



## Note

# Comparison of reactive magnesia- and carbide slag-activated ground granulated blastfurnace slag and Portland cement for stabilisation of a natural soil



Yaolin Yi<sup>a,b,\*</sup>, Xu Zheng<sup>a,1</sup>, Songyu Liu<sup>a,1</sup>, Abir Al-Tabbaa<sup>c</sup>

<sup>a</sup> Institute of Geotechnical Engineering, Southeast University, No.2 Sipailou, Nanjing 210096, China

<sup>b</sup> Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB T6G 2W2, Canada

<sup>c</sup> Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

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## ABSTRACT

In this study, reactive magnesia (MgO)- and carbide slag (CS)-activated ground granulated blastfurnace slag (GGBS) were used to stabilise a natural soil in comparison to Portland cement (PC). X-ray diffraction (XRD), scanning electron microscopy (SEM), and unconfined compressive strength (UCS) test were employed to investigate the microstructural and mechanical properties of stabilised soils. The results indicated that the main hydration products of CS-GGBS stabilised soil included calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and ettringite. For MgO-GGBS stabilised soils, CSH was the only hydration product detected. These hydration products had different microstructure and binding ability, affecting the strength of stabilised soils. There was an optimum MgO or CS content, in a range of 10–20%, for yielding the highest UCS of MG-GGBS or CS-GGBS stabilised soil at the same age. The 90-day UCS of the optimum MgO-GGBS and CS-GGBS stabilised soils was 3.0–3.2 and 2.4–3.2 times that of the PC stabilised soil, respectively.

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## 1. Introduction

Cement soil stabilisation is a popular ground improvement method for geotechnical applications (e.g. Bruce, 2001; Al-Tabbaa, 2003; Terashi, 2003; Al-Tabbaa et al., 2011; Terashi and Kitazume, 2011; Kitazume and Terash, 2013); however, there are significant environmental impacts associated with Portland cement (PC) production, such as high CO<sub>2</sub> emissions (0.95 t CO<sub>2</sub>/t PC), energy consumption (5000 MJ/t PC), and non-renewable resources (1.5 t limestone and clay/t PC) (Higgins, 2007). In this context, the use of industry by-products/wastes has been encouraged, such as ground granulated blastfurnace slag (GGBS), a by-product of the steel industry (Jegandan et al., 2010; Nidzam and Kinuthia, 2010; Wilkinson et al., 2010a, 2010b). Manufacturing 1 t GGBS induces only 0.07 t CO<sub>2</sub> emissions and 1300 MJ energy consumption (Higgins, 2007).

GGBS is usually activated by hydrated lime or quick lime for soil stabilisation applications, including treatment of sulphate-bearing expansive soils (Wild et al., 1996, 1998; Tasong et al., 1999; Wild et al., 1999; Puppala et al., 2003; Higgins, 2005; Puppala et al., 2007; Celik and Nalbantoglu, 2013), manufacture of unfired masonry (Oti et al.,

2008a, 2008b, 2009a, 2009b, 2009c, 2010; Kinuthia and Oti, 2012), treatment of acid sulphate soils (Islam et al., 2014a, 2014b), reducing flooding effects on road embankment (Obuzor et al., 2011a, 2011b, 2012) and other applications (Hughes and Glendinning, 2004; Osinubik, 2006; James et al., 2008; Wilkinson et al., 2010a, 2010b; Hughes et al., 2011; Yi et al., 2015). A summary of the use of lime-GGBS for soil stabilisation can be found in Higgins (2005) and Nidzam and Kinuthia (2010). Lime is generally calcinated from limestone (CaCO<sub>3</sub>), also inducing significant environmental impacts. Carbide slag (CS) is an industry by-product of calcium carbide industry and mainly composed of Ca(OH)<sub>2</sub> (85–95%) and CaCO<sub>3</sub> (1–10%) (Cardoso et al., 2009). Currently, most of the CS in China is landfilled; however, CS has the potential to replace hydrated lime to activate GGBS for soil stabilisation due to their similar chemical compositions.

Recently, reactive magnesia (MgO) was shown to be a novel GGBS activator for soil stabilisation (Yi et al., 2014). Reactive MgO is generally calcinated from magnesite (MgCO<sub>3</sub>) at a lower temperature (~700–800 °C) than dead burned MgO (>1400 °C), and hydrates more rapid (Al-Tabbaa, 2013). Compared to PC, less energy is required for manufacturing reactive MgO (~2400 MJ/t MgO) due to its lower calcination temperature, and renewable energy sources can be used (Liska, 2009). Manufacturing 1 t reactive MgO consumes 2.08 t MgCO<sub>3</sub> and induces ~1.4 t CO<sub>2</sub> emissions (Liska, 2009), which is higher than those of PC. However, the MgO is used as an activator for GGBS and its addition is low, consequently the overall CO<sub>2</sub> emissions associated with MgO-GGBS

\* Corresponding author at: Institute of Geotechnical Engineering, Southeast University, No.2 Sipailou, Nanjing 210096, China. Tel.: +86 25 83795776; fax: +86 25 83795086.

E-mail address: [yaolin@ualberta.ca](mailto:yaolin@ualberta.ca) (Y. Yi).

<sup>1</sup> Tel.: +86 25 83795776; fax: +86 25 83795086.

**Table 1**  
Main chemical composition (by % weight) of raw materials.

Material	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	TiO <sub>2</sub>	Loss on ignition
Soil	4.40	62.20	17.60	0.13	5.91	2.60	3.12	1.04	2.02
MgO	0.20	0.31	0.41	0.55	0.18	96.7	<0.01	<0.01	1.17
CS	67.98	4.01	2.30	0.32	0.13	0.27	<0.01	0.05	24.80
GGBS	34.00	34.30	17.90	1.64	1.02	6.02	0.64	1.17	2.67
PC	48.80	27.40	11.50	3.28	3.43	1.16	1.31	0.48	2.00

are less than those of PC. Although brucite (Mg(OH)<sub>2</sub>), the hydration product of MgO, has lower alkalinity than Ca(OH)<sub>2</sub>, superior strength of MgO-GGBS stabilised model soils was achieved compared to those of hydrated lime-GGBS (Yi et al., 2014). The two model soils were clayey silty sand (made from sharp sand, silica flour and kaolin) and clayey silt (made from silica flour, kaolin and peat) (Yi et al., 2014).

As a new soil stabilisation binder, MgO-GGBS was only preliminarily investigated (Yi et al., 2014), and further validation with natural soils is needed. Additionally, it also would be interesting to use CS to replace hydrated lime to activate GGBS for soil stabilisation, and compare the soil stabilisation efficacy of MgO-GGBS, CS-GGBS, and PC. Hence, in this study, the three binders were used to stabilise a natural soil, and the resulted mechanical performance and hydration products of the stabilised soils were compared. The influences of binder type, binder content, and curing age on the strength of stabilised soils were also discussed.

## 2. Materials and methods

### 2.1. Soil and binders

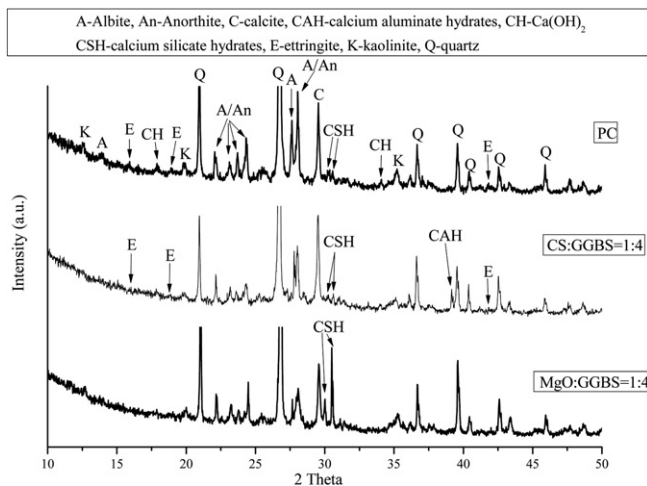
The soil was obtained from a highway construction field (~1 m below ground surface) in Xuzhou, Jiangsu, China, where the soil was stabilised by PC through slurry deep mixing method, i.e. PC slurry was mixed with in-situ soil using deep mixing blades (Bruce, 2001; Terashi, 2003; Kitazume and Terash, 2013). The soil was an alluvial deposit from the abandoned Yellow River during Holocene, Quaternary period; it appeared in yellow-grey colour and had 17.9% sand (grain size: 0.075–2 mm), 75.7% silt (grain size: 0.002–0.075 mm), and 6.4% clay (grain size: <0.002 mm). The soil had a plastic limit of 23%, liquid limit of 33%, moisture content of 20–25% and bulk density of ~1.8 g/cm<sup>3</sup> (ASTM: D7263, 2009; ASTM: D2216, 2010; ASTM: D4318, 2010).

MgO was obtained from Meishen Chemical Co. Ltd., Xintai, China. GGBS, CS, and PC (type 32.5 according to CBMA (China Building

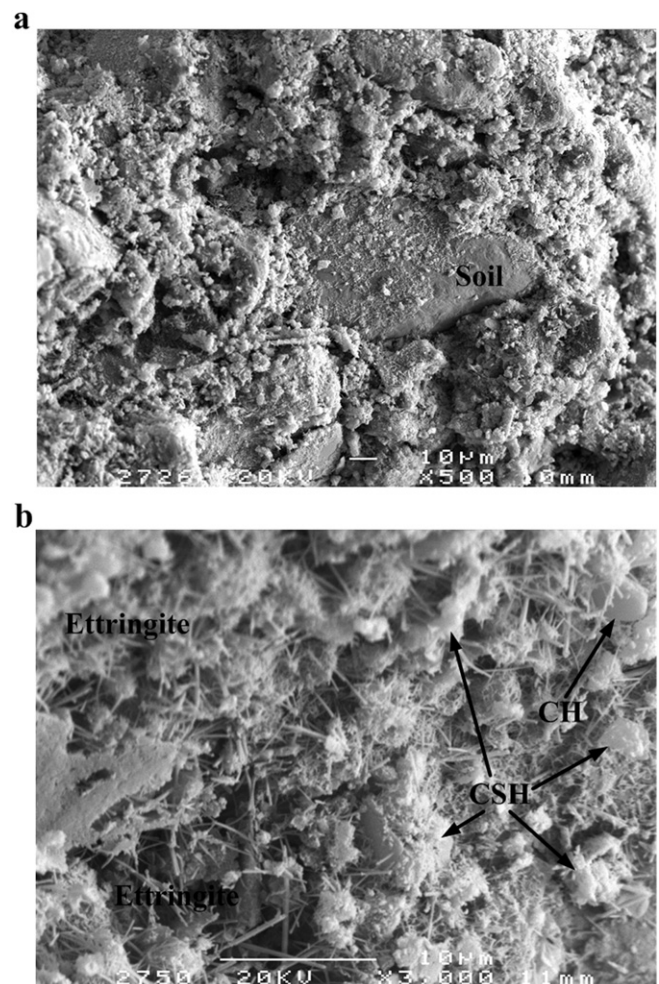
Materials Academy) (2008)) were local materials in Nanjing, China, and were obtained from Nanjing Iron & Steel Group Corp., Weisheng Gas Co. Ltd. and Yuhua Cement Co. Ltd., respectively. The chemical composition of the soil and binder materials was determined by X-ray fluorescence spectrometer (ARL9800 XP, The Thermo Scientific™) according to China Building Materials Test and Certification Center (CBMCC) (2009), as shown in Table 1. Four activators: GGBS mass ratios of 1:19, 1:9, 1:4, and 3:7 (equal to activator contents in the binder of 5%, 10%, 20% and 30%) were used in this study; these ratios were determined according to Yi et al. (2014). Two binder contents, in terms of the mass of binder over dry soil, of 10% and 20% were used; the binder content employed in the field was between those in the laboratory.

### 2.2. Specimen preparation

A soil moisture content of 35%, higher than the in-situ soil moisture content (20–25%), was used to prepare the stabilised soil in laboratory considering the additional water needed for the slurry deep mixing method. For a water/binder ratio of 0.5, which is commonly used for slurry deep mixing method in China, the additional soil moisture contents of 5% and 10% were needed for binder contents of 10% and 20%, respectively; this study chose the maximum value (25% + 10%) to represent the worst soil stabilisation situation. The specimen preparation method in Yi et al. (2015) was used in this study. First, the amounts of dry soil, binders, and water required were calculated and weighted. Second, the dry soil and binders were mixed and homogenised for 10 min in a mixer (300 rpm). Third, water was added in the mixer and the mixing continued



**Fig. 1.** XRD diffractograms of 90-day soils stabilised by PC, CS:GGBS = 1:4 and MgO:GGBS = 1:4 with 20% binder content.



**Fig. 2.** Scanning electron micrographs of 90-day PC stabilised soil with 20% binder content: (a) × 500 and (b) × 3000.

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