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Development of a new ternary blended cementitious binder produced from waste materials for use in soft soil stabilisation

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ABSTRACT

Soil stabilisation using traditional binders such as Ordinary Portland Cement (OPC), has a serious negative environmental impact, specifically carbon dioxide (CO_2) emissions as a result of the manufacture of OPC. Because of this, the use of sustainable binders has become a critical issue to help reduce cement production through the use of by-product materials. This research seeks to develop a new ternary blended cementitious binder (TBCB) to replace cement for soft soil stabilisation. Different ternary mixtures containing wastes i.e., high calcium fly ash (HCFA), palm oil fuel ash (POFA) and rice husk ash (RHA) along with flue gas desulphurisation (FGD) gypsum used as a sulphate activator and grinding agent, were examined. The results illustrate that ternary mixtures improved the engineering and mechanical properties of stabilised soil. The results indicated that the plasticity index (PI) was reduced from 20.2 to 13.0 and the unconfined compressive strength (UCS) increased after 28 days of curing from 202 kPa to 944 kPa using the optimum non-FGD activated mixture. FGD contributed significantly by increasing the UCS to 1464 kPa at 180 days of curing, which surpassed that for the reference cement (1450 kPa), and by improving the soil consistency limits; where the PI decreased to 11.7 using TBCB compared with 14.5 for the soil treated with the reference cement. X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis revealed substantial changes in the diffraction patterns and microstructure components of the TBCB paste over the curing period, confirming the formation of cementitious products. A solid, coherent and compacted structure was achieved after treatment with TBCB as evidenced by the formation of C-S-H, CH and ettringite.

1. Introduction

Climate change and global warming are major risks facing humankind because of their severe effect on the planet. Global warming is linked to the phenomenon of greenhouse gases (GHGs) emissions, CO_2 being the most prevalent of these (Specht et al., 2016). Ordinary Portland Cement (OPC) is one of the most extensively used construction materials worldwide (Karim et al., 2013). It is the most used material after water, having significant advantages as a construction material in different civil engineering industries including soil stabilisation. However, the use of cement has many drawbacks, specifically negative environmental impacts, something which has become a major concern around the world resulting in global debate about how to reduce cement production. Cement manufacturing as a single industry, is estimated to contribute about 6–7% of global CO_2 emissions (Aprianti, 2017; Zhang et al., 2017). Therefore, OPC makes a substantial contribution to global warming and GHGs emissions; finding alternative materials to reduce OPC production has become a vital issue for current and future generations.

Waste, or by-product materials (BMs), are produced in huge quantities every day worldwide. They also have a negative impact on sustainability and the environment due to the cost of disposal and potential contamination to land and groundwater if heavy metals are present as part of their chemical composition (Karim et al., 2013). However, some BMs have high to moderate calcium

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contents such as sewage sludge ash (SSA), ground granulated blast furnace slag (GGBS) and calcium carbide residue (CCR). Such materials have the potential to play the role of cementitious materials, reacting with silicates through a pozzolanic reaction, resulting in cementitious products similar to those obtained from the OPC hydration process (Sun et al., 2015). Other BMs are rich in silica (Si) and alumina (Al), such as pulverised fuel ash (PFA), silica fume (SF), palm oil fuel ash (POFA) and rice husk ash (RHA) which react pozzolanically with the hydrated calcium compounds (Aprianti, 2017). Numerous research projects have been conducted to utilise BMs to replace a portion of cement in binders and then used in diverse construction projects such as concrete for buildings, rigid pavements and soil stabilisation (Kumar et al., 2007; Jaturapitakkul et al., 2011; Horpibulsuk et al., 2012; Kotwica et al., 2017). Recently, researchers attempted to develop new cementitious binders produced completely from OPC-free blended materials using high calcium waste fly ashes mixed with different types of pozzolanic and alkaline wastes and fly ashes (Sadique et al., 2013; Al-Hdabi et al., 2014; Dulaimi et al., 2017).

In terms of soil mechanics, soft soils are considered problematic because of their undesirable properties associated with low compressive strength, high compressibility and dramatic volume change when their water content changes (Kolias et al., 2005). Soil improvements, specifically soil stabilisation, is the most acceptable technique to mitigate these properties and meet the requirements of engineering projects. Soft soil stabilisation has traditionally been achieved by mixing soft soils with binder materials such as lime, cement and/or fly ash. Studies involving lime and OPC as preferred binder materials, rely on their ability to bind soil particles to each other, resulting in an improved material (Farouk and Shahien, 2013; Jafer et al., 2017).

Substantial quantities of POFA and RHA are produced, worldwide, every year (Aprianti et al., 2015). The disposal and transportation of the solid waste generated from POFA and RHA activity is a serious problem, both environmentally and financially, making it necessary to address this problem with some urgency.

POFA is a pozzolanic waste material from the palm oil industry. It is generated in huge quantities, mainly in developing countries (Karim et al., 2013). Indonesia and Malaysia are the primary POFA producers, manufacturing 86% of global supplies (Aprianti, 2017). Shafigh et al. (2014) reported that Malaysia's annual production of crude palm oil is 7 million tonnes, while a hundred thousand tonnes of POFA are produced by Thailand annually, as reported by Jaturapitakkul et al. (2007).

The influence of POFA as a cement replacement, on the compressive strength of mortar, was investigated by Jaturapitakkul et al. (2011). POFA was found to be able to enhance the compressive strength of mortars when replacing OPC type I by 10%–40% by the binder mass. The results showed that because of the efficacy of POFA particles at filling pore voids and its pozzolanic reaction, the compressive strength of mortars increased with an increase in the cement replacement.

In the field of soft soil stabilisation, POFA has been used as a cement replacement in order to improve the Atterberg limits and unconfined compressive strength (UCS) (Pourakbar et al., 2015). Ground POFA was used in two different particle sizes (30 μm and 12 μm) by Mujah et al. (2015) for soil improvement. Shear and one dimensional consolidation tests were conducted to evaluate the effect of different sizes of POFA particles in soil stabilisation, the results indicating that fine grade POFA gave a much more pronounced improvement in comparison to the coarse grade. In addition, the internal friction angle and cohesion of the soil when reinforced with both grades of POFA, increased between 50% and 60%. However, there are few, if any, investigations of POFA as a potential pozzolanic activator for calcium based materials for use in soft soil stabilisation.

RHA is a waste that is produced from the incineration processes of rice husk for power generation purposes and rice processing mills (Karim et al., 2013; Mujah et al., 2015). It is produced in huge quantities in the major rice supplier countries such as China, India, Malaysia, Indonesia and Bangladesh. It was reported that approximately 742 million metric tonnes of rice paddies are produced annually by the rice husk harvest by the end of 2013, while the global annual production of RHA is estimated to be about 7500 thousand tonnes, with an approximate annual growth of 1.1% (Aprianti et al., 2015). RHA is a super-pozzolanic material due to its high silica content (85%–90%), meaning it can be used as a SCM to produce high performance concrete and geopolymer cement as established by recent research (Hwang and Huynh, 2015; Alex et al., 2016; Sua-iam et al., 2016). Research conducted by Nimwinya et al. (2016) used calcined water treatment sludge (WTS) and RHA, activated by alkali solutions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), to produce a sustainable geopolymer binder. The results showed that RHA helped increase the ratio of SiO_2/Al_2O_3 which, in turn, significantly increased the compressive strength of the prepared mortars. The optimum SiO_2/Al_2O_3, at approximately 4.9 and 5.9, provided the highest compressive strength at room temperature and 60 °C, respectively.

Flue gas desulphurisation (FGD) gypsum is a waste or industrial by-product material, which is generated from the wet-type desulphurisation processes used in coal-fired power plants; its main phase is calcium sulphate dehydrate (Zhang et al., 2016a). Due to its major component being calcium sulphate, FGD has been used as a grinding agent, instead of gypsum, and to achieve higher early strength by different researchers. Qiao et al. (2006) used FGD mixed with rejected PFA to produce a binder for stabilisation/solidification processes, as the final stages in the treatment of hazardous waste before sending to landfill. The results of strength tests indicated an acceptable development in compressive strength using a binder containing 10% FGD, the strength achieved being suitable for disposal in landfill. A high-calcium waste fly ash, activated by natural alkaline material, was used as a cement replacement. The mortars prepared using this fly ash were found to exhibit higher compressive strengths at all ages of curing, when the FGD was used as 5% of the added binder, as stated by Sadique et al. (2013).

In spite of the works mentioned above, there is little if any research using POFA, RHA and FGD to activate a calcium based material in soft soil stabilisation, making this research the first to utilise the aforementioned wastes in a ternary blending system. This research was carried out using 100% replacement of traditional binder (OPC) by waste materials to get benefits both in terms of producing an environmentally friendly binder and to offer substantial economic advantages. The influence of different ternary mixtures produced from mixing HCFA, POFA and RHA at different proportions, on the compressive strength of the stabilised soil, along with compaction parameters and consistency limits, were investigated. The prepared samples of the treated soil were exposed to different curing periods, ranging between 3 and 180 days, to evaluate the short and long term performance of the mixtures. Scanning electron microscopy (SEM) testing and energy dispersive X-Ray spectroscopy (EDX) analyses were carried out on the developed binder paste to analyse the improvement gained in the geotechnical properties of the stabilised soil.

2. Materials and methods

2.1. Materials

2.1.1. Soil samples

The soil used in this study was collected from the shoulder of the