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

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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 ablility, 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.

KEYWORDS: soil stabilisation; reactive magnesia; carbide slag; GGBS; Portland cement

1. Introduction

Cement soil stabilisation is a popular ground improvement method for geotechnical applications (e.g. Al-Tabbaa, 2003; Al-Tabbaa et al., 2011; Bruce, 2001; Kitazume and Terash, 2013; Terashi, 2003; Terashi and Kitazume, 2011); however, there are significant environmental impacts associated with Portland cement (PC) production, such as high CO₂ emissions (0.95t CO₂/t PC), energy consumption (5000 MJ/t PC) and non-renewable resources (1.5t 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 1t GGBS induces only 0.07 t CO₂ 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 sulfate-bearing expansive soils (Celik and Nalbantoglu1, 2013; Higgins, 2005; Puppala et al., 2003, 2007; Tasong et al., 1999; Wild et al., 1996, 1998, 1999), manufacture of unfired masonry (Kinuthia and Oti, 2012; Oti et al., 2008a, 2008b, 2009a, 2009b, 2009c, 2010), 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; Hughes et al., 2011; James et al., 2008; Osinubik 2006; Wilkinson et al., 2010a, 2010b; 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 (CaCO₃), also inducing significant environmental impacts. Carbide slag (CS) is an industry by-product of calcium carbide industry and mainly composed of $Ca(OH)_2$ (85-95%) and $CaCO_3$ (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 (MgCO₃) 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 1t reactive MgO consumes 2.08 t MgCO₃ and induces ~1.4 t CO₂ 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 CO₂ emissions associated with MgO-GGBS are less than those of PC. Although brucite (Mg(OH)₂), the hydration product of MgO, has lower alkalinity than Ca(OH)₂, 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; Kitazume and Terash, 2013; Terashi, 2003). 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/cm³ (ASTM, 2009, 2010a, 2010b).

MgO was obtained from Meishen Chemical Co. Ltd, Xintai, China. GGBS, CS and PC (Type 32.5 according to CBMA (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 ScientificTM) according to CBMCC (2009), as shown in Table 1. Four activator: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%, receptively; 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 necessary were calculated and weighted. Second, the dry soil and binders were mixed and homogenised for 10 minutes in a mixer (300 rpm). Third, water was added in the mixer and the mixing continued for an additional 10 minutes. Last, the homogenised mixture was then placed in cylindrical molds, 50 mm in diameter and 100 mm in height. The mixture was placed into the mould in three layers, and each layer was subjected to consistent moderate compaction. The compaction was conducted manually using an 8-mm-diameter steel rod and lasted for 10 minutes. The prepared specimens were placed in a sealed plastic container, where the relative humidity was maintained at 95% \pm 3% and the temperature was maintained at $20^{\circ}C \pm 2^{\circ}C$, and cured for 7, 28 and 90 days. At the designated curing ages, the specimens were de-moulded for density measurement, which took ~ 1 hour, and then subjected to strength testing. It is noted that the specimens with significantly high variation in bulk density were eliminated from strength testing.

2.3. Testing

Unconfined compressive strength (UCS), the key design parameter of stabilised soil for deep mixing application (Bruce, 2001; Terashi and Kitazume, 2011), was tested for all the stabilised soils with a constant displacement rate of 1 mm/min (ASTM, 2007). At one curing age, three specimens were tested for each stabilised soil, and the average and standard deviation of the three UCS values were used to represent the strength.

Microstructural analyses were conducted by employing X-ray diffraction (XRD) and scanning electron microscopy (SEM) for 90-day soils stabilised by PC, CS:GGBS =1:4 and MgO:GGBS = 1:4 with 20% binder content. The samples for microstructural analyses were soaked in ethanol for 7 days to stop hydration reactions, and were then frozen by liquid nitrogen for freeze drying. After that, the samples were placed in a vacuum to sublimate for 48 hours. The dried sample pieces not exceeding 10 mm in size were used for SEM testing, and the ground sample powder, sieved through 75-µm sieves, was used for XRD testing. The XRD testing was performed using a powder diffractometer D8 Discover, Bruker Corp. A Cu-Ka X-ray tube with an input voltage of 40 kV and a current of 200 mA was employed. The samples were scanned for 2 Theta value ranging from 10° to 50°, with a step length of 0.02°, scanning rate of 2°/minute, and slit width of 0.3 mm. The XRD results were analyzed using JADE 5.0, Materials Data, Inc. A Scanning Electron Microscope SM-6300, JEOL Ltd, with an accelerating voltage of 20 kV, was employed to acquire highly magnified microimages (SEM). Prior to examination, samples were mounted on aluminum stubs using carbon tape and paste, and gold-coated in a sputtering machine to induce conductivity. The coated samples were then loaded in to the scanning electron microscope for capturing images.

3. Results and analysis

3.1. X-ray diffraction

The crystalline phases, determined by XRD analysis, of 90-day soils stabilised by PC, CS:GGBS = 1:4 and MgO:GGBS = 1:4 with 20% binder content are presented in Fig. 1. The main minerals of the soil included kaolinite, quartz, calcite, albite and anorthite, the last two being plagioclase feldspar minerals. Typical PC hydration products including calcium silicate hydrate (CSH), $Ca(OH)_2$ and ettringite were detected in the PC stabilised soil (Fig. 1). For PC stabilised marine clay, Yi et al. (2015) detected CSH, ettringite, calcium aluminate hydrate (CAH) and hydrocalumite. The PC used in Yi et al. (2015) was the same as that in this study, but there were more active clay minerals, including illite, clinochlore and kaolinite, in the marine clay. Hence, the difference in hydration products between the two PC-stabilized soils was attributed to their different minerals of the two soils in these two studies. The pozzolanic reactions between soil and $Ca(OH)_2$ was more significant in Yi et al. (2015) than in this study due to that there were more active clay minerals in the former, and hence the produced $Ca(OH)_2$ during PC hydration was consumed. The above results indicate that soil type can affect the hydration products of stabilised soil through soil-binder reactions, which may lead to the consumption of some compounds and/or producing others.

As shown in Fig. 1, CSH, CAH and ettringite were also detected in the CS-GGBS stabilised soil; however, $Ca(OH)_2$ was absent although it's the main composition of CS. The disappearance of $Ca(OH)_2$ in CS-GGBS stabilised soil was attributed to that the GGBS activation reactions consumed $Ca(OH)_2$ (Nidzam and Kinuthia, 2010). For hydrated lime-GGBS stabilised marine clay, Yi et al. (2015) also detected CSH, CAH,

and ettringite without Ca(OH)₂; however, hydrocalumite was presented as well, attributing to the active clay minerals in the marine clay.

For MgO-GGBS stabilised soil, the only hydration product detected through XRD is CSH (Fig. 1). Hydrotalcite, an Mg-Al double layered hydroxide, was observed in previous study (Yi et al., 2014). Here, hydrotalcite was not confidently detected in the MgO-GGBS stabilised soil, which might be due to the fact that some hydrotalcite peaks in XRD diffractograms were overlapped with those of the unstabilised soil in this study. However, hydrotalcite might also be produced in the MgO-GGBS stabilised soil.

3.2. Scanning electron microscopy

Typical SEM images (\times 500 and \times 3000) of 90-day soils stabilised by PC, CS:GGBS = 1:4 and MgO:GGBS = 1:4 with 20% binder content are shown in Figs. 2, 3 and 4, respectively. The soil particle profiles were clearly seen in Figs. 2a, 3a and 4a and the pores between the particles were filled by hydration products. Needle-like etteringte crystals, gel-like CSH and hexagonal plate-shaped Ca(OH)₂ displayed in the PC stabilised soil (Fig. 2b). Ettringite and CSH were also evident in the CS-GGBS stabilised soil, along with cubic-shaped CAH particles (Fig. 3b). For MgO-GGBS stabilised soil, gel-like or reticular CSH was the only hydration product identified (Fig. 4b). All the hydration products identified through visual evaluation of morphology in SEM images were detected by XRD analysis in Fig. 1. These hydration products had different microstructure and binding ability, affecting the strength of stabilised soils.

3.3. Unconfined compressive strength

The average UCS of MgO-GGBS and CS-GGBS stabilised soils, with the margins of error (standard deviation), is plotted against activator content in Fig. 5, where the

average UCS of PC stabilised soil is also plotted as a reference. Fig. 5 indicated that there was an optimum MgO content (10-20%) for MgO-GGBS stabilised soil to yield the highest UCS at the same age. Yi et al. (2014) reported that the optimum MgO content was in a range of 10-20% for two model soils stabilised by MgO-GGBS; the optimum MgO range was the same as that in this study although different GGBS, MgO and soils were used. This finding is very useful for practical design, i.e. the same optimum MgO content can be used for different local materials.

At 7 days, six CS-GGBS stabilised soils were not strong enough to be de-moulded, while the 7-day UCS of the other two stabilised soils (CS:GGBS = 1:4 and 3:7 with 20% binder content) increased with CS content. The 28- and 90-day UCS of CS-GGBS stabilised soil against activator content illustrated a similar profile as that of the MgO-GGBS stabilised soils, with an optimum CS content of 20%. In Yi et al. (2014), an optimum hydrated lime content of 10%, lower than the optimum CS content here, was observed for two model soils stabilised by hydrated lime-GGBS. This was mainly due to that the hydrated lime in Yi et al. (2014) was chemically pure and had higher Ca(OH)₂ content (98%) than that in the CS in this study. The Ca(OH)₂ content in CS was back-calculated to be 89.83% according to the CaO content in Table 1; however, the real value was lower due to the existence of CaCO₃ in CS (Cardoso et al., 2009).

The optimum strength behavior of MgO-GGBS and CS-GGBS stabilised soils was primarily attributed to that the GGBS content dominated the quantity of final hydration products and resulted mechanical strength, and the effect of the activator was mainly to accelerate the hydration process (Yi et al., 2014). The relative UCS of the optimum MgO-GGBS and CS-GGBS stabilised soils over PC stabilised soil (i.e. the ratio of the former over the latter) is presented in Table 2. The MgO-GGBS and CS-GGBS stabilised soils might have lower 7-day UCS than PC stabilised soils, but the formers had higher 90-day UCS, the design value according to China's ground treatment code (CABR, 2012). 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. These results indicated that MgO could activate GGBS more efficiently than CS to achieve higher strength development rate of stabilised soil. However, as an industry waste, CS has more economical and environmental benefits compared to MgO, as demonstrated in Table 3, in which the environmental impacts and cost of MgO-GGBS and CS-GGBS are compared to those of PC. This study indicated that MgO-GGBS and CS-GGBS could replace PC for soil stabilisation.

4. Conclusions

The main hydration products of CS-GGBS stabilised soil were CSH, CAH and ettringite. For MgO-GGBS stabilised soil, CSH was the only hydration product detected. These hydration products had different microstructure and binding ablility, affecting the strength of stabilised soils. There was an optimum MgO or CS content, slightly varying with binder content and curing age, for yielding the highest UCS of MgO-GGBS or CS-GGBS stabilised soil; the 90-day optimum activator content was in a range of 10-20%. 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. This study indicated that CS could replace hydrated lime to activated GGBS for soil stabilization; although its efficacy was lower compared to reactive MgO, as an industry waste, CS has more economical and environmental benefits.

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Table captions

- Table 1. Main chemical composition (by % weight) of raw materials
- Table 2. Relative UCS of the optimum MgO-GGBS and CS-GGBS stabilised soils over

 PC stabilised soil

Table 3. Comparison of the environmental impacts and cost of the binders

Figure captions

- **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) \times 500 and (b) \times 3000

- Fig. 3. Scanning electron micrographs of 90-day CS-GGBS stabilised soil with 20% binder content: (a) \times 500 and (b) \times 3000
- Fig. 4. Scanning electron micrographs of 90-day MgO-GGBS stabilised soil with 20% binder content: (a) \times 500 and (b) \times 3000
- Fig. 5. UCS of stabilised soils at: (a) 7 days, (b) 28 days and (c) 90 days