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Volume change behavior of lime treated gypseous soil — influence of mineralogy and microstructure

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ABSTRACT

Series of oedometer tests and micro-analytical studies (XRD, SEM and EDAX) have been carried out to investigate the influence of varying gypsum content on swell, compressibility and permeability of lime treated montmorillonitic soil after curing for different period. Immediate swell is observed on inundation of compacted samples with water and continuously increased with gypsum content. However, changes in swell are found to be marginal with curing. This is attributed to the formation and growth of ettringite crystals by ionic reactions of aluminum–calcium–sulfate in the presence of water which is confirmed through detailed micro-analysis. The higher swell in uncured specimens and gradual reduction in swell with increase in curing periods are due to relative dominance of formation and growth of ettringite and cementitious compounds, respectively. Also, the ionic reaction products are found to bear a significant influence on the compressibility and permeability behavior.

1. Introduction

Expansive soils pose serious problems to foundation engineers as they undergo high volume changes when subjected to moisture content variation. The extent of volume change depends on several factors such as moisture content, density, soil structure, confining pressure, climate and type of clay minerals (Bell, 1996; Chen, 1988). The resulting change can cause severe damages to the structures constructed over them (Bell, 1996; Chen, 1988; Mitchell and Soga, 2005). In practice, chemical stabilizers such as lime and cement are very widely used to modify the engineering properties for different types of soils including those rich in sulfate content (Hausmann, 1990; Mitchell and Dermatas, 1992; Nalbantoglu and Tuncer, 2001; Petry and Little, 2002). However, it is generally found to have adverse effects in sulfate rich soil (Dermatas, 1995). Hence, there is a need to understand the influence of sulfate on the volume change behavior of lime treated soil to overcome from future possible distress (Petry and Little, 2002).

It is known that gypsum is the main source of sulfate in soils and these soils are known as gypseous/gypsiferous soil (Abdi, 1992; Rajasekaran, 2005; Solis and Zhang, 2008). Calcium-based stabilization of natural expansive soils in the presence of sulfate creates more distress by inducing heave rather than extenuating it (Hunter, 1988; Little et al., 2009; Mitchell and Dermatas, 1992; Petry, 1994; Puppala et al., 1999). Sulfate induced heave has been attributed due to the formation of ettringite mineral at highly alkaline environment ($pH > 10.5$) by reaction of calcium, aluminum and sulfate in the presence of water (Hunter, 1988; Mitchell and Dermatas, 1992; Puppala et al., 2005). The complicated reactions that occur are presented in a simplified form by Hunter (1988) as follows:

$$\begin{aligned}&6Ca^{2+}(\text{from lime}) + 2Al(OH)_4^-(\text{released from clay})\\ &\quad +4(OH)^-(\text{Ionization of lime, pH}{>}12.3)\\ &\quad +3(SO_4)^{2-}(\text{dissolution of sulfate ions})\\ &\quad +26H_2O(\text{water}) \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O\ (\text{Formation of ettringite})\end{aligned}$$

Formation of ettringite is controlled by various factors such as clay minerals present, pH, water content, sulfate content and temperature (Hunter, 1988; Mitchell and Dermatas, 1992; Rajasekaran, 2005). However, the formation of ettringite with time period is intriguing and has been subject of intense research. Hunter (1988) reported that effect of sulfate on the lime stabilized soil affects only the long-term pozzolanic reactions, indicating no immediate formation of ettringite. Similarly, delayed formation of ettringite is only possible in concrete if the temperature goes beyond 70 °C (Taylor et al., 2001). On the contrary, several researchers have reported that formations of ettringite crystals are possible at an early age, within hours immediately after mixing (Little et al., 2009; Puppala et al., 2005; Rahhal and Talero, 2014; Wild et al., 1993). Thus, the effect of sulfate on the volume change behavior of lime treated soil with curing assumes great importance and is prime motive of present work.

In the past, several researchers have focused on the study of sulfate induced heave and related mechanism in various types of soils (Dermatas, 1995; Hunter, 1988; Kota et al., 1996; Little and Little, 1992; Mitchell and Dermatas, 1992; Puppala et al., 1999; Puppala

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et al., 2005; Rollings et al., 1999; Wild et al., 1996; Wild et al., 1998). By and large, one common conclusion is drawn that the formation and hydration of expansive mineral ettringite at temperature above 15 °C and thaumasite at temperatures below 15 °C affect the volume change behavior of soils. However, in most arid regions, where lime stabilization is applied to control the volume change behavior of expansive soils, the formation of ettringite is very common. A clear understanding of compressibility behavior of soil is also necessary before resorting to lime stabilization in the field (Rajasekaran and Rao, 2002) which, according to Burland (1990), is controlled by physico-chemical environment of soil. Attempts have been made previously to study the effect of sulfate on the compressibility of lime treated kaolinite and montmorillonitic soils (Sridharan et al., 1995; Sridharan et al., 1997). However, the effect of the physico-chemical and mineralogical alterations that occur during curing on the volume change behavior of lime treated gypseous soil is not clear and is another motive of current work.

The main motive of this research is to gauge the swell induced in lime treated soil in the presence of varying gypsum content for both uncured and cured specimens at different periods. Further, the work is also aimed to address the effect of varying gypsum content and curing periods on the compressibility behavior of lime treated soil. The mechanism of swell and compressibility is elucidated by performing detailed mineralogical, microstructural and chemical composition analysis through X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive X-ray diffractometer (EDAX), respectively.

2. Materials and methodologies followed

2.1. Materials used

The soil used in the present work is collected from Belgaum district of Karnataka, India. Geotechnical properties of soil are presented in Table 1. The XRD analysis (Fig. 1a) confirms the presence of montmorillonite, quartz and aluminum as predominant minerals. Also, the presence of a honeycomb networking pattern with several voids by SEM image (Fig. 2a) (Mitchell and Soga, 2005) and the ratio of Al:Si (1:2.1) (Fig. 2b) substantiate the presence of montmorillonite mineral (Peethamparan et al., 2009).

Commercially available laboratory reagents lime and gypsum are used as chemical additive. The purity of these additives is verified by XRD, SEM and EDAX analysis. XRD analysis of these additives confirms the presence of calcium hydroxide [$Ca(OH)_2$] except small calcium carbonate ($CaCO_3$) as a small impurity in lime (Fig. 1b) and calcium sulfate dihydrate [$CaSO_4.2(H_2O)$] in gypsum (Fig. 1c) in all major peaks. SEM images of lime (Fig. 2c) and gypsum (Fig. 2e) show the white spherical and flake like structure of different sizes, respectively. Chemical composition examination by EDAX confirms the presence of calcium in lime (Fig. 2d) and calcium along with sulfur in the gypsum (Fig. 2f).

Table 1
Geotechnical properties of expansive soil.

Property	Value
Grain size analysis	
Sand (4.75–0.075 mm), %	6
Silt (0.075–0.002 mm), %	31
Clay (<0.002 mm), %	63
Classification as per IS plasticity chart	CH
Specific gravity	
Specific gravity	2.67
Atterberg's limits	
Liquid limit, %	72.1
Plastic limit, %	31.7
Plasticity index, %	40.4
Shrinkage Limit, %	13.6
Swell properties	
Free swell Index, %	72.7
Swell, %	4.1
Compaction characteristics	
Optimum water content, %	32.5
Max. dry unit weight, kN/m^3	13.4

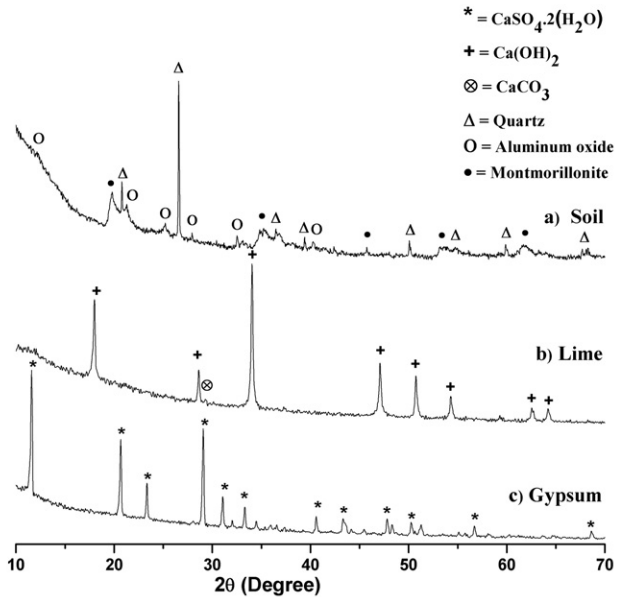

Fig. 1. Mineralogical analysis by XRD of parent soil and additives.

2.2. Sample preparations

The addition of lime and gypsum to prepare different combinations is done as percentage by dry weight of soil. Firstly, mixtures of soil–lime and gypsum are mixed thoroughly in dry state until the mixture appeared homogeneous and uniform. Then, desired amount of water is added and remixed again thoroughly to get uniform moisture distribution. Sample of soil and mixtures of different combinations are kept for mellowing up to 24 h and 1.5 h, respectively and experimental works have been performed after completion of mellowing period. Similar procedures are followed by several researchers (Aldaood et al., 2014a, 2014b; Al-Mukhtar et al., 2010; Al-Mukhtar et al., 2012; Little, 1995).

2.3. Methodologies followed

2.3.1. Determination of swell and compressibility behavior

The swell in lime treated soil and with varying percentages of gypsum are carried out as per Indian Standard Code IS: 2720 (Part 15) (1986). The lime content is kept constant at 6%, which has been found to an optimum for the soil, and is obtained by performing pH test as per the method of Eades and Grim (1966). The samples are compacted statically in 60 mm diameter and 20 mm thickness consolidation rings consistent with maximum dry unit weight (γ_{dmax}) and Optimum Water Content (OWC). The maximum dry density and optimum water content values for all combinations of soil–lime–gypsum are determined by carrying out mini compaction test procedure developed by Sridharan and Sivapullaiah (2005). The samples wrapped in polythene bags are kept in air tight desiccators and cured for 7, 14 and 28 days. The constant water content is ensured by measuring the weight of each sample after completion of desired curing periods. The sample rejected, if the variation in water content is more than 0.5%. The percentage of swell is measured at a nominal seating load of 6.25 kPa. When swell stops, incremental loading is applied to determine compressibility characteristics. A load increment ratio of unity is adopted