Stabilizing sulfate-rich high plasticity clay with moisture activated polymerization

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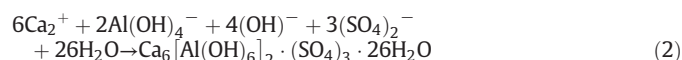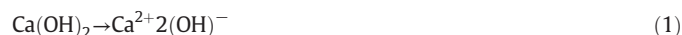
ABSTRACT

Cementitious soil stabilizers such as lime and cement are well known to cause swelling and, possibly, reduction in strength when used to stabilize sulfate-rich soil with high plasticity index (PI). This study explores using a moisture activated liquid polymer - a member of Methylene diphenyl diisocyanate (usually addressed as MDI) family, as a substitute of cementitious stabilizers to stabilize sulfate-rich high plasticity soil. The effect of mixing method, curing time, and polymer dosage on the unconfined compressive strength (UCS) and free swelling potential of polymer stabilized high plasticity clay with 2% sulfate (20,000 ppm) was evaluated in this research. In addition, the susceptibility of lime and polymer stabilized sulfate-rich soils in water was compared. It was found that the mixing method has a great impact on the properties of the stabilized soil, i.e., to obtain the maximum strength the soil should first be mixed with water before the polymer is added. Under moist conditions, the UCS increased significantly with curing time until 4 days. With the determined mixing method and curing time, 0, 4, 7, 10, and 13% of polymer were added to the sulfate-rich high plasticity clay to assess the dosage effect on the UCS and swelling potential. The results showed significant increase in UCS and decrease in swelling potential of the polymer stabilized soil with the increase of polymer dosage. The study further indicated that even though lime or polymer stabilized sulfate-rich high plasticity clay samples were subjected to significant strength degradation after soaked in water for 2 days, the polymer stabilized soil had much higher residual strength.

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1. Introduction

For many years, high plasticity clay (CH) has been effectively treated by cementitious materials, such as lime and cement, to mitigate its swelling and improve its strength. However, since the past decades, engineers and researchers have realized that high plasticity clay with sulfate minerals may experience significant volume increase (i.e., swelling) if stabilized with cementitious materials (Mitchell, 1986; Hunter, 1988; Puppala et al., 1999; Wang et al., 2004; Puppala et al., 2005; Celik and Nalbantoglu, 2013). Many researchers have investigated the causes of swelling of lime stabilized sulfate-rich soil and concluded the formations of two minerals, i.e., ettringite ($Ca_6[Al(OH)_6]2 \cdot (SO_4)_3 \cdot 26H_2O$) and thaumasite ($Ca_6.[Si(OH)_6]_2.(SO_4) \cdot (CO_3)_2 \cdot 24H_2O$), were attributable to the significant swelling (Hunter, 1988 & 1989; Mitchell and Dermatas, 1992; Talluri, 2013). When lime is added, it creates an environment of pH higher than 10 under which calcium, aluminum, sulfate, and water react and form ettringite. In this reaction, lime serves dual

functions, i.e., creating suitable pH conditions and supplying calcium ions as shown in Eqs. (1) and (2):

$$Ca(OH)_2 \rightarrow Ca^{2+} 2(OH)^- \tag{1}$$

$$\begin{aligned} 6Ca_2{}^+ + 2Al(OH)_4{}^- + 4(OH)^- + 3(SO_4)_2{}^- \\ + 26H_2O \rightarrow Ca_6\left[Al(OH)_6\right]_2 \cdot (SO_4)_3 \cdot 26H_2O \end{aligned} \tag{2}$$

The produced ettringite under suitable condition, such as pH about 10 and temperature <15 °C, can further form thaumasite (Talluri, 2013). Even though many factors, such as temperature, concentration of sulfate, or size of sulfate minerals, contribute to the degree of the reactions, the reported volume change due to the formation of ettringite and/or thaumasite is significant and can be up to >200% (Faure, 1991; Harris et al., 2004; Little et al., 2010).

As the sulfate minerals have a wide distribution across the globe, sulfate-induced swelling has caused failure/distress of pavements, buildings, parking lots, and airport taxiways in many geographic zones. Sulfate minerals come from many different sources such as gypsum ($CaSO_4 \cdot 2H_2O$), sodium sulfate (Na_2SO_4), and magnesium sulfate ($MgSO_4$). In addition, pyrite (FeS_2) and anhydrite ($CaSO_4$) can be

converted to gypsum under moist conditions, causing similar problems (Thomas et al., 1989; Burkart et al., 1999; Dubbé et al., 1984; Floyd et al., 2003; Puppala et al., 2003; Roy et al., 2003). The reported sulfate concentration in soil can be as high as 4.4% (44,000 ppm) (Puppala et al., 2013).

In addition to significant swelling, the existence of sulfate can lead to reduction on strength for the stabilized soils. When the sulfate exists in the form of sodium sulfate or magnesium sulfate, the reaction to form ettringite and thaumasite consumes calcium and impedes the pozzolan reaction to form calcium-silicate-hydrate (C-S-H) (e.g., Burkart et al., 1999; Puppala et al., 2005; Talluri, 2013). As a result, the strength of the stabilized sulfate-rich soil is much lower than that of the soil without sulfate.

In order to reduce the sulfate-induced swelling, different measures, such as extended mellowing, double dose applications, increasing field moisture contents, and decreasing compacted densities, have been attempted when lime is used as a stabilizer for sulfate-rich soil (Mitchell and Dermatas, 1992; Petry and Little, 1992; Kota et al., 1996; Wild et al., 1999; Harris et al., 2004). However, it is proven that these measures could be effective only at relatively low to medium sulfate concentrations (i.e., <8000 ppm), but at a high sulfate concentration (i.e., >8000 ppm), low- or non- calcium based stabilizers should be used (Santoni et al., 2002; Rauch et al., 2002; Harris et al., 2006). A number of researchers reported using amorphous silica, Class C and F fly ash, sulfate-resistant cements, and/or ground granulated blast furnace slag (GGBFS) to stabilize the sulfate-rich soil and, at the same time, mitigate the swelling (for example, Sarkar and Little, 1998; Wild et al., 1998; Tasong et al., 1999; Harris et al., 2004; Wang et al., 2004; Harris et al., 2006; Puppala et al., 2006; Talluri, 2013). In recent years, researchers also attempted to use unconventional, non-calcium based stabilizers such as acids, enzymes, lignosulfonates, petroleum emulsions, and tree resin to mitigate the potential swelling of sulfate-rich soil. These unconventional, non-calcium stabilizers are primarily used to reduce the swelling potential but not to improve the strength. The published literature showed disputable effects of acids, enzymes, lignosulfonates, and petroleum emulsions on mitigating the swelling potential of sulfate-rich soils, i.e., some studies showed promising results while others did not (Rauch et al., 2002; Santoni et al., 2002; Harris et al., 2006; Naeini and Ghorbanali, 2010). A salient disadvantage of these non-calcium stabilizers is that the treated soil samples are highly moisture susceptible, and perform poorly under moisture condition.

Alternatively, liquid polymers, increasingly used for soil improvement (Al-Khanbashi and El-Gamal, 2003; Al-Khanbashi and Abdalla, 2006; Zandieh and Yasrobi, 2010; Anagnostopoulos and Pagalianagas, 2012; Naeini et al., 2012), have been assessed for their effects on mitigating sulfate-induced swelling and improving soil strength (Rauch et al., 2002; Santoni et al., 2002; Harris et al., 2006). The reported results also showed disputable effects. Rauch et al. (2002) reported a noticeable effect of liquid polymers on mitigating swelling potential, while Harris et al. (2006) claimed a limited effect according to their laboratory tests. The discrepancy may be associated with the type of polymer being used, the processes involved for stabilization and the applied curing methods (Harris et al., 2006). Mohammed and Vipulanandan (2014) found liquid polymer can improve the strength of the sulfate-rich low plasticity clay (CL), which has much lower swelling potential compared with CH soils. In addition, this study did not assess the swelling potential of the treated soil. In general, there is lack of a systematic study on the dose and curing methods of liquid polymer as well as comprehensive evaluation of the swelling potential and moisture susceptibility of the treated CH soils. Such lack of information has greatly inhibited the applications of liquid polymers in stabilizing sulfate-rich CH soils (Rauch et al., 2002; Santoni et al., 2002).

To address the engineering needs, this study aims at investigating the stabilization process to enable the application of liquid polymer in practice. The main focus of this study includes, but not limited to, assessing the mixing and curing methods, quantifying influence of dosage on the swelling and strength of stabilized soil, and comparing the water susceptibility of sulfate-rich soil after stabilized by a moisture activated liquid polymer.
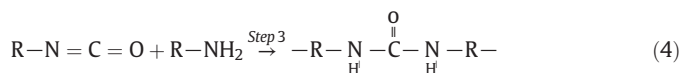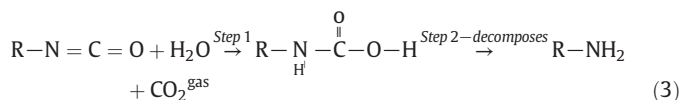
2. Outline of the study

The primary objective of this study was to evaluate the effectiveness of the moisture activated liquid polymer on mitigating swelling and improving strength of sulfate-rich high plasticity clay as well as to develop an appropriate construction method. To fulfill this objective, the study was carried out in two major steps as shown in Fig. 1. In the first step, water and 10% liquid polymer were added to sulfate-rich high plasticity clay with different sequences to examine the effect of mixing methods on the properties of the stabilized soil and, thereafter, the stabilized soil was tested at different curing periods to determine the appropriate curing time. In the second step, soil samples were prepared with different doses of polymer (i.e., 0%, 4%, 7%, 10% and 13% by weight) following the mixing method and curing procedure that were determined in Step 1 and then tested for their strengths and swelling potentials to evaluate the effect of polymer doses. Step 2 also evaluated the water susceptibility of the polymer stabilized soil.

3. Materials

3.1. Polymer

A single component, moisture-activated, hydrophobic polyurethane polymer (AP Soil 600®), which is a member of Methylene diphenyl diisocyanate (usually addressed as MDI) family, was adopted in this study. Such polymer has been increasingly used solely or in conjunction with other polymers for permeation grouting, soil stabilization, and sinkhole remediation (Dolfing and Lolkema, 1972; Hageman et al., 1975). The chemical structure of the precursor is shown in Fig. 2, which will be polymerized when it encounters water as shown by the chemical reactions in Eqs. (2) and (3). When water is added, its NCO (—N≡C═O) groups react readily with OH (—O—H) groups of the water to form mixtures of diisocyanates and amines to produce inert, solid, insoluble polyurea and release carbon dioxide. (Note: N, C, O, and H stand for nitrogen, carbon, oxygen and hydrogen elements, respectively.) The polymer will not react with soil particles or sulfate as the soil minerals and sulfate are inert to the functional groups of the MDI. However, after the liquid polymer reacts with water, it will form a solid polymer that acts as a bonding agent to bond soil particles as well as a barrier to reduce the water infiltration to the soil skeleton. As a result, the soil strength can be increased but swelling potential can be reduced.

$$R-N=C=O+H_2O \overset{Step\ 1}{\to} R-\underset{H}{N}-\overset{O}{\overset{\parallel}{C}}-O-H \overset{Step\ 2-decomposes}{\to} R-NH_2 + CO_2{}^{gas} \tag{3}$$

$$R-N=C=O+R-NH_2 \overset{Step\ 3}{\to} -R-\underset{H}{N}-\overset{O}{\overset{\parallel}{C}}-\underset{H}{N}-R- \tag{4}$$

This liquid precursor has a low viscosity, which makes it very flowable and easy to mix with soils uniformly. The cured polymer has a tensile and compressive strength of 1 and 12.5 MPa, respectively. The primary properties of the liquid polymer as well as the cured polymer are listed in Table 1.

*Provided by the material supplier.

3.2. Sulfate-rich soils

The soil used for this study is yellowish clay. The wet sieve analysis following ASTM C325-07 was conducted to determine the percentage