



# Susceptibility of strength development by lime in gypsiferous soil—A micro mechanistic study



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## ARTICLE INFO

### Article history:

Received 21 January 2015

Received in revised form 3 July 2015

Accepted 7 July 2015

Available online 23 July 2015

### Keywords:

Gypsiferous  
Lime  
Microstructure  
Mineralogy  
Plasticity  
Strength

## ABSTRACT

The role of gypsum on the strength of lime treated soils after a long period of interaction is not well understood yet. The present study is performed to scrutinize the physical and strength behavior of lime treated soil with varying gypsum content. Lime and gypsum contents varying from 0 to 6% are considered in the present study for curing periods up to 28 days. To understand the long-term effects, the work has been extended up to 365 days, particularly with the use of 6% lime content and varying gypsum contents. Atterberg's limits turned out to be marginally affected by cation exchange. Unconfined compressive strength behavior of lime treated soil varies considerably with gypsum content and curing period. However, trivial alteration in strength is observed in the soil treated with lower lime content (up to 4%) and gypsum content up to 6%. On the contrary, strength of soil–6% lime mixture with addition of varying gypsum content shows acceleration in early strength at 14 days curing period. However, the strength at 28 days of curing declines but regains afterwards for 90 days. The trend at longer curing period for 180 and 365 days is, however, not unique but varies with gypsum contents. An attempt has been made to explain these changes on the basis of the form of gypsum, formation and conversion of reacted compounds (CASHH, CASH, CSH and Ettringite). The proposed explanations were supported by detailed characterization through thermal analysis, XRD, SEM and EDAX studies of soil–lime–gypsum mixtures.

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## 1. Introduction

The treatment of natural soils with lime is an attractive technique to enhance their engineering behavior (Consoli et al., 2009; Celauro et al., 2012). The related mechanisms behind the improvement in soil behavior are well understood and sufficient to provide design guidelines for successful lime treatment of a range of soils (Petry & Little, 2002). However, several factors (soil type, type and amount of lime added, curing period and method, moisture content, method of compaction, and time elapsed between mixing and compaction) influence both the short-term (cation exchange and flocculation/agglomeration) and long-term (formation of cementitious gels by pozzolanic reaction) mechanism of lime stabilization (Bell, 1996; Rao and Shivananda, 2005; Osinubi and Nwaiwu, 2006; Al-Mukhtar et al., 2010a, 2010b; Di Sante et al., 2014, 2015). These factors attribute toward the complexity in the process of lime–soil reaction (Diamond and Kinter, 1965; Little et al., 1995). A clear understanding about minerals present in soil is essential before the application of calcium-based stabilizers such as

lime, otherwise, deleterious effects on the structures constructed on the treated soil could develop with time, especially in the case of gypsiferous soil (soil which contains gypsum).

It is reported the presence of gypsum extends over more than 20% of the land surface in the world (Solis and Zhang, 2008). The solubility characteristics and phase transformation of gypsum at temperature–pressure equilibrium create numerous hazards, such as ground subsidence due to hydration (swelling up to 63%) and dehydration (compressibility up to 39%) (Yamamoto and Kennedy, 1969; Yilmaz, 2001; Azam, 2007). It is very difficult to find out significant research results on the effect of gypsum on the properties of soil. However, both beneficial (Yilmaz and Civelekoglu, 2009) and adverse (Bell and Maud, 1994; Jha and Sivapullaiah, 2014) effect of gypsum on the properties of different types of soil have been reported in literature by means of laboratory and field investigation. Several attempts have been made to stabilize the intriguing behavior of gypsiferous soil by grouting either by cementitious grout or chemical grout, by using geosynthetic materials (Cooper and Saunders, 2002), or by utilizing admixtures (lime, cement, fly ash, GGBS and so on) (Taha et al., 1994). It is reported that the heave in the calcium based stabilized soil occurs due to the conversion of cementitious gel to expansive minerals such as ettringite (>15 °C) and thaumasite (<15 °C) in the presence of sulfate in soil or, sulfate contained ground water (Kollmann et al., 1977; Hunter,

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1988). However, several controversies exist regarding the formation of ettringite/thaumasite. Dermatas (1995) reported that the process of ettringite/thaumasite either by through solutions reaction or, by topochemical reaction is still not understood clearly. Moreover, the formation of ettringite is possible in either of two ways such as primary ettringite (i.e., topochemical ettringite formed by the sulfate ion in solution acting on chemically active alumina) and secondary ettringite (i.e., forms after dissolution of primary ettringite and redeposit from solution in cracks and voids) (Rollings et al., 1999). Abdi and Wild (1993) reported the expansion mechanisms induced by formation of ettringite on the basis of several hypothesis that are presented as (i) increase in volume due to the reaction product (crystalline ettringite) exhibiting a lower density and therefore a higher volume than the initial reactants; (ii) expansive forces exerted by the anisotropic growth of ettringite crystals or by morphological changes in crystal habit and crystal growth; and (iii) swelling due either to imbibition of water or transfer of water by osmosis. Moreover in lime stabilized soil, the immediate indication of a soil potential to heave due to the presence of sulfate is not possible sulfate affects only the pozzolanic reactions (Hunter, 1988). On the contrary, Wild et al. (1993) and Puppala et al. (2005) have reported that formation of ettringite rapidly occurs in soil–lime–gypsum systems immediately after mixing. Formation of ettringite leads to the decrease in free moisture content due to the chemical consumption of water during its nucleation and subsequent growth (Kinuthia et al., 1999). Mehta (1973) has reported two major theories regarding the expansion associated with ettringite formation. These are 1) the crystal growth theory, which relates to expansion caused by ettringite to its crystallization pressure and 2) swell theory, which attributes the expansion to the water-adsorption and swelling characteristics of ettringite. Mitchell and Dermatas (1992) mentioned that ettringite forms directly in montmorillonite whereas in kaolinite, ettringite is formed by conversion of initially formed monosulfate due to high availability of alumina.

The literature related with the effects of sulfate on the strength behavior of lime stabilized soil with time elapsed has been vague and inconsistent. A decrease in the strength proved by the reduction in the effective cohesion intercept of lime treated soil with sulfate after curing is mentioned by Sivapullaiah et al. (2000b). Mehta (1983) reported that the reduction of strength is due to the adsorption of sulfate on pozzolanic reactions compounds thus reducing their cementation ability. Kawamura et al. (1986) and Dermatas (1995) mentioned that the development of extensive interlocking soil matrix with filling of voids by formation of ettringite crystal induces significant gain in strength. However, the high strength caused by formation of ettringite depends on the ettringite crystal size and its morphology (Mehta, 1983). Likewise, other researchers (Hasaba et al., 1982; Abdi, 1992; Wild et al., 1993) have also reported the enhancement in the strength of lime stabilized clay and lime–slag–clay mixtures by addition of gypsum. Gypsum acts as catalyst to accelerate the hydration mechanism for lime stabilized soil in the presence of slag and fly ash at short curing period (Smolczyk, 1980; Gollop and Taylor, 1996; Sivapullaiah and Jha, 2014). It is reported that chemical environment affects the characteristic of lime treated soil with time (Rajasekaran, 2005). Thus, the effects of different sulfate levels on the physical and engineering behavior of lime treated soil with time need to be understood and design methods to overcome the loss/reduction in strength need to be developed.

In the present paper, an attempt has been made to examine the effectiveness of lime treated soil in the presence of sulfate (used as gypsum). Both physical (change in soil plasticity) and strength (unconfined compressive strength) properties have been examined in order to accomplish the present objective. Strength of lime treated soil with varying gypsum contents has been studied at different curing periods up to 365 days. The mechanism of alteration in strength is brought out clearly by performing micro scale studies, such as thermal analysis (TA), X-ray diffraction (XRD), and scanning electron microscope (SEM) coupled with energy dispersive X-ray spectroscopy (EDAX).

## 2. Materials and methodologies

### 2.1. Materials used

The soil used for the study is obtained from Belgaum district of Karnataka state in India. Soil is collected from a depth of 1.5 m below the natural ground level by open excavation. The geotechnical properties of soil are presented in Table 1. Particle size analysis of soil shows the presence of clay (<2 μm) as predominated fraction. According to Indian standard classification, soil is classified as highly compressible clayey (CH) and high degree of expansion soil. The X-ray diffraction analysis of soil (Fig. 1a) identified montmorillonite, aluminum oxide and quartz as the predominant minerals. SEM photomicrograph indicates several voids with honeycomb networking pattern (Fig. 2a) (Mitchell and Soga, 2005) and chemical composition analysis by EDAX (Fig. 2b) shows the ratio of Al:Si is 1:2.1 (Peethamparan et al., 2009), confirming the presence of montmorillonite.

Fig. 3 shows the thermogravimetric (TG), derivative thermogravimetric (DTG) and differential thermal analysis (DTA) of parent untreated soil. It is observed on the DTG curve that the two endothermic peaks are at 150 °C and 320 °C. The endothermic peaks at 150 °C and 320 °C (between 250 and 450 °C) are due to the removal of hygroscopic water and the presence of free oxides such as gibbsite [Al(OH)<sub>3</sub>], brucite and goethite which is further confirmed by the detection of aluminum oxide in XRD (Fig. 1a), respectively (Mitchell and Soga, 2005). Further, the strong endothermic peak is observed between 500–600 °C due to the dehydration of lattice of hydroxyl groups of smectite (Al-Mukhtar et al., 2010a). The TG curve of soil shows a continuous mass reduction up to this corresponding region 500–600 °C and is about 10.5%. The weaker endothermic peaks noticed between 800 °C to 1000 °C region are due to the breakage and recrystallization of mica and montmorillonite (Sudo and Shimoda, 1970). The total mass loss of soil up to 1000 °C is about 13%. Similar observation is reported by Sivapullaiah et al. (2010) for Black Cotton Soil.

Hydrated lime [Ca(OH)<sub>2</sub>] has been used as stabilizing agent which is supplied by Thermo Fisher Scientific India Pvt. Ltd. The X-ray diffraction (XRD) analysis of dry powder lime (Fig. 1b) confirmed that all major peaks indicate the presence of hydrated calcium hydroxide [Ca(OH)<sub>2</sub>] except small peaks of calcium carbonate as an impurity.

Gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O), used in the present study, is supplied by Ranbaxy Laboratories Limited. The XRD analysis of gypsum (Fig. 1c) shows the presence of calcium sulfate dihydrate (CaSO<sub>4</sub>·2H<sub>2</sub>O) in all the peaks, confirming the purity.

### 2.2. Testing and analysis

#### 2.2.1. Laboratory works

The amount of lime and gypsum used to prepare soil–lime–gypsum mixtures for each test is expressed as percentage by dry weight of soil. The sample is prepared according to Al-Mukhtar et al. (2010a). A predetermined amount of lime and gypsum has been added to the

**Table 1**  
Geotechnical properties of parent 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 water content, %	32.5
Max. dry unit weight, kN/m <sup>3</sup>	13.4
Unconfined compressive strength, kPa	312.04

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