



Research paper

Structural behaviour of an Australian silty clay (Coode Island silt) stabilised by treatment with slag lime

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ARTICLE INFO

Keywords:

Coode Island silt
Slag lime
Treatment
XRD
SEM

ABSTRACT

A microstructural study of Coode Island Silt (CIS), a soft silty clay from the Melbourne area of Australia, stabilised with slag lime is reported. Slag lime is a blend of 80–85 wt% slag, 15 wt% hydrated lime, $\text{Ca}(\text{OH})_2$ and 3–8 wt% gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and is typically used for soil stabilisation in roading applications. The morphologies of several homogeneous mixtures of slag lime and CIS were studied by Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD), which indicated the formation of the cementitious phases calcium carbonate, calcium silicate hydrate, calcium aluminium silicate hydrate, and calcium aluminium silicate carbonate. The progress of the CIS-slag lime reactions was also investigated by pH measurements. Slag lime was found to very actively promote pozzolanic reactions with CIS, shown by SEM to form crystalline reticular calcium silicate hydrate and other cementitious products. The most effective pozzolanic reactions occurred in a composite containing 12.5 wt% slag lime with CIS and contained the cement mineral ettringite, contributing to its high strength. These composites constitute a new class of materials with excellent potential for construction applications.

1. Introduction

A major part of the Melbourne central business district is built on a soft silty clay deposit known locally as Coode Island Silt (CIS). The poor strength (friction angle of 21°–28° and cohesion of 0–10 kPa) and compressibility properties of this silty clay cause engineering problems which commonly require expensive pile foundations to transfer the load to the deeper mudstone or sandstone layers underlying the CIS (Bouazza et al., 2004). However, this solution is not considered practical for low or medium load-bearing structures due to the cost involved. Techniques to improve the mechanical properties of soft soils with additives such as cement, lime, fly ash, and slag are used in Australia, Europe, Southeast Asia, and Japan (Wild et al., 1998; Bouazza et al., 2004; Kamruzzaman et al., 2006; Åhnberg, 2007; James et al., 2008). However, the individual effect of the various types of industrial wastes (i.e. lime, sludges, slag) on the Unconfined Compressive Strength (UCS) of treated soil is not as desirable as that of combinations of these components with lime (Kamon and Nontananandh, 1991;

Rajasekaran, 2005; James et al., 2008). Ranjbar Pouya et al. (2016) have previously reported a significant improvement in the strength of CIS by using slag lime. James et al. (2008) reported the presence of the cementitious phases crystalline reticular C–S–H and platy C–A–S–H in a SEM study and suggested that these phases were evidence of a pozzolanic reaction of the slag with lime. This reaction can be understood in terms of the formation of crystalline cementitious products which accelerate the bridging (cementation) effect between the lime–slag and clay particles (James et al., 2008).

Pozzolanic reactions occurring in the stabilisation of clays by CaO or $\text{Ca}(\text{OH})_2$ require a high pH environment, especially pH values of 12.4–12.6 (the pH of saturated lime solution) or higher. The solubility of silica and alumina is increased at these high pH levels, resulting in a long-term increase in strength if the system contains sufficient available lime at high pH to support the solubility and pozzolanic reactions (Bouazza et al., 2004; Al-Mukhtar et al., 2014; Vitale et al., 2017).

Previous research on CIS utilisation has not paid attention to the microstructure of the cementitious products in the stabilised treated

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<https://doi.org/10.1016/j.clay.2018.02.045>

Received 23 October 2017; Received in revised form 27 February 2018; Accepted 28 February 2018

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Table 1
Oxide composition of materials determined by X-ray fluorescence (XRF).

Chemical composition (wt%)	Slag-Lime	CIS
Na ₂ O	0.98	–
MgO	0.87	–
Al ₂ O ₃	7.12	13.19
SiO ₂	21.45	67.46
SO ₃	0.05	7.27
Cl	0.06	0.58
K ₂ O	1.01	1.29
CaO	45.32	5.22
TiO ₂	0.55	1.12
Cr ₂ O ₃	0.14	0.01
MnO	11.21	0.01
Fe ₂ O ₃	10.67	3.65
CuO	0.07	0.04
ZnO	0.13	0.01
Ga ₂ O ₃	0.004	–
Rb ₂ O	0.005	–
SrO	0.012	0.02
PbO	0.02	0.01

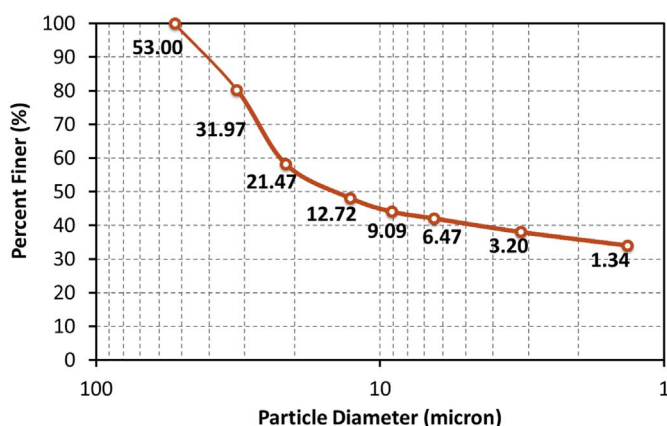


Fig. 1. Particle size distribution of CIS (Ranjbar Pouya, 2018).

CIS. Furthermore, a detailed microstructural study of CIS treated with slag lime has not previously been reported. The present paper presents a study of the microstructural behaviour of a series of CIS samples treated with different amounts of slag lime, using XRD analyses and SEM observations to elucidate the relation between the strength and the microstructural behaviour of the product materials.

2. Experimental

2.1. Sample preparation

The CIS used in this study came from Coode Island located at the convergence of the Yarra River and the Maribyrnong River, 4 km west of central Melbourne, Australia. This silt is predominantly soft silty clay containing marine shelly material and consists mainly of quartz, kaolinite, illite, albite, aragonite, rutile, pyrite, sodium chloride and montmorillonite. The slag lime was the same as utilised in a previous study (Ranjbar Pouya et al., 2016) and is a blend of 80–85 wt% slag, 15% hydrated lime, Ca(OH)₂, 3–8 wt% gypsum, CaSO₄ · 2H₂O and < 1 wt% crystalline SiO₂. The result of X-ray Fluorescence (XRF) analysis of CIS and Slag lime is given in Table 1. Also, the particle size distribution of CIS is shown in Fig. 1.

The lime slurry was prepared by mixing water and lime (water/additive ratio of 1) and transferring to a small-scale centrifuge slurry

mixer (MAT Mischanlagentechnik GmbH - SC Batch Mixer model SC-05-K). This high-speed mixer produces minimum sedimentation, resulting in maximum homogeneity. Five homogenous mixtures of the lime slurry and CIS were then prepared, containing CIS with 2.5, 5, 7.5, 10 and 12.5 wt% of slag lime. The mixtures were then poured into clear cylindrical PVC moulds 50 mm diameter and 130 mm height. The mixture was placed into the mould in three layers of equal height, and a porous loading plunger was gently pressed in by hand to remove any air bubbles. The moulds were capped at the top and bottom with filter papers and porous plates and consolidated by applying a 25 kPa unidimensional pressure to simulate the in-situ vertical stress at a depth of 1.5 m below ground level, and also to maintain the grain to grain contacts throughout the curing. The samples were left under this load for 28 days of curing. Constant humidity during curing was ensured by covering the samples and sealing them in a plastic bag. It should be noted that a minimum of three samples of each mixture were made, and the homogeneity of the samples was double checked after curing by measuring the Unconfined Compressive Strength (UCS) of the samples. The density of the cured samples was measured to be 1.69 g/cm³, while the density of the untreated CIS was 1.63 g/cm³.

2.2. Sample characterisation

The as-synthesised CIS/lime samples were characterised using Vega 3 SEM equipped with an electron dispersive (EDS) detector. All samples were gold coated with a 7–9 nm gold layer. For the EDS studies the SEM was operated at 15 kV. XRD patterns were determined from 10 to 80° 2θ with a 0.02° step using a Panalytical XPert powder diffractometer with CuKα radiation operated at 40 kV and a current of 30 mA. The pH values of the samples were measured by using a digital pH meter and probe (Lutron pH -208) according to the ASTM standard (ASTM, 2006). The samples were prepared by mixing 25 g of each CIS-slag lime mixture and 100 ml of water, then shaking for 30 s every 10 min for 1 h until the specimens are thoroughly mixed. Within 15 min of the end of the 1 h shaking period, the pH of CIS-slag lime-water, the lime-water and the CIS-water mixture were recorded with a sensitivity of ± 0.01 pH unit. The temperature of the mixture was maintained at 25 ± 1 °C when determining the pH.

3. Result and discussion

3.1. XRD analysis

Representative XRD patterns of the CIS samples containing 12.5, 10, 7.5 and 5 wt% slag lime after 28 days curing (Fig. 2) show that quartz (JCPDF file no. 96–901-2601) from the CIS is the main phase present in all the CIS/slag lime samples and that there is no significant difference in the samples containing greater amounts of slag lime. Meonite, Ca₄Al₆Si₆O₂₄CO₃ (JCPDF file no. 96–900-46,065), a calcium aluminium silicate carbonate was detected in all the samples except that containing 12.5 wt% slag lime; in this sample, two other reflections occurring at 4.47 and 3.42 Å were identified as laumonite, C-A-S-H, Ca(Al-Si₂O₆)_{2.4}H₂O (JCPDF file no. 96-900-2890), or C-A-S-H in cement chemists' terminology.

The reflections of CaCO₃ (JCPDF file no. 96-810-3714) and cancrinite, Na₆Ca₂[(CO₃)₂Al₆Si₆O₂₄]-2H₂O (JCPDF file no. 96-900-4051) at 3.49 and 3.19 Å were detected in the sample containing 5 wt% slag lime but diminishing in intensity with increasing amounts of slag lime, suggesting that the cancrinite was being consumed in the pozzolanic reaction of the CIS/slag lime system by the formation of the additional hydrous phases. The XRD diffraction patterns also show an increase in the quantity of ettringite, Ca₆Al₂(SO₄)₃(OH)_{12.26}H₂O (JCPDF file no. 96-901-1104), with increasing amounts of slag lime in the mixture,

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