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Incorporation of reactive magnesia and quicklime in sustainable binders for soil stabilisation

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ABSTRACT

The utilisation of reactive magnesia or quicklime as novel activators for slag offers a range of technical and environmental benefits over conventional caustic alkali activators and showed great potential in soil stabilisation. This paper investigates the mechanical and microstructural properties of two model soils, i.e., a clayey soil and a slightly silty clayey sand, stabilised by ground granulated blastfurnace slag (GGBS) using various techniques including unconfined compressive strength (UCS) test, thermogravimetric analysis (TGA) and scanning electron microscopy (SEM). A number of MgO and CaO mixtures with different MgO/CaO ratios were adopted for slag activation. The activator to GGBS ratio was 1:3 and the dosage of the binder (including MgO, CaO and GGBS) was 12% by weight of the dry soil. The result demonstrated that the increasing MgO/CaO ratio in the binder led to an increase in the UCS of the stabilised clayey soil up to 90 days, due to the increased homogeneity of C–S–H gel structure, the decreased Ca/Si ratio of C–S–H gel and the increased amount of voluminous hydrotalcite-like phases. On the other hand, slag activated with MgO–CaO mixtures showed poorer mechanical performance than slag activated with either MgO or CaO alone for sand stabilisation. In addition, strength enhancement was observed for the stabilised clayey soil upon different soaking conditions up to 7 days. After 28 days, although binders with higher MgO/CaO ratios showed slight strength degradation upon soaking, they still exhibited higher strength than those with lower MgO/CaO ratios.

1. Introduction

Among many ground improvement methods, soil stabilisation with Portland cement (PC) or lime is most widely used in road, rail and airport construction, foundation construction, embankments and deep cement mixing. The introduction of such binder, slurry or powder into soil significantly improved the geotechnical properties of soils including strength, volume stability, durability and permeability. The primary mechanism of soil stabilisation with PC is through the hydration of PC which leads to the formation of cementitious calcium silicate hydrates (C–S–H), calcium aluminate hydrates (C–A–H) and calcium aluminium silicate hydrates (C–A–S–H). In case of the stabilisation with lime, the addition of lime into soils immediately results in the cation exchange between the metallic ions associated with the surface of the clay particles and the calcium ions of the hydrated lime, which leads to the flocculation process. In addition, pozzolanic reaction occurs between the silica and some alumina of the lattices of the clay minerals in the high alkaline environment produced by lime, forming secondary cementitious products as mentioned above (Bell, 1996; Lemaire et al., 2013).

Due to the calcination of limestone and the consumption of fossil fuels, the production of PC contributes approximately 5–8% of global man-made CO_2 emissions (Provis and van Deventer, 2014). Consequently, the search for more sustainable and environmental binders has led to the development of alkali-activated cements (AACs), which utilise a large portion of supplementary cementitious materials (SCMs) such as blastfurnace slag, fly ash, metakaolin and silica fume with the use of alkali activators (Demirboğa and Gül, 2006; Memon et al., 2007; Provis, 2013; Shi et al., 2006, 2011; Singhal et al., 2008). Among those SCMs, ground granulated blastfurnace slag (GGBS) has been demonstrated to be a promising option to partially replace PC or lime in soil stabilisation (Nidzam and Kinuthia, 2010; Obuzor et al., 2011a,b, 2012; Sargent et al., 2013; Tasong et al., 1999; Veith, 2000; Wild et al., 1998, 1999; Yi et al., 2014a), where PC or lime is used as an alkali activator for the slag to accelerate the hydration of slag. The benefits of using GGBS in soil stabilisation are not only in terms of low energy costs and positive environmental impact, but also in terms of enhanced mechanical properties and durability. The combination of GGBS and PC or lime is also very effective in reducing the expansion of the stabilised soil in the presence of sulfates or sulfides (Celik and Nalbantoglu, 2013; Tasong et al., 1999; Wild et al., 1999).

The benefits of incorporating reactive magnesia (MgO) in cementitious components for a number of applications have been investigated

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over the last 15 years or so and many promising applications have emerged (Al-Tabbaa, 2013). Reactive MgO is mainly produced from the processing of magnesite, magnesium chloride-rich brine or sea water at a much lower temperature (~700–1000 °C) than dead burned magnesia in PC (~1400 °C). Under those low temperatures, the MgO has high surface area, high reactivity, and low crystallinity (Shand, 2006). The use of reactive MgO with GGBS for soil stabilisation is a recent development offering a range of mechanical and durable advantages over PC or lime-slag blends (Jegandan et al., 2010; Yi et al., 2012, 2014b,c). Yi et al. (2014c) found that MgO–GGBS blend in the ratio of 1:9 by weight induced a higher unconfined compressive strength of stabilised sand and clayey silt than lime–GGBS blend at the same ratio at 7 days, although they obtained a similar strength range at 90 days. Additionally, the soil treated by GGBS–MgO mixture with proper ratio may achieve a strength ~1.3–4 times higher than the corresponding PC treated soil. Jegandan et al. (2010) and Yi et al. (2014b) found that the combination of MgO and GGBS in stabilisation produced higher resistance to sulfate and acid attack than PC stabilised soil, since no expansive phase ettringite formed in MgO–GGBS stabilised soil. In addition, the more effective ability of reactive MgO to immobilise heavy metals than PC has promoted the application of reactive MgO in land remediation technology (Al-Tabbaa et al., 2011).

An important obstacle to the wide application of MgO–GGBS in soil stabilisation should be related to the economic issue. Given the global production of MgO around 20 million tonnes per year, the price of MgO with potential in slag activation varies from US$180 to US$350 per ton in China (Beijing HL Consulting Company, 2009), higher than that of CaO (i.e., US$30 to US$80 per ton in China). In this context, the combination of MgO–CaO, as a way to cut down the cost of using MgO, is of worth being investigated, but with limited literature. Lu et al. (1957) investigated the use of calcitic lime [CaO, $Ca(OH)_2$] and dolomitic lime [MgO–CaO, MgO–$Ca(OH)_2$, $Mg(OH)_2$–$Ca(OH)_2$] in soil–lime stabilisation, but without using cementitious binders. The results indicated that the strengths of stabilised soils tended to be higher with dolomitic lime. Gu et al. (2014) studied the mechanical properties of GGBS paste activated with MgO–CaO mixtures and the result demonstrated that the use of CaO in MgO–GGBS blends can significantly accelerate the hydration rate in the early age while better long term mechanical performance was observed when the ratio of CaO to MgO was smaller than 1/19. So far, however, the utilisation of reactive MgO and CaO mixtures blended with slag in soil stabilisation has not been investigated yet.

This paper presents the experimental study on the stabilisation of two model soils, a clayey soil and a slightly clayey silty sand, using reactive MgO, CaO and GGBS blends, with CaO/MgO ratio at 3/0, 1.5/1.5, 0.2/2.8 and 0/3. The mechanical properties and microstructure characteristics of the stabilised soils were explored by a range of tests including unconfined compressive strength (UCS), water content measurement, scanning electron microscopy (SEM) and thermogravimetric analysis (TGA). In addition, the durability of stabilised clayey soil subjected to different soaking conditions was also studied.

2. Materials

2.1. Model soils

Two model soils: a clayey soil and a slightly clayey silty sand, were used. The clayey soil consists of 40 wt.% kaolin clay, 35 wt.% silica flour and 25 wt.% sand. The sand consists of 5 wt.% kaolin clay, 5 wt.% silica flour and 90 wt.% sand. The kaolin clay, with a liquid limit of 51% and plastic limit of 30%, was obtained from Richard Baker Harrison, UK. The silica flour, 87% particle of which passes 75 μm sieve, was obtained from David Ball Group, UK. Its specific gravity was between 2.64 and 2.66. The sharp sand, with D_{50} of 0.8 mm and coefficient of uniformity of 4.3, was obtained from Ridgeons, UK. The chemical compositions of kaolin clay and silica flour are included in Table 1. The compaction test indicated that the optimal water content of the clayey soil and the maximum dry density are 24% and 1.54 g/cm^3, respectively.

Table 1
Chemical compositions and physical properties of raw materials (from suppliers' datasheets).

	Kaolin	Silica flour	MgO	CaO	GGBS
Chemical composition					
SiO_2	45–55	99.2	0.9	0.9	37.0
Al_2O_3	30–39	0.3	0.22	0.13	13.0
CaO	0–0.3	0.01	0.9	94.0	40.0
MgO	0–0.6	<0.02	>93.2	0.5	8.0
K_2O	0–5	0.04	–	–	0.6
Na_2O	0–0.3	<0.03	–	–	0.3
SO_3	–	–	–	0.06	1.0
Fe_2O_3	0–2	–	0.5	0.08	–
$CaCO_3$	–	–	–	3.7	–
Physical properties					
Specific surface area (m^2/kg)	–	–	9000	–	493
Bulk density (kg/m^3)	–	–	–	1020	1050

The kaolin clay, silica flour and sand were first oven dried at 105 °C for 24 h, then left to cool to room temperature in sealed plastic bags. The model soils were prepared by homogeneously mixing these materials in a mixer for 5 min.

2.2. Binders

Reactive MgO (from Richard Baker Harrison) or quicklime (CaO, from Tarmac and Buxton Lime and Cement, UK) blended with GGBS (from Hanson, UK) is used as binder for soil stabilisation. Their chemical compositions and physical properties are also shown in Table 1. The reactivity of the reactive MgO is ~100 s determined by the acetic acid test according to Shand (2006) and is categorised as a medium reactive MgO (Jin and Al-Tabbaa, 2013). This type of reactive MgO is selected for its proper reactivity and cost, and it has been reported to be able to effectively activate the slag, with the long term compressive strength outperforming CaO activated slag (Gu et al., 2014; Jin et al., 2015).

3. Methodology

3.1. Sample preparation

The total content of the binders was fixed at 12% by weight of the stabilised soil, and the activator (MgO, CaO or their combinations) to GGBS ratio was set as 1:3. Four binder compositions were used in this study by varying the ratio of MgO to CaO (Table 2).

The binders were mixed homogeneously with the model soils in dry powder form in a mixer for 5 min, and then predetermined amount of distilled water was added. For the clayey soil, the initial water content was 26%, slightly higher than the optimal water content (i.e., 24%) since the hydration heat of binders may cause the evaporation of water during mixing, especially in the presence of CaO. For the sand, the initial water content was 10%. After homogeneously mixed with water, the wet stabilised soils were cast into cylindrical plastic moulds and statically compacted to $\Phi 50 \times 100$ mm in two layers. The dry density of stabilised clayey soil was controlled at 1.54 g/cm^3 and that of stabilised sand was 1.70 g/cm^3. Without demoulding, the samples

Table 2
Compositions of binders for soil stabilisation.

Binder nomenclature	Binder composition	Ratio
C3S9	CaO:GGBS	3:9
M1.5C1.5S9	MgO:CaO:GGBS	1.5:1.5:9
M2.8C0.2S9	MgO:CaO:GGBS	2.8:0.2:9
M3S9	MgO:GGBS	3:9