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Mechanism of improvement in the strength and volume change behavior of lime stabilized soil

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ABSTRACT

An attempt has been made to bring out the influence on strength and volume change behavior of fabric changes and new cementitious compound formation in a soil upon addition of various lime contents and with curing periods. The effects of changes in fabric of treatment with various lime contents (0, 2, 4 and 6%) and with curing periods (0, 7, 14 and 28 days) have been evaluated by one-dimensional consolidation tests, in terms of void ratio changes and compressibility. The strength of soil treated with different lime contents with curing periods up to 28 days, and with the optimum lime content of 6% up to one year has been determined by unconfined compression tests. Comparison of effects of lime on the strength and volume change behavior of the soil brings out that the formation of flocculated fabric and cation exchange significantly reduces the compressibility of soil but marginally increases the strength. Cementation of soil particles and filling with cementitious compounds of the voids of flocculated fabric in the soil marginally reduces the compressibility but significantly increases the strength. Thus, the mechanism of volume change behavior of soil treated with lower lime content at short curing periods is distinctly different from that of the soil treated with optimum lime content at longer curing periods. This is consistent with the increase in the permeability caused by the addition from 2 to 4% lime and the decrease following the addition of 6% lime. Changes consistent with mechanical behavior have been determined by scanning electron microscope, X-ray diffraction and thermal analyses, energy dispersive X-ray spectrometer and pH value in microstructure, mineralogy, chemical composition and alkalinity, respectively.

1. Introduction

Arrangement of particles, particle group and pore space in a soil, generally termed as fabric, influence specific engineering properties such as strength, hydraulic conductivity and compressibility of soil (Mitchell and Soga, 1993). Inter-particle forces at the time of deposition as well as the geologic and stress history of the deposit, the depositional environment and weathering history of the deposit attribute the fabric of natural clays (Mitchell, 1956; Sachan and Penumadu, 2007). Further, fabric of soils greatly varies depending on the mineralogy of the soil, especially while interacting with various stabilizing agents such as chemical, waste stabilizers (Mitchell and Soga, 1993; Osula, 1996; Bell, 1996; Sivapullaiah and Jha, 2014; McCarthy et al., 2014; Jha and Sivapullaiah, 2014). Hence, the analysis of clay fabric has a particular problem because of extremely small size particles of some mineral such as montmorillonite (flake may be only 0.96 nm in thickness), the range of sizes is enormous (pores in clays can be as large as 0.1 mm) (Griffiths and Joshi, 1990). Sachan and Penumadu (2007) reported that the space between two particles and the angle between two particles control geometric arrangement or fabric of particles with soil mass whereas the space between two particles causes change in void ratio of soil matrix, the change in anisotropy of soil mass is related to the angle between two particles. Researchers have described the fabric in general terms such as flocculated-random orientation (edge-to-face contacts) of soil platelets, forming an open-ended structure of soil, and dispersed-parallel arrangement (face-to-face contacts) of soil platelets, forming the closure structure of the soil (Barden and Sides, 1971; Collins and McGown, 1974).

Tests have been performed to study the engineering behavior affected by change in the fabric of soil (Mitchell, 1956; Seed and Chan, 1960; Brewer, 1965; Olsen and Mesri, 1970; Barden and Sides, 1971; Lemaire et al., 2013). It is considered that the shear strength parameters of clay are affected by the arrangement of particles within the soil matrix (McKyes, 1971; Yimsiri and Soga, 2000; Sachan and Penumadu, 2007). Moreover, the explanation about the mechanical behavior of clays is given on the basis of fabric concept by most of the researchers (Seed and Chan, 1959; Sloane and Kell, 1966; Duncan, 1966; McKyes, 1971; Prashant and Penumadu, 2007). The influence of fabric on the

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different types of soils has been established by many researchers (Sloane and Kell, 1966; Martin and Ladd, 1975; Griffiths and Joshi, 1990; Prashant and Penumadu, 2007; Sachan and Penumadu, 2007). Griffiths and Joshi (1990) have concluded by studying four different types of soils that pore size distributions in the soil matrix are related to the maximum consolidation stress, causing decrease in total void volume of soil with higher stress and vice versa. However, some researchers have reported that montmorillonite and kaolinite clay treated with calcium hydroxide increase the value of frictional angle and cohesion values even when the soil is normally consolidated (Nagaraj, 1964; Bai and Smart, 1997). No information is available on the effect of fabric on both strength and volume change behavior and their relationship with other geotechnical properties. The main motivation of the present paper is to bring out these relationships for the lime stabilized soil at different curing periods. It is known that cation exchange, flocculation and formation of pozzolanic reaction compounds are the major reasons for improvement in geotechnical properties of soils with addition of lime (Bell, 1996; Okyay and Dias, 2010). But, the relative dominance of these factors on different geotechnical properties of soil is not well understood. In addition, it is not clear whether the optimum lime content is same for the soil to improve the different geotechnical properties.

In the previous studies, the examination of fabric or arrangement of particles in cohesive soil has been carried out using several analytical techniques. Al-Mukhtar et al. (1996) studied the effect of overburden pressure, excavation and desaturation on soil fabric by using mercury intrusion tests and transmission electron microscopy (TEM). Cuisinier et al. (2011) also studied the role of lime stabilization on silt size microstructure and saturated hydraulic conductivity with mercury intrusion porosimetry. They reported that the applied mechanical and hydraulic stress state condition depends on the type of soil fabric. McKyes (1971) used three techniques such as polarized light microscopy, scanning electron microscopy and transmission electron microscopy for fabric viewing as applied to shear distortion of clay. The changes in the fabric due to the variation in consolidation stress, directional change of consolidation stress and disturbance during removal were brought by X-ray diffraction analyses (Martin and Ladd, 1975). Likewise, Sloane and Kell (1966) determined the alteration in fabric of commercial kaolinite after mechanical compaction from scanning electron microscope. Sachan and Penumadu (2007) performed experiments to determine the effect of microfabric on the shear behavior of kaolinite soil by preparing flocculated and dispersed specimen in laboratory using the slurry consolidation technique. The particle arrangement and thickness of the diffuse double layer are main governing constraints for strength parameters. However, the other physicochemical issues such as ion exchange capacity, pore fluid, pH value, electrolyte concentration cause alteration in particle arrangement and a diffuse double layer of clay (Mitchell and Soga, 1993). A clear understanding about strength behavior of lime treated soil still needs in term of volume change behavior to understand the influence of fabric change with time period.

The present research work contracts with role of fabric on the variation of strength and volume change behavior of expansive soil up to the long term curing period in the presence of hydrated lime [$Ca(OH)_2$]. The fabric examination of lime treated soil at different curing periods is scrutinized in terms of void ratio by performing one-dimensional consolidation test. The effects of changes in fabric on volume change behavior and the improvement in strength are compared. Moreover, the mechanisms of effect of lime on the soil plasticity, compaction characteristics and swell percentage are also investigated. The micro-examination of fabric due to lime–soil reaction is carried out by scanning electron microscope (SEM). In addition, mineralogical and chemical changes, which are responsible for fabric change, are studied by energy dispersive X-ray spectroscopy (EDAX) analysis, X-ray diffraction (XRD) and thermal analysis (TGA).

2. Materials and methods

2.1. Materials used

2.1.1. Soil characteristics

The physical properties of soil are presented in Table 1. The soil was obtained from Belgum district of Karnataka state in India. Soil is collected from a depth of 1.5 m below the natural ground level by open excavation. Particle size analysis of soil shows the presence of clay (<2 μm) as predominated size particle. According to Indian standard classification, soil is classified as clay of high compressibility (CH) and high degree of expansion. The X-ray diffraction analysis [Fig. 1(a)] indentified montmorillonite, aluminum oxide and quartz as dominant minerals in soil. SEM image indicates a honeycomb networking pattern with several voids [Fig. 2(a)] and the ratio of Al:Si is found to be 1:2.1 from EDAX analysis [Fig. 2(b)], confirming the presence of montmorillonite in the soil (Mitchell, 1993; Peethamparan et al., 2009).

The thermogravimetric (TG), derivative thermogravimetric (DTG) and differential thermal analysis (DTA) of parent soil is presented in Fig. 3. It is observed from the DTG curves that the three major endothermic peaks in the range of 100–200 °C, 250–350 °C and 450–550 °C have appeared. However, the relatively weak endothermic peak is also pronounced between 800–1000 °C. The endothermic peak between 100–200 °C is due to the removal of hygroscopic water (Mitchell, 1993). It is reported that clay having single endothermic peak between 100–200 °C is due to the loss of structural hydroxyls of montmorillonite. The loss of structural hydroxyls of montmorillonite occurs in two stages — first is due to the loss of hydroxyl bond and second is due to the complete breakdown of montmorillonite structure (Sweeney, 1981). The appearance of endothermic peaks between 250–350 °C is due to the removal of adsorbed water (Mitchell, 1993). Moreover, the strong endothermic peak between 500–600 °C reveals the dehydration of lattice of hydroxyl groups of smectite (Al-Mukhtar et al., 2010; Sivapullaiah et al., 2010). The weaker endothermic peaks between 800 °C and 1000 °C confirm the breakage and recrystallization of mica and montmorillonite (Sudo and Shimoda, 1970; Sweeney, 1981). This is in agreement with the results of XRD and SEM studies. Further, sharp reduction in mass at the endothermic peaks between 100–200 °C, 250–350 °C and 450–550 °C occurs by 0.5, 4.5 and 9.5%, respectively. However, the reduction in mass up to 600 °C is 10.5% and marginal thereafter. The total mass loss of soil up to 1000 °C is about 13%. Thus, the studies clearly confirm the presence of montmorillonite in the soil. Similar observation has been made by Sivapullaiah et al. (2010) for Black Cotton soil.

2.1.2. Lime

Dry powder hydrated lime [$Ca(OH)_2$], supplied by Thermo Fisher Scientific India Pvt. Ltd. has been used as a stabilizing agent. The X-ray diffraction (XRD) analysis of dry powder lime [Fig. 1(b)] confirmed the purity that all major peaks indicate the presence of hydrated calcium hydroxide [$Ca(OH)_2$].

Table 1
Physical properties of soil.

Property	Soil
Specific gravity	2.67
Sand (4.75–0.075 mm), %	6
Silt (0.075–0.002 mm), %	31
Clay (<0.002 mm), %	63
Liquid limit, %	72.1
Plastic limit, %	31.7
Plasticity index, %	40.4
Shrinkage limit, %	13.6
Free swell index, %	72.7
Optimum moisture content, %	32.5
Max. dry unit weight, kN/m^3	13.4