, which is significant from engineering, economical and environmental perspectives.

2. Materials and methods

The schematic of the WTS/RHA geopolymer producing process is illustrated in Fig. 1. The details are as follows:

2.1. Precursor preparation

WTS was obtained from the Bangkhen water treatment plant of the Bangkok metropolis, Thailand. To remove the impurities in the WTS, the WTS was mixed with water at a WTS/water ratio of approximately 0.8–1.2 by mass and then the WTS slurry was passed through a sieve (number 325) and oven-dried at 100 °C for 24 h. The dried WTS was milled by an electric mortar and passed through a sieve (number 325) before being calcined at 600 °C for 2 h to obtain the calcined WTS powder. RHA was obtained from the Korat Yong-sa-nguan Company Limited, Thailand. The RHA was wet milled by a ball mill for 6 h and then dried at 100 °C for 24 h before being passed through a sieve (number 325).

2.2. Sample preparation

Sodium hydroxide (NaOH) pellets and distilled water were mixed to obtain a concentration of 10 M, then allowed to cool down at a room temperature (27–30 °C). NaOH solution was mixed with sodium silicate (Na_2SiO_3) solution to prepare the alkali activator solution. Na_2SiO_3 consists of Na_2O = 8.0%, SiO_2 = 27.0% and H_2O = 65.0%. The ratio of Na_2SiO_3 solution to NaOH solution was fixed at 1.5 by weight. The mixed solution was stored for 24 h prior to usage.

The calcined WTS powder and RHA powder were mixed at various WTS/RHA ratios of 100:0, 85:15, 70:30, 60:40 and 50:50. The mixed powder was then mixed with an alkali activator solution by a mortar at a solid to liquid ratio of 1.0. The geopolymer paste was poured into a 50 mm × 50 mm × 50 mm steel mold and compacted, as described in ASTM C109 (2002). The geopolymer samples along with the molds were then sealed with vinyl sheet to prevent moisture evaporation during curing either at the ambient room temperature (27–30 °C) or 60 °C. Both room temperature-cured and 60 °C-cured samples were dismantled and immediately wrapped within vinyl sheet after 24 h. The room temperature cured samples were next cured for an additional 6 days (7 days of curing) whereas the 60 °C-cured samples were cured in the oven at 60 °C for an additional 6 days. The density and UCS of all of the geopolymer samples were measured after 7 days of curing. The carefully broken and small samples of 7-day cured (both room temperature and 60 °C) geopolymers with WTS/RHA ratios of 50:50 were taken for SEM analysis to investigate the role of heat curing on the density and UCS of calcined WTS–RHA geopolymers.

2.3. Characterization techniques

The chemical compositions, morphologies, and particle size distributions of the WTS, RHA and calcined WTS–RHA geopolymers were evaluated by X-ray fluorescence (XRF, HORIBA XGT-5200), scanning electron microscopy (SEM, JOEL JSM-6010LV), and laser particle size analysis (Horiba, LA-950), respectively. The densities of WTS and RHA were measured by a pycnometer following ASTM D854-14 (2014). The setting time of the geopolymer pastes was examined according to ASTM C266 (2013). The density and UCS of the 7 days cured geopolymer were measured following ASTM C138 (2009) and ASTM C109 (2002), respectively.