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Research paper

Strengthening montmorillonitic and kaolinitic clays using a calcium-based non-traditional additive: A micro-level study

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ABSTRACT

Chemical stabilization of clays is commonly used to improve unfavorable engineering properties. Though the effects of non-traditional additives on soil improvement have been investigated in recent years, documented research studies on the macro- and micro-level characteristics of problematic clays stabilized by non-traditional additives are fairly limited. The current study examines the time-dependent changes induced in the strength, mineralogy, morphology, molecular and micro-fabric characteristics of montmorillonitic and kaolinitic clays stabilized with a non-traditional calcium-based additive, which is commercially available under the product name SH-85. The physico-chemical bonding mechanisms induced by the stabilization process were studied at a micro-level using various spectroscopic and microscopic techniques, such as X-ray diffractometry (XRD), field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectrometry (EDAX), Fourier transform infrared spectroscopy (FTIR), Brunauer, Emmett and Teller (BET) surface area analysis and particle size analysis (PSA) using a laser diffraction approach. Unconfined compressive strength (UCS) tests were also performed on stabilized specimens at various curing times to examine macro-level characteristics. The UCS test results showed that the 6% and 9% additive content were optimal for montmorillonitic and kaolinitic clays, respectively, with the UCS of both stabilized clays improving significantly after 7 days of curing. This relatively rapid curing reaction process is very advantageous and cost-effective for geotechnical engineering applications. The micro-level study revealed that the calcium-based additive modified the porous network of the stabilized clays. The pores were filled and particles were bonded by cementitious products, including calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) for the stabilized montmorillonitic and kaolinitic clays, respectively.

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1. Introduction

Soil stabilization is the process of improving the physical and engineering properties of a soil to achieve a predetermined target level of performance. Various underlying mechanisms of soil stabilization can be employed by a given soil improvement process, including mechanical, chemical, biological, and electrical means (e.g., Arulrajah et al., 2013; Bo et al., 2014; Du et al., 2013, 2014a, 2014b; Horpibulsuk et al., 2006; Jiang et al., 2015; Kavitha et al., 2015; Latifi et al., 2016b; Latifi et al., 2015a, 2015b, 2015c, 2015d; Marto et al., 2013; Shen et al., 2013a, 2013b; Wu et al., 2015). Among these alternatives, chemical stabilization has emerged as a cost-effective and flexible option, which is commonly deployed in conjunction with a physical or mechanical soil improvement approach (e.g., Al-Mukhtar et al., 2010; Latifi et al., 2014; Liu, 2007). Chemical stabilization is useful for a wide variety of

geotechnical engineering applications such as slope stabilization and erosion control, foundation and embankment treatment, reducing contaminant transport, and earthquake-induced liquefaction mitigation (e.g., Chinkulkijniwat et al., 2015; Horpibulsuk et al., 2009, 2010a).

The engineering properties of a chemically stabilized soil are improved either immediately or gradually through a chemical reaction between the soil solids and pore fluid and the chemical stabilizer (Blanck et al., 2014). For some stabilizers, the soil structure is improved by a filling of large pores and particle grouping as cementitious products are grown over time (Horpibulsuk et al., 2010b). Soil stabilizers are generally categorized as “traditional” or “non-traditional” (Marto et al., 2014). Traditional chemical stabilizers include cement, lime, fly ash and bituminous materials while non-traditional additives include enzymes, liquid polymers, resins, acids, silicates, ions and lignin derivatives, which are sometimes used in combination (Latifi et al., 2013; Sukmak et al., 2013, 2015; Suksiripattanapong et al., 2015a, 2015b; Tingle et al., 2007). Non-traditional additives can be produced using different kinds of chemical agents that induce different chemical reactions

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when mixed with soil. Usually a dominant or primary stabilization mechanism can be supported by secondary mechanisms due to the insertion of complementary chemical additives to the stabilization mixture (Latifi et al., 2015b).

Clays are often problematic when encountered in various geotechnical engineering applications such as foundation support or slope stabilization, as they can have relatively low strength, high compressibility, and/or a large tendency for swelling. Consequently, given their relatively poor initial engineering properties in some field situations, clays can benefit significantly from a well-designed soil improvement process (e.g., Horpibulsuk et al., 2003, 2004; Mohammadinia et al., 2014). Two commonly encountered clay minerals are montmorillonite and kaolinite, which can have low shear strengths, and which exhibit high swelling and low- to non-swelling behaviour, respectively (Horpibulsuk et al., 2011a, 2011b). Kaolinitic soil formation is common in areas where rainfall is high and drainage is good for the leaching of iron and cations. Each kaolinite particle is comprised of a sequence of hexagonally formed layers that are bound together by hydrogen bonds, in a fashion that is analogous in structure to the pages of a book (Miranda-Trevino and Coles, 2003). Accordingly, water and cations are not present among the structural layers of kaolinite, so kaolinitic soil tends to exhibit a lower plasticity and less tendency for swelling than other clay minerals (Latifi et al., 2015d). Montmorillonite has a high electrolyte content, high pH and plenty of silica. Climatic conditions with poor leaching and drainage are favorable for the formation of montmorillonitic soil (Miranda-Trevino and Coles, 2003). Associated water molecules and exchangeable cations are readily absorbed among the interlayer areas of montmorillonite, resulting in the expansion of the crystal lattice; this corresponds to highly plastic clay behavior with a large tendency for swelling relative to other clay minerals (Latifi et al., 2015d).

Stabilization mechanisms for traditional stabilizers have been extensively investigated, and rational application guidelines and laboratory testing manuals are available for their effective use in geotechnical engineering practice (e.g., Chew et al., 2004; Cuisinier et al., 2011a, 2011b; Horpibulsuk et al., 2014, 2015; Nalbantoglu and Tuncer, 2001; Prikryl et al., 2003; Rahmat and Ismail, 2011; Sukmak et al., 2014; Yong and Ouhadi, 2007; Yunsheng et al., 2010). On the other hand, though various types of non-traditional additives in liquid and powder forms are extensively marketed by a number of companies, little guidance for their effective use in practice is available. Additionally, many non-traditional stabilizing compounds have a proprietary chemical composition, which makes it difficult to evaluate the chemical stabilizing mechanisms that may occur for a given soil type, and which also consequently makes it difficult to predict their performance for use as a soil stabilizer in practice. In recent years, a number of researchers have reported on engineering property improvement of soils stabilized with non-traditional calcium-based additives (e.g., Horpibulsuk et al., 2012, 2013; Hossain and Mol, 2011; Kampala and Horpibulsuk, 2013; Latifi et al., 2016a, 2016c; Marto et al., 2014; Peethamparan et al., 2008; Sukmak et al., 2013; Turkoz et al., 2014; Phetchuay et al., 2016 and Phummiphan et al., 2015). Little information is readily available on the corresponding mineralogical, morphological, molecular and micro-fabric characteristics of high swelling and non-swelling low strength clays that are stabilized with non-traditional additives; this information is essential for understanding the chemical stabilization mechanisms that are involved with non-traditional additives (Tingle et al., 2007).

In this study, both macro- and micro-level characteristics of high-swelling Green Bentonite (GB), and low-swelling White Kaolin (WK) stabilized with a novel non-traditional calcium-based additive (SH-85) are examined. Unconfined compression strength (UCS) testing was utilized to compare the shear strength of untreated and stabilized clays. Potential chemical stabilization mechanisms are discussed using the results obtained from a series of microscopic and spectroscopic tests, including X-ray diffractometry (XRD), field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectrometry (EDAX), Fourier transform infrared spectroscopy (FTIR), Brunauer, Emmett and

Teller (BET) surface area analysis, and particle size analysis (PSA) using a laser diffraction approach. The results from these tests and the associated discussion provide useful insight for researchers and practicing engineers into the underlying mechanisms of chemical stabilization that occur for soil improvement performed using this calcium-based non-traditional additive. Additionally, since the bentonite and kaolinite represent high- and low-swell behavior, respectively, the output of this research is useful for assessing the behavior of other calcium-based non-traditional additive-stabilized clays that exhibit intermediate swelling behavior (Latifi et al., 2015d).

2. Materials and testing program

2.1. Materials

The clays examined in this study were a Green Bentonite (GB) and a White Kaolinite (WK). A series of XRD tests conducted in accordance with recommendations made by the Joint Committee for Powder Diffraction Standards (JCPDS, 1995) indicated that the GB was comprised mainly of a sodium montmorillonite mineral while the WK was dominated by kaolinite and illite minerals along with some minor quartz constituents. Both clays are quarry products and were purchased in 25 kg bags obtained from a soil processing facility in Tapah (Perak), located in the Western Malaysian Peninsula. The engineering properties and chemical characteristics of the GB and WK that were used are illustrated in Table 1 and Table 2, respectively. A new locally manufactured non-traditional powder formed stabilizer, which is commercially available under the product name SH-85, was used as the calcium-based additive in this study. Table 3 shows the associated chemical compositions of the non-traditional additive obtained using an energy dispersive X-ray spectrometer (EDAX) test (Fig. 1) that was performed in accordance with ASTM Standard, E986-04; these results confirm that the compound that was used is a calcium-based additive.

2.2. Sample preparation and testing program

In order to create uniform specimens for purposes of testing, the clays were first oven dried and then sieved through a 2 mm mesh. Both clays were mixed with the selected additive in proportions at 3%, 6%, 9% and 12% of the dry weight of soil. A series of standard Proctor compaction tests (BSI 1377: Part 4: 1990a) were performed to determine the optimum moisture contents for untreated and stabilized soils. In order to prepare a homogeneous mixture to make unconfined compressive strength (UCS) test specimens, distilled water was added to the dry powder mixture to yield the optimum moisture content level, and hand mixing was performed using palette knives to ensure moisture uniformity. The UCS test specimens were then created by compressing a known mass of the clay/stabilizer/water mixture into a steel cylindrical mold of known volume using a hydraulic jack to achieve the desired density. Finally, the cylindrical UCS specimens were extruded using a steel plunger, and trimmed and wrapped using several layers of plastic cling film. Test specimens were cured for either 3, 7, 14 or 28 days in a temperature controlled room (27 ± 2 °C) before a given UCS test (Liu et al., 2011). The soil improvement index was determined from UCS test results (BSI 1924: Part 2: 1990b) for specimens tested at various curing time intervals. The axial loading rate in the UCS tests was 1% per minute (Latifi et al., 2015b). An automated data acquisition unit was used to record the applied load and axial deformation during each UCS test. The failure of each UCS specimen was defined by its peak axial stress. To ensure the accuracy of the results, at least four specimens for each clay/stabilizer mixture, mix proportion, and curing time were prepared.

In the present study, X-ray diffraction (XRD) testing was performed on both untreated and stabilized specimens, in order to: (1) assess mineralogical changes of the soil structure due to the presence of the chemical stabilizer, and (2) assess the formation of crystalline cementitious

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