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Micro-structural analysis of strength development in low- and high swelling clays stabilized with magnesium chloride solution — A green soil stabilizer

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ABSTRACT

Although the effects of chemical additives on the geotechnical properties of soils have been investigated in recent years, the strength properties and micro-structural characteristics of clayey soils stabilized with magnesium chloride ($MgCl_2$) solution, a green soil stabilizer, have not been clearly brought out. The objective of this study is therefore to investigate the time-dependent engineering properties, mineralogy, morphology and molecular characteristics of $MgCl_2$ stabilized tropical fine-grained soils. Bentonite and kaolin, which represent high and low swelling clays, respectively were employed as the soils tested in this study. Compaction, unconfined compression strength (UCS) and standard direct shear tests were undertaken to assess the engineering properties of the stabilized clayey soils. The mechanisms that may have contributed to the stabilization process were discussed based on the micro-structural analysis using different 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) and Brunauer, Emmett and Teller (N_2-BET) surface area analysis. From an engineering point of view, the $MgCl_2$ improved the compressive strength of the bentonite and kaolin significantly. The 7-day UCS of $MgCl_2$ stabilized bentonite and kaolin were approximately 2 times higher than that of unstabilized ones. The micro-structural study revealed that the stabilization process modified the porous network of the tested clayey soils. The pores of the soils had been filled by newly formed crystalline compounds known as magnesium silicate hydrate (M-S-H) and magnesium aluminate hydrate (M-A-H) for the bentonite and kaolin, respectively.

1. Introduction

There are myriad problems associated with engineering construction on problematic soil deposits. The problematic soils are generally loose, expansive, dispersive, highly compressible and highly permeable. When infrastructures such as road embankments, bridge foundations and so on are constructed on these soil deposits, several geotechnical engineering problems are encountered. Soil stabilization is the process of improving the physical and engineering properties of problematic soils to some predetermined targets. It operates in various ways including mechanical, biological, physical, chemical and electrical techniques. Among these techniques, chemical stabilization in order to improve the soil strength parameters and loading capacity is receiving the most interesting (Al-Mukhtar et al., 2010; Basha et al., 2005; Billong et al., 2009; Horpibulsuk et al., 2008, 2009a,b, 2010a,b; Jianli et al., 2010; Latifi et al., 2014; Mohammadinia et al., 2014; Murty and Praveen, 2008; Nalbantoğlu, 2004; Přikryl et al., 2003; Shen et al., 2013; Yong and Ouhadi, 2007). Soil stabilizers are categorized as traditional stabilizers or non-traditional additives (Marto et al., 2014). Traditional stabilizers such as lime, cement, zeolite, gypsum, industrial wastes and fly ash are commonly used (Al-Rawas et al., 2005; Bell, 1996; Biggs and Mahony, 2004; Yilmaz and Civelekoglu, 2009; Eisazadeh et al., 2012a, b; Horpibulsuk et al., 2011; Kavitha et al., 2015; Mohammadinia et al., 2014; Olugbenga et al., 2012; Rahmat and Ismail, 2011; Solanki and Zaman, 2012; Turkoz and Vural, 2013; Yunsheng et al., 2010). On the other hand, non-traditional additives consist of various combinations such as enzymes, liquid polymers, resins, acids, silicates, ions, and lignin derivatives (Horpibulsuk et al., 2015; Latifi et al., 2015a,b; Sukmak et al., 2013, 2015; Suksiripattanapong et al., 2015; Tingle et al., 1989).

It has been well established that a number of non-traditional soil additives, which are not calcium-based, are effective for soil stabilization (Al-Khanbashi and Abdalla, 2006; Blanck et al., 2013; Brandon et al., 2009; Indraratna et al., 2012; Latifi et al., 2015a,b; Liu, 2007; Liu et al., 2011; Naeini et al., 2012; Ou et al., 2011; Rauch et al., 2002; Santoni et al., 2005; Turkoz et al., 2014). Commercial non-traditional chemical

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additives are usually concentrated liquids that are generally diluted with water and then sprayed on the soil prior to compaction. The literature indicates that hexahydrated magnesium chloride or bischofite ($MgCl_2 \cdot 6H_2O$) is commonly used for road pavement applications to control dust and humidity, to minimize coarse particle scattering and to prevent ice formation (Ketcham et al., 1996; Nixon and Williams, 2001; Thenoux and Vera, 2002; Transportation Research Board, 1991). This bischofite is regarded as a green binder alternative to Portland cement, which is widely used for soil stabilization. The production of Portland cement is an energy-intensive process and emits a significant amount of greenhouse gas into the atmosphere.

Bischofite, which belongs to the halide group, is a sea salt concentrate that originates in the Permian period (nearly 200 million years ago). The main bischofite compound is magnesium chloride ($MgCl_2$; up to 350 g/L). Magnesium chloride ($MgCl_2$) solution, which does not corrode vehicles, damage cement and asphalt or harm plants or living creatures, has long been used as a green stabilizer in pavement applications in parts of the world such as North America, Scandinavia and Europe (Canada Environmental, 2001; Goodrich et al., 2009; Piechota et al., 2004; Randolph, 1997; Singh et al., 2003).

$MgCl_2$, a hygroscopic salt, has the ability to stabilize road material and control fugitive dust by drawing moisture from the air and keeping the road damp by resisting evaporation. The dust suppressants are also used to control maintenance costs and erosion from non-paved roads, and are associated with economic and safety benefits. As the usage of $MgCl_2$ is becoming more common, its potential to improve the geotechnical properties of problematic soils is receiving increasing attention. $MgCl_2$ also has the capacity to retain the absorbed moisture for an extended period of time, which depends upon the prevalent climatic conditions. The quantity of water absorbed is proportional to the exposed surface of the salt, the air's relative humidity and the concentration of $MgCl_2$ in the solution (Jianli et al., 2010; Turkoz et al., 2014).

In recent years, some studies reported on the successful application of $MgCl_2$ solution to improve the swell potential, strength characteristics and dispersibility of problematic soils (Acaz, 2011; Turkoz et al., 2014; Turkoz and Tosun, 2011). However, the investigation of the micro-structural characteristics of clayey soils stabilized with magnesium chloride ($MgCl_2$) solution has still been limited. Investigation of the micro-structural characteristics (fabric and cementation bond) is important to understand the engineering property improvement of the stabilized material with influential factors. Analysis of the strength development of $MgCl_2$ stabilized clayey soil based on mineralogical, morphological, and molecular results is thus the focus of this research. Two typical fine-grained soils, bentonite and kaolin, which represent high- and low-swelling clay, were used as the tested soils. Unconfined compression strength (UCS) and standard direct shear tests were undertaken to evaluate the strength characteristics of stabilized soils compared with those of unstabilized ones. Various spectroscopic and microscopic techniques were undertaken to examine the stabilization process mechanism and influence of $MgCl_2$ content and curing time on strength development. The spectroscopic and microscopic techniques include X-ray diffractometry (XRD), energy-dispersive X-ray spectrometry (EDAX), field emission scanning electron microscopy (FESEM), Fourier transform infrared spectroscopy (FTIR) and Brunauer, Emmett and Teller (BET) surface area analysis.

2. Materials and testing program

2.1. Materials

The two tested soils were pure sodium bentonite, an expansive soil composed mainly of montmorillonite, and brown kaolin. Both soils were purchased in 25 kg bags and prepared in Tapah (Perak), located in the Western Malaysian Peninsula. It is worth mentioning that the bentonite and kaolin represent high- and low-swelling clays and hence the output of this research is useful for assessing the behavior of other $MgCl_2$ stabilized clays, which have intermediate swelling behavior (Horpibulsuk et al., 2011). The engineering properties and chemical characteristics of the bentonite and kaolin are illustrated in Table 1 and Table 2, respectively. The values of the engineering and chemical properties of the bentonite and kaolin are similar to those reported by Eisazadeh et al. (2012a,b; 2013; 2015), given that their tested soils were obtained from the same source as these tested soils.

The magnesium chloride ($MgCl_2$) solution used was obtained from Merck Chemicals Company in Malaysia. Although $MgCl_2$ can be used in either solid or solution form for soil stabilization, the solution form is more common. Table 3 shows the general chemical properties of the $MgCl_2$ solution.

2.2. Sample preparation and testing program

2.2.1. Sample preparation

The soils were first oven dried and then passed through a 2 mm sieve to remove the bigger particles. The optimum moisture content (OMC) and maximum dry unit weight of both the untreated soils and the $MgCl_2$ stabilized soils under standard Proctor energy were determined according to the British Standard. The $MgCl_2$ contents were 2%, 4%, 6%, 8%, 10%, and 12% by dry weight of soils. The tested soils were thoroughly mixed with $MgCl_2$ solution by hand and palette knives and then transferred to UCS molds. The soil–$MgCl_2$ mixture at target dry density and moisture content predetermined from the standard Proctor test results was compressed in a steel cylindrical mold fitted with a collar. The compaction was done by a hydraulic jack based on clause 4.1.5 of BS 1924: Part 2: 1990b. Finally, the cylindrical samples were extruded using a steel plunger, trimmed, and wrapped in several layers of cling film. These samples were cured for 3, 7, 14, and 28 days in a temperature-controlled room (27 ± 2°C) before UCS testing (Latifi et al., 2015a,b). To ensure the accuracy of the results, at least four samples for each soil mixture and the four curing periods were prepared.

The shear strength parameters of the samples were determined by standard direct shear testing. Two-layered compaction was performed on the soil samples, which were 60 mm in diameter and 20 mm in height. Samples were then sealed in a plastic bag and cured in a humid room with a controlled temperature (27 ± 2°C) (Latifi et al., 2015a,b). The unstabilized soil samples were sheared immediately as control samples, but stabilized samples were only sheared after being cured. The samples were identified using designated notations: B for bentonite soil, K for kaolin clay, UNT for untreated/unstabilized soil, T for treated/stabilized soil, and D for days of curing period.

2.2.2. Testing program

The soil improvement index was determined by conducting a series of UCS tests (BS 1924: Part 2: 1990) on the samples at different time

Table 1
Engineering and chemical properties of bentonite.

Engineering and chemical properties	Values
pH (L/S = 2.5)	9.12
Specific gravity	2.64
External surface area ($m^2\ g^{-1}$)	28.60
Liquid limit, LL (%)	302
Plastic limit, PL (%)	42
Plasticity index, PI (%)	260
Maximum dry density ($mg\ m^{-3}$)	1.29
Optimum moisture content (%)	38
Unconfined compressive strength (kPa)	286
SiO_2	64.50
Al_2O_3	20.72
Fe_2O_3	7.69
MgO	2.11
Na_2O	3.18
CO_2	1.80