Abstract

Stabilization of expansive soils with various calcium–based stabilizers (lime and cement) directly or in combinations with other solid waste materials such as fly ash and ground granulated blast furnace slag (GGBS) etc. is common approach by many foundation engineers to improve the properties, and conquer the distress caused by undesirable swell–shrink in the soil. Several researches have also been dedicated to understanding the complex ionic reactions and their products, and the mechanisms by which they affect the behaviour of expansive soils. Also, protocol for the lime stabilization of soil is established for the determination of optimum lime content (OLC) based essentially on the compressive strength test. The mechanism of lime treatment works mainly through cementation of flocculated matrix caused by the reduction in repulsion between soil particles with pozzolanic reaction compounds. However, no detailed studies have been carried out to establish the relation between change in fabric and its influence on the properties of expansive soil. It is also not clear whether the optimum lime content will be the same to improve different properties viz., strength and volume change. Hence, the research is directed to address these issues by performing elaborate experimental investigations on geotechnical properties and understanding the mechanism in improvement through fundamental physico–chemical and micro–analytical studies.

There are several cases documented in literatures where recent heaving and premature failures of structures constructed on lime and cement–treated soils containing sulfates exhibits, leading to question the validity of calcium-based stabilization. The failures in sulfate bearing soils are attributed to the formation and growth of ettringite/thaumasite minerals in certain environmental regime. It is Stabilization of expansive soils with various calcium–based stabilizers (lime and cement) directly or in combinations with other solid waste materials such as fly ash and ground granulated blast furnace slag (GGBS) etc. is common approach by many foundation engineers to improve the properties, and conquer the distress caused by undesirable swell–shrink in the soil. Several researches have also been dedicated to understand the complex ionic reactions and their products, and the mechanisms by which they affect the behaviour of expansive soils. Also, protocol for the lime stabilization of soil is established for the determination of optimum lime content (OLC) based essentially on the compressive strength test. The mechanism of lime treatment works mainly through cementation of flocculated matrix caused by the reduction in repulsion between soil particles with pozzolanic reaction compounds. However, no detailed studies have been carried out to establish the relation between change in fabric and its influence on the properties of expansive soil. It is also not clear whether the optimum lime content will be the same to improve different properties viz., strength and volume change. Hence, the research is directed to address these issues by performing elaborate

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Several remedial measures are adopted to control the sulfate induced heave in lime treated soil. Fly ash is often used to suppress this undesirable heave. Utilization of fly ash supplies additional pozzolans (silica and aluminium) with collection of adequate divalent and trivalent cations (Ca2+, Al3+, Fe3+, etc.). However, the effect of additional aluminium supplied by the fly ash on ionic reactions, particularly with ettringite formation in lime treated gypseous soil is not well understood.

It is interesting to know that gypsum is frequently used as an accelerating agent to improve properties of fly ash with lime. Hence, an attempt has been made to understand the role of fly ash on the properties of expansive soil treated with varying lime content and the same combination by using diminutive amount of gypsum with a view to find a solution to overcome the adverse effect of sulfate, particularly in the form of gypsum. Mechanism of the strength and volume change behaviour of soil treated with varying lime content in the presence of diminutive gypsum content are investigated and explained.

Though, fly ash has been recommended to control the sulfate induced heave in lime treated soil, no particular attention is given to quantify the amount of fly ash to suppress the heave. Also, the effect of intrusion of additional ions (silica and alumina), which are known to affect mineralogy and microstructure, altering the particle size by fly ash to soil is not understood. Hence, work is extended to compare and explore the effect of varying fly ash content on the behaviour of soil, lime treated soil and lime treated gypseous soil and deduce the mechanism through physico–chemical and micro–analyses studies.

Extensive studies carried on the above aspects are presented in the thesis in eight chapters. **Chapter 1** presents the relevant background and the scope of the works. **Chapter 2** describes different types of experiments and the methodologies adopted along with the sources of parent materials (soil, fly ash, lime and gypsum) used and their physical and chemical properties. The expansive soil (also named as Black Cotton soil in India) used in this study dominates with clay sized particles and montmorillonite minerals. Fly ash used in this study contains mullite and quartz minerals as predominant minerals and appears like spherical particles of different size. The physical properties of soil and fly ash are presented. Chemical additives such as hydrated lime and gypsum used are obtained from standard manufacturers.

Chapter 3 brings out the influence of varying amounts of lime on strength and volume change behaviour of the expansive soil after curing for different periods. It was found out that the OLC for the soil is about 6% as indicated by pH tests. Comparison of variation in the strength and volume change behaviour of the soil treated with lime content lower than OLC at shorter curing periods brings out that the formation of flocculated fabric and cation exchange, which occur immediately, significantly reduces the compressibility of soil but can only increase the strength marginally. Soil treated with OLC at longer periods of curing reveals that cementation of soil particles and filling with cementitious compounds of the voids of flocculated fabric in the soil marginally reduces the compressibility further but significantly increases the strength. Thus, the permeability of soil with OLC is less than with lower lime contents. The fabric changes and formation of cementitious compounds is supported by various micro–mechanistic and physico–chemical techniques. Thus, the mechanism of volume change behaviour of soil treated with lower lime content at shorter curing periods is distinct from that of the soil treated with OLC and after curing for different period.

Chapter 4 elaborates the change in the behaviour of expansive soil in the presence of varying percentage of gypsum and after curing for different period. The results show that the strength of soil deteriorates with higher gypsum content at both short term and long-term curing periods. Formations of zeolite and the presence of unreacted gypsum are mainly responsible for the reduction in strength of soil with increasing amount of gypsum. Swell of the soil increases with increase in gypsum content up to 2% but reduces with further increase in gypsum content. In both cases, the swell reduces with increase in curing period. Consequently, the compressibility of soil increases with increase in gypsum content and reduces generally with increase in curing period. Thus, minimal changes in the compressibility are observed for soil containing higher gypsum, particularly with increase in curing periods. It has been observed that increase in swell and compression in soil with lower gypsum is due to the formation of zeolite and weaker cemented matrix. However, the presence of unreacted gypsum particles in soil matrix and suppression of zeolite with formation of cementitious compounds reduce the swell and compression with higher gypsum and longer curing periods.

Chapter 5 scrutinizes the behaviour of lime treated soil with varying gypsum content after curing for different period. It is interesting to note that even though Atterberg's limits are only affected marginally, the strength behaviour 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 in the presence of varying gypsum content shows acceleration in strength gain. The strength after curing for 28 days declines but regains after curing for 90 days. The trend is not unique after curing period for longer periods of 180 and 365 days but varies with gypsum contents. An attempt has been made to explain these changes on the basis of formation and alteration of reacted compounds.

The results on the volume change behaviour of soil show that swell is observed on compacted samples immediately after inundating with water and is 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 aluminium–calcium–sulfate in the presence of water. 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 behaviour.

Attempts have been made to use fly ash to overcome the adverse effects of gypsum in the expansive soil with different lime contents and cured for different period. Studies carried out with 10% fly ash on soil treated with varying lime content and in the presence of 1% gypsum are elaborated in **Chapter 6**. It is interesting to note that significant increase in strength of soil–fly ash mix has only been observed with 6% lime and increase in curing periods. The strength variation is due to cation exchange and flocculation initially, and binding of particles with cementitious compounds formed subsequently with higher curing. Presence of 1% gypsum accelerates the strength of soil–lime–fly ash mix after curing for periods of 14 days. This is due to rapid formation of cementitious compounds and accommodation of ettringite crystal within voids. A decline in strength is observed after curing for 28 days but increased continuously with further increase in curing up to 365 days. The rearrangement of clay matrix and suppression of sulfate effects with formation of cementitious compounds are mainly responsible for the observed changes in strength.

It is also established that increase in lime content improves the volume change behaviour to soil–fly ash mix but leads to rapid increase in swell and increase in the compressibility in the presence of gypsum, particularly when the samples are not cured. Higher amounts of lime and curing periods are found to conquer the adverse effect of gypsum. The behavioural changes in swell and compressibility of specimens, with and without gypsum, have been attributed to the alterations in the microstructure by the formation of cementitious products and growth of ettringite crystal.

Efforts made to further improve the behaviour of lime treated gypseous soil with increasing amount of fly ash are reported in **Chapter 7**. The results revealed that gypsum leads to accelerate the strength of soil–lime–fly ash at shorter curing periods and acceleration in strength is significant with higher fly ash content. However, gypsum causes overall strength deterioration of soil–lime–fly ash which pronounces more with increase in gypsum content. In spite of strength deterioration, fly ash improves the strength of lime treated gypseous soil which generally increases with increase in fly ash content for any gypsum content of lime treated soil. In general, lower fly ash content appears beneficial for lower gypsum content and vice–versa, particularly at longer periods of curing.

It is noted that the swell in lime treated gypseous soil varies significantly with the amount of fly ash. The void ratio of lime treated soil increases drastically in the presence of gypsum for any particular fly ash content. Further, chemically induced pre–consolidation effect, and thereby, enhancement in vertical yield stress increases with addition of fly ash, leading to improve the compressibility behaviour of lime treated gypseous soil. Based on the volume change behaviour, it appears that 20% can be taken as Optimum Fly ash Content (OFC) for the suppression of sulfate induced heave in lime treated expansive soil. The relative dominance of change in gradation, formation of cementitious compounds and ettringite crystals of various aspect ratios and quantities significantly influence the strength and volume change behaviour of lime treated gypseous soil with fly ash.

Detailed conclusions of the studies are presented in **Chapter 8**.