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Research paper

Stabilisation of soft soil using binary blending of high calcium fly ash and palm oil fuel ash

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ABSTRACT

Lime and/or Ordinary Portland cement (OPC) are the traditional binders used in soft soil stabilisation. However, their manufacture has a negative impact on the environment. This paper reports the results of experimental work for the optimisation of a binary blended cementitious binder (BBCB) using two types of fly ash as an alternative for use in soft soil stabilisation. The optimum content of the high calcium fly ash (HCFA) was initially determined along with the effect of grinding activation on the performance of HCFA. Subsequently, the effect of palm oil fuel ash (POFA) pozzolanic reactivity on the engineering properties of soft soil, stabilised with HCFA, was investigated by producing different binary mixtures of HCFA and POFA. Based on the Atterberg limits and unconfined compressive strength (UCS) tests, the combination of POFA with HCFA results in a considerably lower plasticity index (PI) and higher compressive strength than those obtained from the soil treated with HCFA alone. Substantial changes in the microstructure and binders of the stabilised soil over curing time were evidenced by SEM imaging and XRD analysis. A solid and coherent structure was achieved after treatment with BBCB as evidenced by the formation of C—S—H, portlandite and ettringite as well as secondary calcite.

1. Introduction

Soil stabilisation was technically introduced several decades ago. It is used to alter undesirable soil properties, to increase shear strength and decrease compressibility, thus meeting engineering specifications for project sites (Venda Oliveira et al., 2011; Kalkan, 2013). Soft soil stabilisation has traditionally been achieved by mixing soft soils with lime, cement, and/or special additives such as pozzolanic materials. Studies involving lime and Ordinary Portland Cement (OPC) as preferred binder materials, report on their ability to bind soil particles to each other, resulting in an improved material (Farouk and Shahien, 2013; Önal, 2014; Modarres and Nosoudy, 2015). However, the manufacture of 1 t of OPC consumes 1.5 t of raw materials involving an energy consumption of 5.6 GJ/t and CO_2 emissions of approximately 0.9 t. Cement manufacture represents 6% of total global CO_2 emissions, constituting a substantial environmental burden (Song and Chen, 2016; Zhang et al., 2017). An annual growth of 6.95% has been recorded, the highest increase being 9.0% in 2010 and 2011, with a slowdown to 3.0% in 2012 reaching 3.7 billion tonnes. Reflecting a 5% per annum predicted increase in the global cement market (Merchant Research and Consulting Ltd., 2013), recent data for the manufacture of cement shows tonnage at 4 and 4.3 billion tonnes in 2013 and 2015, respectively (CEM-Bureau, 2015).

Due to a negative environmental impact and the relatively high cost of cement production, researchers have been motivated to create more environmentally friendly and cost-effective materials to replace or reduce the use of OPC in the concrete industry. These materials are generally by-products, or waste materials, most of them fly ashes (Sivrikaya et al., 2014). Fly ashes are most likely to have pozzolanic properties, which by themselves do not have any cementitious properties, but when added to cement, react to boost the hydration process; such materials are classified as class F fly ash (ASTM International, 2003; Lin et al., 2007). Some fly ashes have an adequate free lime content which means they exhibit high hydration reactivity when mixed with water and are classified as class C fly ash. Such fly ashes have been used as cement-based materials to produce new cementitious material which has been used instead of OPC in numerous construction projects (Edeh et al., 2014; Jafer et al., 2015; Dulaimi et al., 2017; Jafer

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Abbreviations: BBCB, binary blended cementitious binder; HCFA, high calcium fly ash; LDPA, Laser Diffraction Particle Analyser; LOI, loss on ignition; MDD, maximum dry density; OMC, optimum moisture content; OPC, Ordinary Portland cement; POFA, palm oil fuel ash; PSD, particle size distribution; SCMs, supplementary cementitious materials; SEM, scanning electron microscopy; UCS, unconfined compressive strength; XRD, X-ray diffraction; XRF, X-ray fluorescence

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et al., 2018).

Much research has been conducted using waste materials mixed with OPC or lime, to produce new cementitious materials which perform better than OPC or lime alone. These products have been used in a range of diverse construction projects, such as concrete for building, rigid pavements and soft soil stabilisation. In such cases, these waste materials are called supplementary cementitious materials (SCMs). They either have a high amorphous silica content, which facilitates pozzolanic reactivity in the presence of a free lime, such as palm oil fly ash (POFA), rice husk ash, pulverised fuel ash and silica fume (Kumar et al., 2007; Jaturapitakkul et al., 2011), or have a good proportion of free lime, performing as cement when mixed with water, such as ground blast furnace slag, sewage sludge ash, and calcium carbide residue (Fava et al., 2011; Horpibulsuk et al., 2012; Dave et al., 2016).

POFA is a pozzolanic waste material produced from the palm oil industry, generated in huge quantities, mainly in developing countries (Karim et al., 2013). Indonesia and Malaysia are the dominant palm oil production countries, manufacturing 86% of global supplies making them the premier POFA producers (Aprianti, 2017). It was reported by Shafigh et al. (2014) that Malaysia's production of crude palm oil is 7 million tonnes per annum, a hundred thousand tonnes of POFA per year reported to be produced by Thailand (Jaturapitakkul et al., 2007). The disposal and transportation of the solid waste generated from POFA activity is however a serious problem regarding both the environment and cost making it necessary to address this problem, not only in terms of landfill issues but also increasing construction costs and air pollution.

The effect of the partial replacement of cement by POFA on the compressive strength and sulphate resistance of mortars was investigated by Tangchirapat et al. (2009). Compressive strength with 10% POFA increased by 102% - 104% over that for OPC type I. The use of ground POFA (10–40%) as a cement replacement resulted in a significant reduced rate of mortar expansion in its first year of aging but the compressive strength was less than that for their reference mortars. In the field of soft soil stabilisation, POFA has been used as a cement replacement material in order to improve Atterberg limits and unconfined compressive strength (Ahmad et al., 2011; Pourakbar et al., 2015). However, there are few, if any, investigations of POFA as a potential pozzolanic activator with class C fly ash for use in soft soil stabilisation.

Many researchers have utilised binary, ternary and even quaternary blending systems to produce new cementitious materials from different types of waste materials and fly ashes. Chemical activation methods have been used by some researchers to activate base cementitious materials by adding alkaline and/or pozzolanic materials; others have applied a grinding process using ball mills or mortars for mechanical activation (Antiohos et al., 2007; O'Rourke et al., 2009; Sadique et al., 2012; Dave et al., 2016; Soriano et al., 2016).

This study aims to improve the compressive strength of a soft soil from Hightown, near Liverpool, using a binary-blended cementitious binder (BBCB) consisting of high-calcium fly ash (HCFA) and POFA.

2. Materials and methods

2.1. Soil samples

The soil used in this study was collected from a site located in Hightown to the north of Liverpool, United Kingdom. The site is a riverbank of the River Alt estuary. The soil samples were extracted from depths ranging between 30 and 50 cm below ground level. The site in general is an alluvial plain; the soil is described as medium-soft, dark grey, silty clay with a trace of sand.

Fig. 1 shows the particle size distribution (obtained from sieve and hydrometer analysis) of the soil used in this study. It contains 13.1% sand, 43.9% silt and 43.0% clay, the main physical and geotechnical properties of the soil are listed in Table 1 along with the results of pH and Loss on Ignition (LOI) tests. An LOI test was performed according to British standard 1377-3 (British Standard, 1999a) by adopting a procedure as explained in clause 4. This test was to determine the organic matter content in the original soil, found to be equal to 7.95%; this value denotes that the soft soil used in this study is considered as medium organic soil according to BS EN ISO 14688-2:2004 + A1 (European Committee for Standardization, 2013). Based on BS EN ISO 14688-2:2004 + A2013 (European Committee for Standardization, 2013), the grain distribution and Atterberg limits (LL and PI), this soil is classed as an intermediate plasticity silty clay with sand (CI).

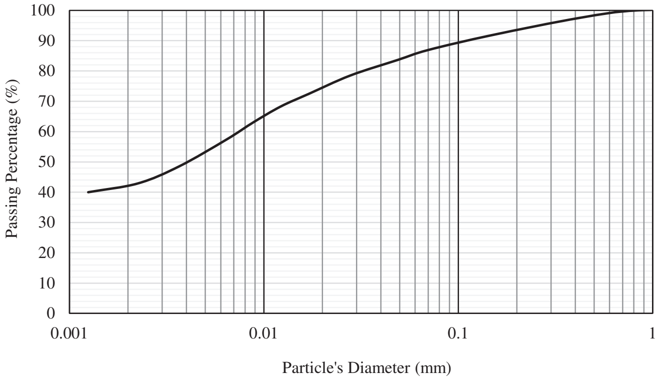

Fig. 1. Particle size distribution of the silty clay.

Table 1
Physical and geotechnical properties of the silty clay.

Property	Value
Natural moisture content NMC %	36.8
Liquid limit LL %	44
Plastic limit PL %	23.8
Plasticity index PI	20.2
Sand %	13.1
Silt %	43.9
Clay %	43
Specific gravity (Gs)	2.57
γ_{dmax} Mg/m^3	1.57
Optimum moisture content OMC %	23
pH	7.78
Organic matter content %	7.95
Unconfined compressive strength for undisturbed soil (kPa)	66.46

Mg/m^3 = Mega gram/cubic metre.

2.2. Binder materials

Two different types of waste material fly ash were used in this study to produce the binary blended cementitious material:

1. High calcium fly ash (HCFA), generated from power plants using an incineration process at temperatures between 850 °C and 1100 °C by means of a fluidised bed combustion system and;
2. Palm oil fuel ash (POFA), a waste material produced from the incineration processes applied to palm oil fibres at temperatures ranging between 800 and 1000 °C, imported from the Sg. Tengi Palm Oil Factory, Kuala Kubu Bharu, Selangor, Malaysia.

2.3. Analytical techniques used for characterisation

2.3.1. Particle size distribution (PSD) of the binder materials

The PSD of the binder materials was obtained using a Laser Diffraction Particle Analyser (LDPA) brand Beckman Coulter LS 13 320. PSD curves of the fly ashes are shown in Fig. 2 alongside that of OPC for comparison purposes. It should be noted that the POFA was sieved first to remove materials which were not completely combusted using a sieve size 150 μm. It was then ground with a pestle and mortar grinder