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Research paper

Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag

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ABSTRACT

Although Portland cement (PC) is widely used for marine soft clay stabilization, there are significant environmental impacts associated with its production. Hence, the use of industrial by-products has been encouraged. In this paper, quicklime and hydrated lime were used to activate ground granulated blastfurnace slag (GGBS), a by-product of the steel industry, for stabilization of marine soft clay in comparison to PC. X-ray diffraction (XRD), scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and unconfined compressive strength (UCS),were used to investigate the microstructural and mechanical properties of stabilized clays. The microstructural analysis results revealed that the main hydration products in the two types of lime-GGBS stabilized clays were calcium silicate hydrates (CSH), calcium aluminates (CAH), calcium aluminum silicate hydrates (CASH), and alumino-ferrite monosulfate (AFm), and both types of lime-activated GGBS stabilized clays could yield lower porosity than PC stabilized clay. The UCS results demonstrated that hydrated lime-activated GGBS achieved slightly higher 90-day UCS in stabilized clay than quicklime-activated GGBS, and the optimum 90-day UCS, with a lime/GGBS ratio of 0.10, was 1.7 times that of PC stabilized clay. This study indicated that both environmental and economical benefits could be expected from replacing PC with lime-GGBS for soft clay stabilization.

1. Introduction

There is a large amount of marine soft clay, with high water content, high compressibility, and low shear strength, along the coast of China. In this area, dry jet mixing is one of the most widely used soft ground improvement methods. The dry jet mixing method introduces powdered binder into the ground to form stabilized clay with improved geotechnical properties (e.g. Bergado et al., 1996; Porbaha, 1998; Holm, 2003; Terashi, 2003; Kitazume and Terash, 2013). This method was developed in Sweden and Japan in the mid-1960s using quicklime (CaO) as the binder, which was later replaced with Portland cement (PC) in Japan and with lime (CaO or $Ca(OH)_2$) and PC blends in Nordic countries to achieve enhanced strength (Holm, 2003; Terashi, 2003). However, there are significant environmental impacts associated with PC production in terms of high energy consumption (5000 MJ/t PC), non-renewable resources (1.5 t limestone and clay/t PC), and CO_2 emissions (0.95 t CO_2/t PC) (Higgins, 2007). Hence, the use of industrial by-products for soil stabilization has been encouraged (Jegandan et al., 2010; Nidzam and Kinuthia, 2010).

Ground granulated blastfurnace slag (GGBS) is a by-product of the steel industry. During the production of iron, a composite of iron-ore, coke, and limestone is fed into the blastfurnace, whereby iron-ore is reduced to iron and separated from the remaining slag. The slag is tapped-off and cooled rapidly to retain its cementitious properties. It is then dried and ground to an appropriate fineness (GGBS) for use as a cementitious material. Currently, the price of GGBS in China is only about 60–80% of that of PC. The generation of 1 tonne of GGBS uses nearly 1300 MJ of energy and induces approximately 0.07 tonne of CO_2 emissions (Higgins, 2007); these values are much lower than those associated with PC production.

However, GGBS is a latent hydraulic material and is usually blended with PC or activated by lime for soil stabilization (Higgins, 2005; Nidzam and Kinuthia, 2010). Many applications of GGBS and lime blends in soil stabilization have been for suppressing the expansion associated with the presence of sulfates or sulfides in lime stabilized soil by partially substituting GGBS for lime (Higgins, 2005; Nidzam and Kinuthia, 2010). Laboratory investigations have illustrated that a proper substitution of lime with GGBS substantially reduced expansion in stabilizing sulfates or sulfide-containing clays (Wild et al., 1996; 1998; 1999; Tasong et al., 1999). The lime used in these laboratory studies (Wild et al., 1996,

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1998, 1999; Tasong et al., 1999) was hydrated lime; however, the use of quicklime was also common in field applications (Higgins, 2005).

Another application of lime-activated GGBS is for Lower Oxford Clay stabilization in the production of unfired bricks (Oti et al., 2008a, 2008b, 2009a, 2009b, 2009c, 2010a, 2010b; Kinuthia and Oti, 2012). Their results have demonstrated that the lime-GGBS could achieve greater strength than PC-GGBS or PC-lime. Both quicklime and hydrated lime were used in selected studies (Oti et al., 2009a, 2009b, 2009c, 2010a; Kinuthia and Oti, 2012), and the comparison demonstrated that the quicklime outperformed the hydrated lime in strength, with an optimum lime/GGBS ratio of 0.20 (Oti et al., 2008a). Freeze and thaw results (Oti et al., 2009a, 2010b) suggested that the unfired clay bricks were able to withstand 100 repeated freeze–thaw cycles. Microstructural results from scanning electron microscopy (SEM) and energy dispersive X-ray analysis suggested that a large quantity of calcium silicate hydrate (CSH) gel formed in the lime-activated GGBS stabilized Lower Oxford Clay (Oti et al., 2009b). James et al. (2008) studied the hydrated lime-GGBS treated model clay (kaolin and bentonite mixture) and found that its strength was higher when compared with lime or GGBS alone. Investigation into the durability behavior of lime-GGBS stabilized Lower Oxford Clay for overcoming the deleterious effect of flooding has also produced promising results (Obuzor et al., 2011a, 2011b, 2012).

However, there is little literature available on marine soft clay stabilization using lime-activated GGBS for dry jet mixing applications. Hence, this study investigates the capability of quicklime- and hydrated lime-activated GGBS (CaO-GGBS and $Ca(OH)_2$-GGBS) for marine soft clay stabilization compared to PC (control). A range of tests were conducted to investigate the microstructural and mechanical properties of stabilized clays, including X-ray diffraction (XRD), scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and unconfined compressive strength (UCS).

2. Materials and methods

2.1. Marine soft clay and binders

The marine soft clay used in this study was obtained approximately 2.5 m below ground surface in a highway construction field in Ganyun, Lianyungang, Jiangsu Province, China (Fig. 1). This marine clay had a plastic limit of 30% (by weight), liquid limit of 58% (by weight), and in-situ water content in the range of 50–60% (by weight) (ASTM, 2010a; 2010b). The specific gravity of the clay was 2.70 (ASTM, 2010c), the bulk density was about 1.7 g/cm^3 (ASTM, 2009), and the void ratio was approximately 1.4. The undrained shear strength, determined by an in-situ vane shear test (ASTM, 2008), was in the range of 20–26 kPa. These values indicated that this marine clay had high water content, high compressibility, and low shear strength, and required treatment before the construction of highway embankment.

Fig. 1. Sampling site.

The water content of clay used in the laboratory soil stabilization was 60% (by weight), which was the clay's highest in-situ water content.

GGBS and PC (PC 32.5 according to CBMA (2008)) were obtained from Nanjing Iron & Steel Group Corp. and Yuhua Cement Co. Ltd., respectively, both in Nanjing, China. Quicklime (CaO) and hydrated lime ($Ca(OH)_2$), obtained from Nanjing Wenhua Chemical Co. Ltd., were chemically pure, with mass fractions of CaO and $Ca(OH)_2$ higher than 98% and 95% (provided by the manufacturers), respectively. The main chemical composition, determined by an X-ray fluorescence spectrometer (ARL9800 XP, The Thermo Scientific™) according to CBMCC (2009), of GGBS and PC is presented in Table 1. The binders were applied to the soil in dry form (i.e. no additional water was added to produce binder slurry) in order to simulate the dry jet mixing method. The cement content, in terms of the weight of PC over the weight of dry clay, of 20% was used as suggested by CABR (2012). The GGBS content, in terms of the weight of GGBS over the weight of dry soil (G/S), of 20% was used to represent the binder content in lime-activated GGBS stabilized clay. Four lime/GGBS (L/G) ratios of 0.05, 0.10, 0.20, and 0.40 (by mass) were used to investigate the effect of the activator on the clay stabilization efficacy. These four ratios were selected based on previous experience as summarized in Higgins (2005) and Nidzam and Kinuthia (2010).

2.2. Stabilized clay sample preparation

The marine clay was first dried in an oven at a temperature of 105 °C, then was ground into powder and sieved through a 2-mm sieve. The raw materials (i.e. dry clay, binders, and water) were calculated and weighed according to the design program. The dry clay and binders were initially mixed and homogenized for 10 min in a bench-top mixer (300 rpm), after which the mixture was inspected, water was added, and mixing continued for an additional 10 min to make the stabilized clay. The homogenized mix was then placed in cylindrical molds, 50 mm in diameter and 100 mm in height. The mix 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 min. The prepared samples were placed in a sealed plastic container where the relative humidity was maintained at 95% ± 3% and the temperature was maintained at 20 °C ± 2 °C. The stabilized clay samples were de-moulded and subjected to testing after 7, 28, and 90 days of curing. The bulk densities of the de-moulded samples were measured, and the samples with significantly high variation in bulk density were eliminated from testing.

2.3. Testing procedure

Microstructural analyses were conducted by employing X-ray diffraction (XRD), scanning electron microscopy (SEM), and mercury intrusion porosimetry (MIP) for 28-day clays stabilized by PC, CaO-GGBS, and $Ca(OH)_2$-GGBS with an L/G ratio of 0.20 (the optimum at 28 days). 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 h. The dried sample pieces not exceeding 10 mm in size were used for SEM and MIP 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-Kα X-ray tube with an input voltage of

Table 1
Main chemical composition (by % weight) of GGBS and PC.

Material	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	K_2O	TiO_2	Loss on ignition
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