A STUDY ON MITIGATING THE EFFECT OF SULPHATES IN LIME STABILISED COCHIN MARINE CLAYS

A Thesis

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Certificate

*Certified that this thesis entitled **"A Study on Mitigating the Effect of Sulphates in Lime Stabilised Cochin Marine Clays"**, submitted to Cochin University of Science and Technology, Kochi – 22, for the award of Ph. D. Degree, is the record of bonafide research carried out by Smt. Anitha G. Pillai, under my supervision and guidance at School of Engineering, Cochin University of Science and Technology. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship or other similar title or recognition from this or any other institution.*

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Declaration

*I, Anitha G. Pillai hereby declare that the work presented in the thesis entitled "**A Study on Mitigating the Effect of Sulphates in Lime Stabilised Cochin Marine Clays**", being submitted to Cochin University of Science and Technology for the award of Doctor of Philosophy under the Faculty of Engineering, is the outcome of the original work done by me under the supervision of Dr. Benny Mathews Abraham, Professor of Civil Engineering, School of Engineering, Cochin University of Science and Technology, Kochi-22. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship or other similar title or recognition from this or any other institution.*

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Abstract

Soft clays known for their high compressibility, low stiffness and low shear strength are always associated with large settlement. In place soil treatment using calcium-based stabilizers like lime and cement is a feasible solution to readdress strength deficiencies and problematic shrink/swell behaviour of unstable subgrade soils. Out of these, lime has been proved unambiguously as the most effective and economical stabilising agent for marine clays. Lime stabilisation creates long-term chemical changes in unstable clay soils to create strong, but flexible, permanent structural layers in foundations and other pavement systems.

Even though calcium-based stabilizers can improve engineering properties of soft clays, problems can arise when they are used in soils rich in sulphates. It is possible for marine clays to be enriched with sulphates, either by nature or due to the discharge of nearby industrial wastes containing sulphates. The presence of sulphates is reported to adversely affect the cation exchange and pozzolanic reactions of cement and lime treated soil systems. The anions of sulphates may combine with the available calcium and alumina, and form insoluble ettringite in the soil system. Literature on sulphate attack in lime treated marine clays reports that formation of ettringite in lime-sodium sulphate-clay system is capable of adversely affecting the engineering behaviour of marine clays.

Only very few studies have been conducted on soft marine clays found along the coastal belt of Kerala and that too, is limited to Cochin marine clays. The studies conducted also have the limitation that the strength behaviour of lime stabilised clay was investigated only for one year. Practically no data pertaining to long term adverse effects likely to be brought about by sulphates on the strength and compressibility characteristics of Cochin marine clays is available.

The overriding goal of this investigation was thus to examine the effectiveness of lime stabilisation in Cochin marine clays under varying sulphate contents. The study aims to reveal the changes brought about by varying sulphate contents on both physical and engineering properties of these clays stabilised by lime and the results for various curing periods up to two years is presented in this thesis.

Quite often the load causing an unacceptable settlement may be less than the load required to cause shear failure and therefore attempt has been made in this research to highlight sulphate induced changes in both the compressibility and strength characteristics of lime treated Cochin marine clays.

The study also aimed at comparing the available IS methods for sulphate quantification and has attempted to determine the threshold level of sulphate likely make these clays vulnerable by lime stabilisation.

Clays used in this study were obtained from two different sites in Kochi and contained sulphate in two different concentrations viz., 0.5% and 0.1%. Two different lime percentages were tried out, 3% and 6%. Sulphate content was varied from 1% to 4% by addition of reagent grade sodium sulphate. The long term influence of naturally present sulphate is also investigated.

X-ray diffraction studies and SEM studies have been undertaken to understand how the soil-lime reactions are affected in the presence of sodium sulphate.

Natural sulphate content of 0.1% did not seem to have influenced normal soil lime reactions but 0.5% sulphate could induce significant changes adversely in both compressibility and strength behaviour of lime treated clays after long duration.

Compressibility is seen to increase drastically with increasing sulphate content suggesting formation of ettringite on curing for longer periods. Increase in compression index and decrease in bond strength with curing period underlined the adverse effects induced in lime treated marine clays by the presence of sulphates. Presence of sulphate in concentrations ranging from 0.5 % to 4% is capable of adversely affecting the strength of lime treated marine clays. Considerable decrease is observed with increasing concentrations of sulphate. Ettringite formation due to domination of sodium ions in the system was confirmed in mineralogical studies made. Barium chloride and barium hydroxide is capable of bringing about beneficial changes both in compressibility and strength characteristics of lime treated Cochin marine clays in the presence of varying concentrations of sulphate and is strongly influenced by curing time. Clay containing sodium sulphate has increased strength values when either of barium compounds was used with lime as compared with specimens treated with lime only. Barium hydroxide is observed to remarkably increase the strength as compared to barium chloride, when used in conjunction with lime to counteract the effect of sulphate.

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Chapter 1

INTRODUCTION

Marine clays located in coastal and offshore areas of the world forms one of the important groups of fine grained soils and lots of civil construction activities take place in such marine clays throughout the world. Since these clays are characterised by low strength and high compressibility, the design and construction of many coastal and offshore structures in these deposits are confronted with many geotechnical problems. Such low strength and high compressible soils are generally associated with increased moisture content and they are weak in strength due to the presence of swelling clay minerals such as montmorillonite, vermiculite and chlorite.

It is prohibitively expensive to remove large volumes of unsatisfactory soils present at sites and replace them with more suitable material particularly, if it is to be transported for large distances. Therefore, much emphasis has been placed upon finding methods of modifying the properties of soils and improving their engineering behaviour.

This process is generally referred to as soil stabilization, and in its widest meaning comprises every physical, physico-chemical, and chemical methods employed to enable a soil to serve better its intended engineering purpose. Lime stabilization is one of the many processes available and is commonly resorted to improve the geotechnical properties of expansive and soft clays.

Lime, in one form or the other, has been used to modify the properties of fine grained deposits. References to the use of lime for improving soil go back several hundred years BC, when the Romans were constructing the pyramids of Shenshi (McDowell, 1959). The early Chinese used clayey gravels stabilized with lime for massive bridge footings. Other early uses were in India where lime-stabilized soil was used for making rough roads, and in the construction of masonry dams (Dahawan and Mehta, 1985). The addition of lime converts the soil into a rigid granular mass, the particles of which are strongly bound by pozzolanic cementitious compounds formed by reaction with soil silica and lime in the presence of water. The formation of these compounds, and hence the strength, increases with increased curing period. Many engineers all over the world have realized this advantage and hence, in many situations, lime is used to improve the soil characteristics in several civil engineering applications (Seco et al. 2011)

Greater Cochin area forms part of a coastal belt which was first uplifted and then partially submerged by sea water and is covered by thick marine clay deposits. Structures resting on these soils are subjected to distresses caused by large scale total and differential settlements. It has been proved conclusively that the most effective stabilising agent for marine clays in Cochin is lime. Lime stabilization reactions which result in the formation of inter-particle cementation bonds that improves the strength and reduces the compressibility of clay is well understood through several studies (Jose et al. 1987; Jose 1989)

In spite of advances in lime (calcium hydroxide) soil stabilisation techniques, it has been found that soluble sulphates, present in certain sulphate bearing soils, react with calcium hydroxide and free aluminium to form the water sensitive mineral ettringite ($3CaO. Al_2O_3.3CaSO_4.32H_2O$). Expansion due to the growth of ettringite in lime stabilised soils often produce severe problems, for instance, in construction and performance of pavement foundation systems.

Researchers worldwide have hence cautioned the use of lime in sulphate enriched environment or in marine clays containing sodium sulphate. The amount and type of sulphates present in soil, namely sodium sulphate or calcium sulphate, and the amount and type of clay mineral present are properties which play key roles in the post – stabilisation expansion developed over time in lime treated sulphate soils. Even though many investigators have brought out the adverse effects of the presence of sulphates in lime stabilised soils, a systematic study to understand the long term physical and engineering properties of soil in the presence of sulphates is highly desirable and not reported in the literature. The present study is aimed at understanding the long term effect of varying concentrations of sodium sulphate on the physical properties of two lime stabilised Cochin marine clays. The soil used for this purpose is marine clay containing 0.5% and 0.1% natural sulphate. Effect of lime stabilisation of bentonite – sand mixture in the presence of sodium sulphate is also studied. The experiments that were carried out, results obtained on the effect of presence of sulphates on the physical and engineering properties of soil and the remedial measures to counteract the detrimental effect of sulphates on long term strength and compressibility characteristics of lime stabilised sulphate bearing marine clays has been brought out in this thesis.

The contents of the various chapters in this thesis are briefly described below.

Chapter 2 presents a detailed review of the literature available on the investigations carried out by earlier researchers for understanding the behaviour of lime stabilised soils in sulphate enriched environment and based on this extensive review the scope and objectives of the present investigation has been brought out.

Chapter 3 describes the materials used, and the test procedures adopted. Sulphate content is one of the most important properties to be considered when evaluating the possibility of lime stabilisation of sulphate bearing clayey soils. The quantity of sulphates present generally dictates the extent to which ettringite will form. Simply, greater the content of soluble sulphates in soil, greater the potential for the growth of ettringite. The various methods available for quantification of sulphates has been described in this chapter. The soils used in this study are essentially naturally occurring marine clay with 0.5% and 0.1% sulphate and bentonite- sand mixture. The amount of lime added to these soils was usually 6%. However, the physical properties were determined for 3% and 6% lime content. Physical & engineering properties with the sulphate content varying from 0.5% to a maximum of 4% are presented in this thesis for the two types of soils considered. Details of method of mixing, preparation of samples and curing for various tests are presented. Amount of lime, other additives, their combinations, and curing period are projected in the experimental program in various chapters.

The long term effects of varying percentages of sulphate on the physical properties, grain size distribution and free swell index of marine clays containing sulphate stabilized with 3% and 6% lime is presented in **Chapter 4**. Variation in physical properties due to addition of barium compounds to mitigate the effect of sulphate is also brought out in this chapter. Barium compounds, in an amount effective to react with sulphates present in soils, thereby, decreasing the tendency of the lime stabilised soil to form ettringite was the basic principle adopted.

Chapter 5 deals with the effect of sulphate content on the compressibility characteristics of lime treated marine clays. Effects on the consolidation properties for various curing periods are presented in this chapter. Pre - cured samples were used for this study. Investigations were also carried out to understand the effect of treatment with barium compounds on the compressibility behaviour of the cured samples.

The variation in the unconfined compressive strength of lime treated marine clays with varying sulphate percentages is reported in **Chapter 6**. Apart from unfolding the negative effect on the strength, of sulphate containing soils on curing, attempt is also made to understand the effect brought about by addition of barium compounds on the long term strength of lime treated soils containing sulphate. Scanning Electron Microscopy (SEM) studies has been used to support the obtained results. The changes that occurred in the soil have been attributed to the formation of cementation compounds and these compounds have been identified by using X-ray Diffraction Technique (XRD).

The several conclusions arrived from the experimental investigations conducted are summarised and presented in **Chapter 7**.

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Chapter 2

REVIEW OF LITERATURE

Contents

2.1 Introduction

Extensive urbanization and industrialization in low land and coastal regions of many countries has necessitated improving very soft ground in its shear strength and compressibility so as to handle its stability and settlement problems. The ground improvement by chemical admixture such as lime or cement has been widely used for many years. Chemical stabilization with lime or cement is a ground improvement technique in which cementing agents are mixed with soft soil using mixing machine. In the presence of water, these materials react and produce cementing products that are responsible for ameliorating the engineering properties. Several investigators have shown that soil becomes more friable and the particle arrangement changes towards flocculation and clusters/aggregation after lime treatment. The improvements in the engineering behaviour of treated soil systems were mainly attributed to the aggregation effects (Ingles, 1962; Wild et al. 1989; Berube et al.1990). Nevertheless, literature also points out that lime treatment techniques should be approached carefully for clay containing a high percentage of sodium sulphate. Problems can arise when calcium-based stabilizers are used in soils rich in sulphate-bearing minerals. Stabilization of such soils in the presence of excess moisture may lead to the formation of minerals such as ettringite and/or thaumasite and can cause distress or even destruction of pavement structures due to heaving(Little and Nair, 2009; TxDOT, 2000)

2.2 Stabilisation with lime

Lime is formed by the decomposition of limestone at elevated temperatures. When lime is combined with water and the soluble silica and alumina present in clay, a chemical reaction occurs, resulting in the formation of new compounds. When combined with water, its primary function is alteration of particle structure and increased resistance to shrink-swell and moisture susceptibility. A secondary result is binding of particles (when combined with clay) and strength gain. There is no limitation in the specifications on the amount of time allowed to complete compaction. Traditional lime stabilization is defined as lime mixed into the soil and immediately compacted without allowing the lime/soil mixture to sit/mellow for an extended period of time before compaction (TxDOT, 2005)

Lime, in one form or another, has been used to modify the properties of fine grained deposits and use of lime as the soil stabiliser dates back to the Roman period. (Broms and Boman, 1975; Okumura and Terashi, 1975; Bell, 1988a, 1988b; Locat et al. 1990, 1996). Usually hydrated lime is used as stabilising agent since quick lime is very sensitive to high humidity. Use of hydrated lime as a stabilising agent will generate two processes, i.e., modification and stabilisation. Dry mixing method is used in preparation of lime stabilised samples to achieve maximum efficiency.

Lime stabilisation is commonly resorted to in order to improve the strength and reduce the compressibility of weak clay deposits. Researchers have illustrated that the lime addition on strength of clay soils depends on several factors. These include soil type, curing time and method, moisture content, and soil unit weight and time elapsed between mixing and compaction. The safety of a structure is influenced by the soil compressibility as much as by the shear strength. One of the benefits of lime stabilisation is that it imparts a yield stress to the clay soils.

The beneficial effects due to lime reactivity with the soil were brought out by many investigators. Treatment of soils with lime has brought many beneficial effects, such as improvements in the plasticity characteristics and strength behaviour with time (e.g., Kamon, 1992; Rajasekaran and Narasimha Rao, 1996).

It is well established that the use of lime in fine-grained soils makes the system less sensitive to changes in stress and other environmental factors (Kamon and Nontananandh, 1991; Sivapullaiah et al. 1998).

The lime-soil mechanisms include cation exchange capacity, flocculation, and/or aggregation and pozzolanic reactions. Thompson (1966) reported the application of lime stabilization for soils in Illinois, U.S.A. These results suggested that the plasticity, compressibility and the strength properties are improved by lime treatment.

The work of Diamond and Kinter (1964) showed that the formation of cementation compounds was mainly responsible for the improvement in the soil behaviour.

Ingles and Metcalf (1972) suggested that lime reacted with the clay minerals of the soil to form a tough water-insoluble compound (calcium silicate), which could cement the soil particles.

2.2.1 Mechanism(s) involved in lime treated clay

The major strength gain of lime treated clay is mainly derived from three reactions namely: hydration of soil, ion exchange, and pozzolanic reaction. Other mechanisms such as carbonation cause minor strength increase and can be neglected. Short term reaction includes hydration (for quicklime) and flocculation (cation exchange). Longer term reactions are cementation and carbonation. The use of lime as a stabilizing additive is mainly due to its well-known effects when mixed with soils. The natural stabilizing agent for cohesive soils is calcium hydroxide, hydrated lime or slaked lime. Calcium hydroxide is not itself a binder, but will produce a binder (consisting of calcium silicate hydrates) by slow chemical reactions principally with the silicates in the clay mineral of cohesive soils.

A large amount of heat is released when quicklime (CaO) is mixed with soil. This is due to the hydration of quicklime with the pore water in the soil. The increase in the temperature can, at times, be so high that the pore water starts to boil as shown in equation 2.1 (Broms, 1987). An immediate reduction of natural water contents occurs when quicklime is mixed with cohesive soil, as water is consumed in the hydration process.

$CaO + H_2O \rightarrow Ca(OH)_2$ + Heat (280 cal/gm of CaO) 2.1

The calcium hydroxide, $Ca(OH)_2$, from the hydration of quicklime or when using calcium hydroxide as stabilizer, dissociates in the water, increasing the electrolytic concentration and the pH of the pore water, and dissolving the SiO_2 and Al_2O_3 from the clay particles.

$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^-$ 2.2

(ionization of calcium hydroxide; pH rises to 12.4). These processes will result in ion exchange, flocculation and pozzolanic reactions.

2.2.2 Predominant factors controlling the strength of lime stabilized clay

There are many factors that control the strength development of lime stabilized clay. The main factors have investigated by the previous research such as water content, clay mineral, type of soil, organic matter, sulphide, diatom, curing time, curing temperature, type and content of lime, soil pH etc.

i) Water content

In the case of low water content clay, the water content is not the main influence because it is applied at approximately optimum moisture content. On the other hand, the water content is a predominant factor on strength of lime stabilized high water content clay. The relationships between shear strength and water content; at any quicklime content follow a power law (Locat et al. 1990).

ii) *Clay mineral*

Clay mineral has been found to be a major factor in soil-lime stabilization. Montmorillonite and kaolinite clay respond better to lime than illitic and chloritic clay. The dominant halloysite clay attains lower strengths than any other type (Koslanant et al. 2006)

iii) *Type of soil and organic matter*

For lime treatment to be successful, the clay content of the soil should not be less than 20% and the sum of the silt and clay fractions should preferably exceed 35%, which is normally the case when the plasticity index of the soil is larger than 10 (Broms, 1984). The shear strength increase of the stabilized soil is highly dependent on pozzolanic reaction, i.e., the reactions of lime with silicates and aluminates in the soil. The increase in strength with time is in general highest for normally consolidated silty clays, with low plasticity index and low water content. The strength increase in lime treated organic soils is often very low; even a relatively small amount of organic material can have a large effect on the strength increase (Broms, 1984). Generally, the effect of lime decreases with increasing water content (Miura et al., 1988).

2.3 Effect of lime on the physical and engineering properties of clays

i) *Liquid limit*

Some researchers report decrease in the liquid limit on addition of lime (Wang et. al., 1963; Jan and Walker, 1963), but others report that this parameter may increase substantially (Clare and Cruchley, 1957;

Zolkov, 1962). Both increase and decrease in liquid limit of soils also have been reported by different investigators (Woods and Yoder, 1962; Lund and Ramsey, 1959; Taylor and Arman, 1960). The reduction in the liquid limit has been attributed to the depression of double layer and (i) to form clusters and which will reduce the rigidity of the held water and (ii) to the formation of aggregates. Normally reduction in liquid limit takes place on the addition of lime in montmorillonitic clays and the liquid limit increases in kaolinitic clays (Sridharan et. al. 1997 and Sivapulliah et al. 1993).

ii) Plastic limit and plasticity index

While the liquid limit can decrease or increase on addition of lime, plasticity index usually decreases immediately on addition of lime. Thus, lime addition improves workability. However, the pozzolanic reactions influence the plasticity index and the mechanism involved for the changes has not been well recorded. Very small quantities (1% to 3%) of lime are required to bring about the changes in plasticity. However, increase in plasticity index has been reported for Kaolinitic soils (Anon, 1975). Immediately on addition of lime, the plastic limit of soils increases. This increase depends on the amount of lime added up to "lime fixation point" with no additional changes on further addition beyond lime fixation point. The amount of lime that is necessary for a complete lime fixation of the clay was usually found to be correlated with the clay content of the soil.

$$L_m = \frac{\text{percentage of clay fraction}}{35} + 1.25$$

The increase in the plastic limit for various clayey soils changes in the order (Mateos, 1964).

Montmorillonite>Illite> Kaolinite

The Changes in plasticity are a function of time, although eventually there will be an equilibrium condition.

iii) Shrinkage properties

The shrinkage characteristics of clayey soils can be improved greatly by addition of lime. With about 8% addition of lime, all types of limes cause similar increase in the shrinkage limit. Increase in shrinkage limit and decrease in the shrinkage void ratio clearly indicate that the soils shrink less upon drying (Mateos, 1964).

iv) Strength and strength parameters

On addition of lime, generally the strength for most of the soils increases immediately and increases further with curing. Immediate strength gain can be observed in soil stabilized with lime as shown in Fig. 2.1 (Thompson, 1970). Apart from immediate short term strength gain, there is long term strength gain also, which is dependent on the mineralogical properties and soil conditions. The strength of the lime - soil mixture is influenced by several factors, such as soil type, type and amount of lime added, curing time and method, moisture content, unit weight and the time elapsed between mixing and compaction (Ingles and Metcalf, 1972).

Montmorillonitic clay gives lower strength with dolamitic lime [$Ca(OH)_2$+ MgO] than with high calcium lime or semi-hydrated lime. On the other hand, kaolinitic clay gives higher strength with semi-hydrated lime and lower strengths are obtained with high calcium lime. Montmorillonitic and kaolinitic clays give higher strengths with lime than illitic and chlorite clays. Expansive clays respond more quickly to strength increase, although the final strength achieved is greater in kaolinitic clays. The 28 days strength decreased in kaolinitic soils progressively as the clay content increased, whereas the converse occurred in montmorillonitic soils. There is no significant correlation between clay content and lime reactivity of soils except for montmorillonite + mixed layer clay content (Thompson, 1966).

Soil mixed with low lime content attains maximum strength in less time than with higher lime contents. Strength does not increase linearly with lime content and in fact, excessive addition of lime reduces the strength.

Strength increases rapidly in the first seven days of curing and beyond this period the rate of increase in strength is very slow. This indicates the formation of cementitious compounds due to soil – lime reactions at an early stage.

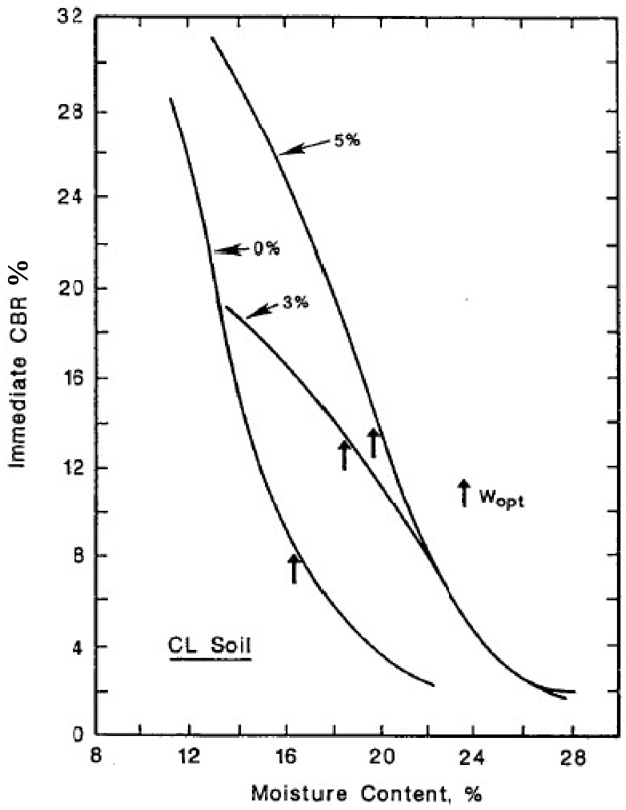

Fig. 2.1 CBR moisture content relationships for natural and lime treated ML soil (Thompson, 1970)

Higher temperatures accelerate the curing process giving higher strength. If the temperature is less, lime-soil reactions are very slow. Pozzolanic reaction retards when temperature is below 40°C. Higher relative humidifies favourable for lime soil reactions. Strength development retards or ceases in cold weather. After the winter period, lime soil reactions continue and go as long as free lime is available in the system.

v) *Compaction characteristics*

The unconfined compressive strength of lime treated soils varies depending on the moisture condition of the soil. It is desirable to mix lime on the wet of the optimum moisture content. But lime treatment changes the maximum dry density on addition of lime. The maximum dry density decreases by about 6% on addition of lime (Rogers, 1988). Lime treatment usually flattens the compaction curve. This gives the advantage that density can be achieved over a wide range of water content. Also, optimum moisture content increases on addition of lime and reduces the dry density at the same compactive effort. The decrease in density depends on the amount of lime added and the type and amount of minerals present. Optimum moisture content increases with increase in clay content and reduce maximum dry density. However, Croft (1964) found out that for Kaolinitic soils maximum dry density increases. A noticeable decrease in dry density occurs with increase in time intervals between mixing and compaction. The maximum dry density occurs at higher water contents. (Bell, 1988b).

Strength of lime stabilized soil depends on their moisture contents, decreases with increase in moisture content. Lime soil mixture compacted on wet of optimum moisture content gives higher strength, after a brief period of curing than on dry of optimum moisture contents. This is because of diffusion of lime into soil is more homogeneous.

Clay – water - electrolyte system induces attractive and repulsive forces, called as inter- particle forces. The net attractive force imparts cohesive strength to the soil. Force due to cementation is also called as cohesive part of strength.

2.4 Effect of sulphate on lime stabilised soils

Even though lime treatment is commonly resorted to improve the geotechnical properties of expansive clays and soft clays it has a detrimental effect on soil behaviour if adequate amounts of sulphate are present in soil. Sulphate induced heave of soils stabilized with calcium-based stabilizers occurs due to the presence of primary and secondary sources of sulphate in soils. The occurrence of native sulphate in natural soils constitutes primary sulphate source. Sulphates present in construction wastes, industrial wastes and spilled chemicals constitute the secondary sulphate source, (Rao et al. 2005).

Sulphate occurrence is not normally uniform but rather exists in seams and stratified pockets (Little, 2009).

Sherwood (1962) observed that cracking and swelling in specimens of heavy clays stabilised with 10% lime and cured at constant moisture content for one week when immersed in solutions of either sodium sulphate or magnesium sulphate at concentrations below 1.5% as SO_3. He attributed this due to the reaction between clay fraction and sulphate. This is more likely to occur when the soil contains appreciable clay fraction and when the moisture content of the soil is liable to increase above that at which it is compacted. At other circumstances, sulphate may appear to have beneficial effect.

Hunter (1988) indicated that lime treated sulphate bearing clay is risky even at relatively low sulphate concentrations.

Studies on cement and lime treated soils has showed swelling and pavement failures due to the formation of high swelling minerals such as ettringite and thaumasite (Mitchell, 1986; Hunter, 1988; Rajasekaran, 1994).

Ettringite formation is a complex phenomenon and there are many controversial issues regarding its stability with time (Rajasekaran, 1994).

Before the application of lime stabilisation techniques, it is essential to understand the nature of sulphates present in the soils, soil–lime reactions, mechanisms involved in ettringite formation and its related problems. It is necessary to examine the nature of lime stabilised soils and the adverse conditions of ettringite formation. Limited information is available on ettringite formation in sulphate enriched marine clays (Rajasekaran, 1994; Rajasekaran et al. 1997).

In sulphate enriched environments, cation exchange reactions influence the Atterberg limits and compaction characteristics of lime treated Kaolinitic clays (Kinuthia et al. 1999). The rapid formation of ettringite affects the clay properties, including its consistency and compaction characteristics and also influences the cation exchange processes. The addition of gypsum and magnesium sulphate lowered the liquid limit as well as the plasticity index values of lime – treated Kaolinite (Rajasekaran et al. 1997). However the presence of small levels of sodium sulphate lowered the liquid limit and plasticity index values but at greater concentrations; no further changes in the Atterberg limits occurred.

The pozzolanic reactions involved in the formation of ettringite results in swelling as reported by Hunter (1988), Mitchell and Dermatas (1992). Sherwood (1993) clarified that, due to swelling, the presence of sulphates in soils decreases the strength.

The various problems associated with lime–soil reactions due to sulphates depends on the type and solubility of sulphate, the sulphate concentration, and the clay content as reported by Litteton (1995).

Sherwood (1993) explained that the presence of sulphate in soils induces detrimental effects to materials strength due to the swelling. The various problems associated with lime–soil reactions due to sulphate environment depends on the type and solubility of sulphate, amount of sulphates present and clay content as reported by Littleton (1995). Sridhran et al. (1995) reported that the presence of sodium sulphate in the soil system converts lime into insoluble gypsum and sodium hydroxide (equation 2.3) and thus reduces the lime available for the reactions with soil. However, the presence of sodium hydroxide increases the pH, and thus the dissolution of silica from the soil.

$Ca\ (OH)_2 + Na_2\ SO_4 \rightarrow Ca\ (SO)_4 + 2\ NaOH$..................................... 2.3

The formation of these compounds is confirmed by Kujala, 1983 and Mitchell, 1986). These compounds have large affinity to water and expand. This can have adverse effect on soil properties. The effect of alteration of soil – lime reactions on the strength of lime treated montmorillonite has been brought out by Sivapullaiah et al. (2000). It was shown that the stress – strain curves and effective stress paths of montmorillonitic soil exhibited the behaviour of normally consolidated soil rather than cemented soil. The rate of formation of soil lime reaction products depends on several factors and the type of soil plays a significant role. Thus the effect of sulphate can also vary depending on soil type.

When lime is added to soil, pozzolanic reactions take place to form Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH). But when soluble sulphate is present in the soil in high concentrations; it reacts with calcium from lime and alumina from soil to form calcium-aluminate-sulphate-hydrate (CASH). If the concentration of sulphate is not very high, then monosulphoaluminate may form instead. The growth of calcium-aluminate sulphate-hydrate is harmful because of the high volume expansion (Natarajan, 2004).

The adverse effects produced in monovalent sulphates enriched soils are severe especially in sodium sulphate system, whereas divalent and higher valent sulphates enriched soil systems do not produce any adverse effects (Rajasekaran, 2005).

In an experimental work conducted by Rajasekaran et al. (2002) to study the effect of soil – lime reactions on the permeability of soft marine clay especially in salt water environment it has been reported that quicklime – sodium sulphate column treated soil system indicates a lower strength improvement which may be due to the excessive diffusion and domination of sodium (Na^+) ions. With the addition of sodium compound, the crowding of monovalent sodium cations around the particles cannot be avoided. Further, there is a possibility that sodium sulphate reacts with clay minerals and form ettringite which weaken the system with time.

2.4.1 Soil – lime – sulphate reactions

The lime - soil reactions have been classified as short term and long term reactions by many investigators (Brooms and Borman, 1975; Okamura and

Terashi, 1975; Rajasekaran, 2005). Short term reactions consists of flocculation, lime migration, pH, cation exchange reactions, carbonation and these reactions affect the physical properties of the soil such as Atterberg limits and grain size distribution. The long term reaction is the pozzolanic reaction which includes the formation of various reaction products resulting in the growth of aggregates and affect the strength and compressibility of clays. Various factors that influence lime treated soil properties are cations, concentration of sulphates and clay mineral composition (available alumina and silica). The anions of sulphate combine with the available calcium and alumina and form insoluble ettringite in the soil system. The formation of ettringite increases the porosity and simultaneously decreases the free moisture content during ettringite nucleation and its subsequent growth (Sivapullaiah, 2011).

Depending on the chemical environment, the lime stabilized material characteristics can be affected with time, and it may deteriorate the strength of treated soil systems. The addition of lime in sulphate containing soil certainly increases cation exchange, i.e. calcium ions concentration, but not to the expected level since some portion of calcium has been leached away or tied up with insoluble minerals. The above compounds formation does not affect the soil–lime reactions such as cation exchange, agglomeration and carbonation except long term pozzolanic reaction. Hence, the sulphate induced heave in lime treated soil should be observed for long duration (Rajasekaran and Narasimha Rao, 2005).

2.4.2 Ettringite formation

Ettringite is a hydrous calcium alumino-sulphate mineral that precipitates in environments with high pH and high sulphate activity (Perkins and Palmer, 1999). Ettringite often forms when a calcium-based stabilizer is added to sulphate-bearing clay soils (Mitchell, 1986). The formation of ettringite during lime stabilisation of cohesive soils is shown in Figure 2.2.

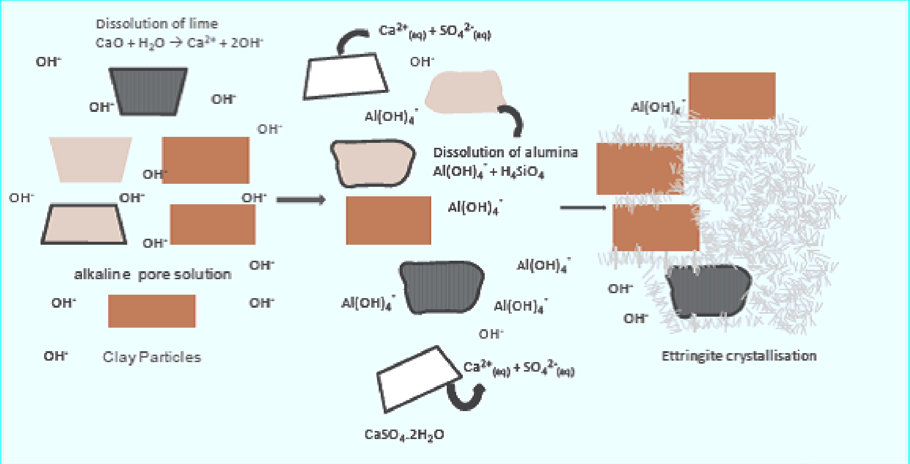

Fig. 2.2 Ettringite formation in lime stabilised cohesive soils (Buttress, 2013)

Ettringite, which tends to form very small (µm), fibrous crystals (Fig. 2.3) damages the soil structure through mineral expansion during its precipitation (Moore et. al., 1970).

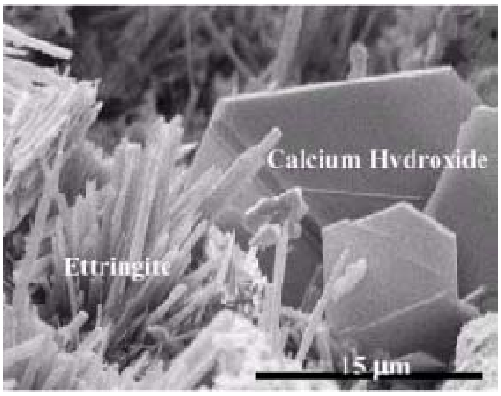

Fig. 2.3 Fibrous crystals of ettringite

In the absence of sulphate, the reactions between lime and soil in the presence of water produce calcium silicate hydrates and aluminate. The amount of compounds formed increases with time. In the presence of sulphate, the modified reactions lead to the formation of ettringite/ or thaumasite. The sequence of geochemical reactions as simplified by Hunter (1988) for lime induced heave is as follows:

$CaO + H_2O \rightarrow Ca(OH)_2$ (Hydration of quicklime)

$Ca(OH)_2 \rightarrow Ca^{2+} + 2\,(OH)$ (Ionization of calcium hydroxide; pH rises to 12.3)

$6Ca^{2+} + 2Al(OH)^-_4 + 4(OH)^- + 3(SO_4)^{2-} + 26H_2O$

$\rightarrow Ca_6[Al(OH)_6]_2 . (SO_4)_3 . 26H_2O$ (formation of ettrigite)

$Ca_6[Al(OH)_6]_2 . (SO_4)_3 . 26H_2O + 2H_2SiO_4^{2-} + 2CO_3^{2-} + O_2 \rightarrow Ca_6[Si(OH)_6]_2 . (SO_4)_2 . (CO_3)_2 . 24H_2O + Al\,(OH)_4^- + SO_4^{2-} + 4OH^- + 2H_2O$ (Isostructural substitution as ettringite changes to thaumasite)

X-ray diffraction (XRD) and scanning electron microscopy (SEM) can be used as vital tools to identify the formation of ettringite in the stabilized materials (Rajasekaran, 2005). The formation of needle shaped ettringite in sulphate dominated lime treated systems has been reported by few investigators. The formation of ettringite in the sulphate contained lime–kaolinite (Tsatsos and Dermatas, 1998), and quicklime–sodium sulphate soil systems can be seen in Figs. 2.4(a) and 2.4(b), respectively (Rajasekaran, 2005).

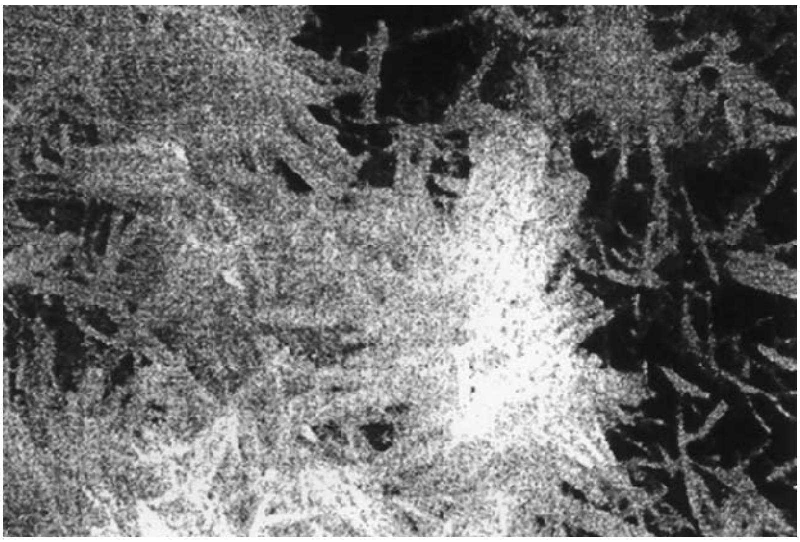

Fig.2.4(a) Ettringite formation in koalinite–lime system (after 6 months curing) (Rajasekaran, 2005)

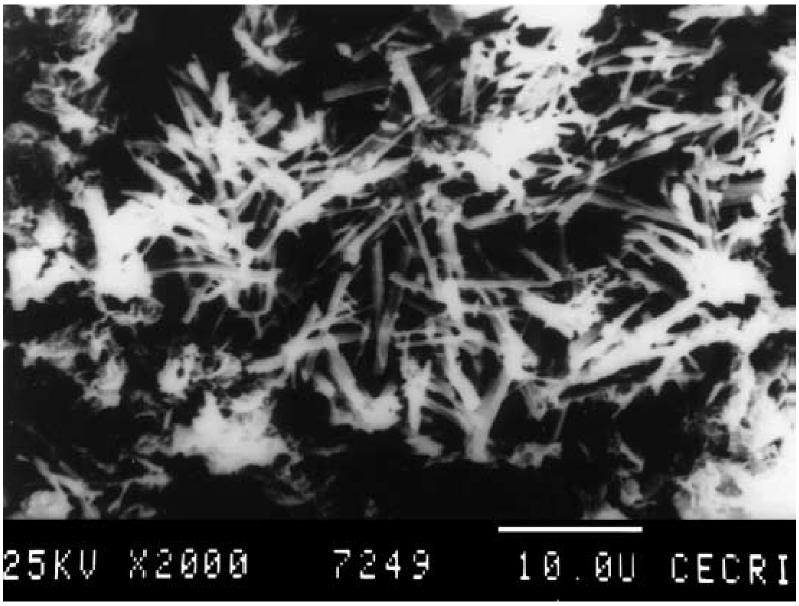

Fig.2.4(b) Ettringite formation in quicklime–sodium sulphate treated marine clay (after 45 days treatment) (Rajasekaran, 2005)

2.4.2.1 Factors influencing ettringite formation

i) pH

The pH of soil system increases in the presence of lime. At higher pH above 9, silica and alumina are dissolved (Rajasekaran, 1994). Lime reacts with the dissolved silica and alumina in the presence of high alkaline environment thereby forming ettringite.

ii) Moisture content

The formation of ettringite is encouraged in the presence of moisture content.

iii) Temperature

Several investigators have shown that temperature plays an important role in ettringite formation. (Mehta and Klien, 1966; Hunter, 1988; Mitchell and Dermatas, 1992). The rate of ettringite formation and swelling would be greater at higher temperatures. (Rollings et al. 1999).

iv) Clay content and sulphate level in soil

The percentage of clay present in the soil has great impact on sulphate induced heave of lime stabilised soils. Loss of strength was insignificant in the soil specimens containing less clay content (Sherwood, 1982). It has been reported about significant swelling in bentonite – lime system even in the presence of low level of sulphate (Raja, 1990).

Hunter (1988) reported that lime-treated sulphate bearing clay swelled and disintegrated after a few years when used for road construction.

Sridharan et al. (1995) have shown that the presence of sulphate increases the compressibility of lime treated black cotton soil after curing for long periods.

Raja (1990) reported that sulphates present in the calcium bentonite affect the physical as well as engineering behaviour of the soil. His results indicated an increase in liquid limit (20–25%) and compression index values (from 2.7 to 3.3) of the soil.

2.4.3 Ettringite in marine clays

Oceans consist of 70% of earth, and it is enriched with various natural minerals such as soil, gas, manganese nodules etc. (Poulos, 1988). The necessity to tap these marine resources has recently increased the construction of structures either at the offshore or onshore. However the hostile wave conditions, presence of large depth of water and weak marine clays at the potential locations pose severe foundation problems (Rajasekaran et al. 1999). The application of deep lime mixing technique to improve the behaviour of marine clays either lime column or lime grouting is not new (Okumura and Terashi, 1975; Rajasekaran, 1994; Rao et al. 1992; Rajasekaran and Narasimha Rao, 1996). The presence of sodium sulphate in lime treated marine clay affects the properties of soil system, whereas the presence of gypsum (calcium sulphate) improves the marine clay properties (Rajasekaran and Narasimha Rao, 1996; 1988 a, b, c; Narasimha Rao and Rajasekaran, 1996; Rajasekaran and Narasimha Rao, 1998 a–c). Also, the marine clays are sometimes enriched with sulphates due to the discharge of nearby industrial wastes containing sulphates or by nature. Hence it is essential to study the sulphate induced changes on the lime treated marine clays.

Lime–soil reactions can be classified into short term and long term reactions. Short term reactions include flocculation, lime migration, pH and cation exchange reactions, carbonation, and the above reactions affect the physical properties of the soil system such as Atterberg limits and particle size distribution. Whereas, the long term pozzolanic reactions include the formation of various new reaction products, which result in the growth of aggregates and affect the strength and compressibility of clays (Rajasekaran, 2005).

Cation exchange reactions influence the Atterberg limits and compaction characteristics of lime treated kaolinite clay containing sulphates (Leroueil and Le Bihan, 1996).

2.5 Cochin marine clays and its stabilisation with lime

The Port city of Cochin, the queen of the Arabian Sea, has been witnessing phenomenal growth over the last few decades. Increasing population, housing and construction of various facilities have been a problem with urbanization worldwide, and Cochin is no exception. Most of the industries of the state are situated in and around Cochin making it the commercial capital of Kerala. Heavy industrial structures and high rise buildings have sprung up in and around Kochi during the last two decades. In early days, areas having clay deposit were avoided for construction. But depleting land has necessitated construction activities along the coastline, covered with thick soft clay deposits, which has always posed challenging problems to foundation engineers. Studies on the nature and engineering behaviour of this soft clay covering long stretches of coastal line and methods to improve their geotechnical properties have been thus of great relevance.

Cochin marine clays are seen to possess high liquid limits (83 – 175 %) with their natural water contents marginally less. The high shrinkage limit (≈20) indicates the existence of relatively flocculant fabric (Jose et al. 1988).

Poor shear strength and extremely high compressibility of Cochin marine clays pose many problems to the geotechnical engineers. Structures resting on these soils are subjected to distresses caused by large scale total and differential settlements. Embankments and highways also face problems from the poor strength characteristics of these clays. Hence it is imperative that the strength characteristics of these soils are improved through stabilisation before the commencement of any construction (Jose et al. 1987).

Jose et. Al. (1991) reports that17 stabilizing agents were tried on moist samples of Cochin marine clays, viz., 1. Sodium hydroxide, 2. Sodium chloride, 3. Sodium silicate, 4. Potassium hydroxide, 5. Potassium chloride, 6. Potassium dichromate, 7. Ferric chloride, 8. Calcium chloride, 9. Calcium carbonate, 10. Calcium sulphate, 11. Sodium carbonate, 12. Sodium hexametaphosphate, 13. Potassium permanganate, 14. Magnesium chloride, 15. Aluminium chloride, 16. Lime, 17. Cement. These additives were mixed with moist soil by 6% of weight. The shear strength of treated marine clays showed that out of the seventeen additives tried, lime and cement showed impressive gains in strength. Even though stabilization with cement showed promising results, consistent results with cement can be obtained only after successful standardization of the additive. Thus lime showed the highest potential as a stabilizing agent for Cochin marine clays.

The physical properties get significantly influenced with the addition of lime. As curing time increases, the liquid limit and shrinkage limit increase, indicating that the soil becomes more flocculant. A reduction is also noted in the clay size fraction. One of the difficulties experienced in the study of lime treated soils is the large number of specimens that are to be prepared and kept for curing (Jose et al. 1987).

Consolidation settlements of marine clay deposits can be drastically cut down by lime treatment (Jose et al.1987).

Significant improvement is noticed both in strength and compressibility characteristics and they are strongly influenced by the curing time. The investigation indicates that about 6% lime seems to be optimum from economic considerations (Jose et al. 1991). As lime content increases, the curing period required for the development of maximum shear strength also increases.

2.6 Scope and objectives

Lime–soil reactions can be classified into short term and long term reactions. Short term reactions include flocculation, lime migration, pH and cation exchange reactions, carbonation, and the above reactions affect the physical properties of the soil system such as Atterberg limits and particle size distribution. Whereas the long term pozzolanic reactions include the formation of various new reaction products, which result in the growth of aggregates and affect the strength and compressibility of clays. (Rajasekaran, 2005).

In the technical memorandum (2000) put forward as guidelines for stabilization of soil containing sulphates a brief background explaining the scope of the problems associated with sulphate bearing soils when stabilized, has been presented. Practical explanation of the reactions, which results in distress in sulphate soils, stabilized with lime and other calcium-based stabilizers also have been presented. The memorandum stresses the need regarding more careful attention to testing, mix design, construction and quality control required when dealing with sulphate bearing soils. The memorandum reports that if the total level of soluble sulphate is below 0.3% by weight of soils then lime stabilization should not be of significant concern. Total soluble sulphate levels between 0.3% and 0.5% is of moderate concern and total soluble sulphate levels between 0.5% and 0.8% represents moderate to high risks and in levels greater than 0.8% are generally of high risk to stabilize with lime.

Though extensive studies have been conducted on the physical and engineering properties of lime treated Cochin marine clays, they have the limitation that the strength behaviour of lime-stabilised clay was investigated only for one year and the samples studied had no natural sulphate content. Results pertaining to long term effects on the physical, strength and compressibility characteristics of marine clays in the presence of sulphates thus are not available. No data pertaining to the threshold level of sulphate, at which Cochin marine clays can begin showing variations in already gained strength after stabilisation with lime, is available. Hence a systematic long term study to understand the influence of sulphate on lime treated Cochin marine clays will provide a guideline for application of lime, rather than just going by the fact that one has to cautiously adopt lime stabilisation techniques in sulphate enriched environment.

Though it has been proved that soil-lime reactions are altered in the presence of sulphate (Sivapullaiah et al. 2006), no data is available on the effect of presence of sulphate on the physical and engineering properties of lime treated Cochin marine clays with time.

Rajasekaran (2005) has reported a comprehensive list of work carried out by several researchers on clays and soils treated with lime in various parts of the world and the safe criteria of sulphate levels for application of lime, suggested by quite a few investigators. These levels vary greatly for different soils from different areas and hence there is a need to understand the effect of varying sulphate percentages on clays treated with lime in this part of the world.

Raja (1990) reported the successful use of barium chloride to reduce the swelling characteristics of lime treated calcium bentonite. The addition of barium compounds prior to lime treatment was reported by Ferris et al. (1991). The use of barium hydroxide in lime–kaolinite–sulphate mixture eliminates the ettringite formation as reported by Tsatsos and Dermatas (1998).

Hence it is proposed to study the effectiveness of lime stabilisation as resorted to in clays containing sulphate and to identify the threshold level of sulphate likely to cause damages in Cochin marine clay. Clay samples were obtained from two different sites containing two different percentages of natural sulphate. The study focuses mainly on evaluating the long term influence of natural sulphate present in clays as well the effect of varying concentrations of sulphate on the physical and engineering properties lime treated Cochin marine clays. It is also proposed to study and understand the effect of barium compounds in mitigating the deleterious long term effect of sulphate on lime treated marine clays.

* * *

Chapter 3

MATERIALS AND METHODS

Contents

3.1 Introduction

The details of clay samples and the various additives used along with the procedures of various tests conducted are presented in this chapter.

3.2 Materials

3.2.1 Cochin marine clay

The results reported in this chapter are from studies conducted on marine clays collected from Panampilly Nagar and Kaloor separated by about 27 km, located in Cochin. The depth at which marine clay deposits, usually overlain by loose sandy soils, found in these areas, varies from 2m to 9m, and in Panampilly Nagar and Kaloor, thick deposits of marine clays are encountered at about 4m to 5m from ground level. At both sites clay was collected from a depth of 7m to 9m by augering from bore holes whose sides protected by casing pipes. The samples were thoroughly mixed to obtain a uniform mass and transferred into polyethylene bags, sealed and stored without loss of moisture.

3.2.1.1 Geology of the origin

The geotechnical features of any soil mainly depend on the geology of the region. The soil deposits are predominantly brought by various rivers from the Western Ghats into the Arabian Sea. Earlier studies carried out by King (1884) established that the coastal line of Kerala was originally further east, almost at the foot of the laterite and gneissic surface between Cochin and Varkala. A basin of lagoons was formed all along the coastal line, the largest of which is Vembanad Lake. The bore hole data of the soil profile taken along the coastal area on the west coast of Vembanad Lake have shown that soft clay deposits of considerable thickness were occurring below the sand layer and these deposits are less soft than those in the east. Also, the geotechnical investigation carried out around the Cochin area clearly indicates that the soil deposits are of underconsolidated clays deposited in a partially marine environment (Rajasekaran et al. 1994).

3.2.2 Lime

Specially selected uniform shells were used for the preparation of the stabilising agent. The shells were burnt to remove CO_2 completely when they change to brittle white shells of calcium oxide which were preserved in air tight multilayer polyethylene bags. Just sufficient water was sprinkled over the lime shells taken from these bags, on each day till all the shells crumble to fine powder which was then sieved through IS 425 microns sieve. This method of preparation of lime was used because of its simplicity and ease with which it can be prepared for field application.

3.2.3 Other additives

Presence of sulphate has been reported in the literature as harmful for lime stabilisation. From fundamental chemistry point of view, the effect of sulphate can be countered by converting the sulphate from soluble or sparingly soluble form to almost insoluble form. This can be accomplished by addition of soluble salts like barium chloride (Ferris et al. 1991; Ramesh, 1993 and Rajasekaran et al. 2005).

Sulphates occur in soils in the form of sparingly soluble calcium sulphate. Sodium and magnesium sulphate usually occur in clayey soils since gravel and sands are leached free from soluble constituents by percolating waters (Ramesh, 1993).

Magnitude of the effect of sulphates on consistency values followed the series such as $Ca^{2+} < Mg2^{+} < K^{+} < Na^{+}$.

Literature available on lime stabilisation of Cochin marine clays, has not studied whether or not sulphates are present in these clays, and if present at what concentrations? Reports available does not also throw light on deleterious influence of these sulphates on the stabilised material.

Extensive study on effect of varying concentrations of sodium sulphate on the physical and engineering properties of clay which contains 0.5% natural sulphate has been presented in this thesis.

No definite conclusions have been reached regarding the critical sulphate levels which cause swelling. Rajasekaran and Rao (2005) has further summarised, available literature on the effect of varying percentages of sulphate on field and laboratory tests conducted worldwide and has reported that even a sulphate content of 0.03 to 0.05% in soils can be harmful for treatment with lime, though it is not very common.

TxDOT, 2005 reports that, if the total level of soluble sulphates is below 0.3%, then lime stabilization should not be of significant concern at all. Studies where hence extended on clay with natural sulphate content lower than 0.3%, obtained from Kaloor.

Two different barium compounds, barium chloride and barium hydroxide have been tried for verifying and understanding their effect in arresting the effect of sulphate.

Additives, viz., sodium sulphate [Na_2SO_4], barium chloride [$BaCl_2$], barium hydroxide [$Ba(OH)_2$] used were of laboratory grade.

3.3 Test procedures

3.3.1 Determination of sulphate content

IS 2720 Part 27 lays down the procedure for determining the total soluble sulphate content of soils by: (a) precipitation method or standard method (b) volumetric method or subsidiary method, and (c) calorimetric or turbidimetric method.

a) Precipitation method (standard method)

The method depends upon preparing an aqueous extract of the soil and determining the sulphate content of this extract or an aliquot portion of it by the precipitation of sulphate as barium sulphate, filtering off the precipitate and weighing it. The soil sample is brought to a state in which it may be crumbled, if necessary, by drying it in an oven maintained at 105 to 110°C. The aggregations of particles are broken up in mortar with rubber covered pestle or the mechanical device. The sample is thoroughly mixed and then sub-divided by quartering.

Procedure

10 g of soil from the sample prepared was taken in a 250 ml bottle with 100 ml of distilled water. Occasional shaking for 2 hours by means of the mechanical shaker was done. The soil suspension was allowed to stand overnight, filtered and 25 ml of filtrate was taken in a beaker and concentrated hydrochloric acid was added to just neutralize the solution if it is found alkaline to phenolphthalein indicator. Further 4 ml concentrated hydrochloric acid was added to make the solution acidic. The solution was then boiled. After removing the solution from the source of heat, hot barium chloride solution was added in a fine stream with constant stirring, till there is no precipitation with a further addition. The beaker was placed on a steam-bath for a minimum period of 4 hours and the precipitate was allowed to settle. The precipitate was filtered through ashless filter paper, washed free from chloride ions, dried and ignited. (The filtration may also be done through a pre-weighed sintered glass crucible or a Gooch crucible.) In the case of filter paper, after drying, ashing was done on a low flame and the precipitate then ignited in a muffle furnace at 600 to 700°C for half an hour (or over a burner). It was then cooled in a desiccator, weighed and the weight of the residue was noted. This is the weight of barium sulphate. A

corresponding weight of sodium sulphate was then calculated and thus its percentage determined.

Calculated as follows:

a) Sulphates (as SO_4), percent by mass
$= 41.15\, W_1/W_2$

b) Sulphates (as Na_2SO_4), percent by mass
$= 60.85 W_1/W_2$

where, W_1 = mass in g of the precipitate, and
W_2 = mass in g of the soil contained in the solution taken for precipitation.

b) Volumetric method (subsidiary method)

The volumetric method depends upon insoluble barium sulphate forming and settling rapidly when barium chloride solution is added to the sulphate solution. The barium chloride reagent is added in excess and the excess is determined by the standard solution of barium chromate. With the formation of potassium chromate, the slight excess of chromate reagent becomes evident from the resultant yellow colour of the supernatant solution. The end point can be further tested (confirmed) by silver nitrate solution used as an external indicator. A brick red colouration is obtained when a drop of silver nitrate is added to a drop of the chromate solution.

Procedure

10 g of the soil specimen was weighed in a beaker and about 50 ml water was added. It was stirred well, filtered, the soil on filter paper was

washed with a small quantity of water and the filtrate was made to 100 ml. 10 ml of the water extract was pipetted in a conical flask, it was made slightly acidic by adding concentrated hydrochloric acid and heated to boiling. While boiling, barium chloride solution (N/4) was added from the burette till the precipitation is complete and barium chloride solution is in slight excess. Solution was neutralized with ammonium hydroxide and excess of barium chloride was titrated against potassium chromate solution (N/4). The end point was confirmed, by using silver nitrate solution as an external indicator.

Sodium sulphate was calculated as follows:

Sulphates as sodium sulphate in soil, percent by mass = 0.0177 x 100(x-y)

Where,

x = volume of N/4 barium chloride added, ml;

y = volume of N/4 potassium chromate solution used in back titration; and

x - y = N/4 barium chloride actually used for precipitating sulphate.

c) Colorimetric or turbidimetric method (subsidiary method)

Procedure

20 g air-dry soil specimen was weighed in a 250-ml conical flask. 100 ml of Morgan’s extraction solution was added. (Morgan’s solution is prepared by adding 100 g of sodium acetate and 30 ml of 99.5 percent acetic acid dissolved and mixed in 500 ml of water and the volume made to 1 litre) The suspension was shaken for one-half hour and filtered

through Whatman's No. 42 filter paper or equivalent. 10 or 20 ml aliquot was taken and transferred to a 25 ml volumetric flask. 1 g of barium chloride crystals (ground to pass 50-micron IS sieve and to be retained on 250-micron IS sieve) was added to the aliquot in the flask and shaken for 1 minute. 1 to 2 ml of 25 percent gum acatia was added, and distilled water was poured up to the mark of volumetric flask and shaken for a minute. The suspension was precipitated and readings taken between 5 to 30 minutes after precipitation by turbidimeter (or by photoelectric calorimeter using blue filter). Sulphate is then determined by the standard sulphate curve.

Preparation of Standard Sulphate Curve

a) *Stock Solution* - Dissolve 0.888 g anhydrous sodium sulphate Na_2SO_4/m1 alcoholic, ammonium chloride (NH_4Cl). This gives a concentration of 0.60 mg of SO_4/ml. Absolute alcohol should be used for the preparation of the solution.

b) *Working Standard Solution* - Dilute 0.60 mg SO_4/ml stock solution with alcoholic (N) ammonium chloride to give 0.06 mg SO_4/ml. Take 2, 4, 6, 8, 10 ml of this to give a range of 0.12 – 0.60 mg of SO_4.

c) The standard curve should be prepared by taking readings with photoelectric calorimeter using blue filter or by turbidimeter using the working standard solution.

3.3.1.1 Amount of Sulphate

Soluble sulphates present in water are measured in parts per million (ppm) and often expressed either in ppm or percent. 10,000ppm is equivalent to 1.0%. Therefore 3,000ppm is equivalent to 0.3% and 5,000ppm to 0.5%. The soluble sulphate content should be reported on a dry soil basis to ensure consistency of test results (Texas DoT, 2000).

Studies, conducted on Cochin marine clay, have proved that lime is the most effective stabilizing agent for marine clays of Cochin (Jose et. al., 1987). But like any other marine clay, presence of sulphate can adversely affect the strength behaviour of these clays also. Rajasekaran et al. (1994) has reported a variation of sulphate content from 0.16% to 0.45% for soil samples collected at different locations on the Cochin coastal areas. The only fool proof way to know whether or not sulphates will be a problem is to test the soil for presence of sulphates.

Test for the determination of sulphate content was conducted on the Panampilly Nagar clay as per all the three procedures detailed above. The obtained value of sulphate content using three methods suggested in IS 2720 Part 27 is summarized in Table 3.1. Thus clay obtained from Panampilly Nagar (hereinafter to be designated as clay 1) yielded a sulphate content of approximately 5000ppm. The results indicate that sulphate content obtained by three methods is almost same. Errors are likely to creep in most, in precipitation method of determination of total soluble sulphates.

Table 3.1 Sulphate content of Panampilly Nagar clay (clay 1)

Sl. No.	Method used	Total soluble sulphate (%)
1	Precipitation method	0.49
2	Volumetric method	0.49
3	Turbidimetric method	0.50

Lime, in one form or another, has been used to modify the properties of fine grained deposits. Treatment of soils with lime has brought many beneficial effects, such as improvements in the plasticity characteristics and strength behaviour with time (Narasimha Rao and Rajasekaran, 1996). It is well established that the use of lime in fine-grained soils makes the system less sensitive to changes in stress and other environmental factors. Sivapullaiah et al. 1998). Many engineers have realized this advantage all over the world and hence, in many situations, lime is used to improve soil characteristics in civil engineering applications.

TxDOT, 2000 reports that, if the total level of soluble sulphates is below 0.3%, or 3,000 parts per million (ppm), by weight of soil, then lime stabilization should not be of significant concern and the potential for a harmful reaction is low. Total soluble sulphate levels of between 0.3% (3,000 ppm) and 0.5% (5,000 ppm) are of moderate concern. Generally, these sulphate levels do not result in harmful disruption, but on occasions have caused localized distress. Localized distress is often due to seams of higher sulphate concentration not detected in testing. Total soluble sulphate levels between 0.5% (5,000 ppm) and 0.8% (8,000 ppm) present are moderate to high risk. Total soluble sulphate levels of greater than 0.8% (8,000 ppm) are generally of high risk to stabilize with lime. Soils with total soluble sulphate contents greater than 1.0% (10,000 ppm) generally are not suitable for lime stabilization because of the high risk of sulphate-induced disruption and failure.

So far, suitable guidelines have not been developed for treating the soils containing sulphates. This has resulted in developing various techniques to treat the clays using either chemical mixing or in situ techniques.

To understand the effect of natural sulphate present in soil as well as to better understand the role of various concentration of sulphate, clay 1 obtained from Panampilly Nagar was mixed with two different percentages of lime, 3% and 6% and varying concentrations of sodium sulphate, 0.5%, 1%, 1.5% & 3.5 % by dry weight. Extensive studies using barium chloride as an additive to nullify the effect of sulphate was done on this clay.

The results obtained from studies on Panampilly Nagar clay were used to narrow down the studies on Kaloor clay (hereinafter to be designated as clay 2). Sulphate content of clay 2 as obtained by three methods is tabulated in Table 3.2.

Table 3.2 Sulphate content of Kaloor clay (clay 2)

Sl. No.	Method used	Total soluble sulphate (%)
1	Precipitation method	0.10
2	Volumetric method	0.11
3	Turbidimetric method	0.12

3.3.2 Sample preparation

3.3.2.1 Clay + lime

Portions of thoroughly mixed moist representative clay were taken and its moisture content was determined. Estimated amount of lime as percentage of dry weight of the soil was then mixed with the moist soil. Required quantity of water was added to bring the mixture to its liquid limit consistency. The index properties of the treated soil were determined immediately. It was then moulded in PVC rings of 100mm diameter and 40mm height taking care to see that air was not entrapped. PVC foam plates were placed on either side of the ring, tied with rubber bands and the entire assembly was kept in polyethylene bags and kept in humid condition for curing.

Samples using clay 1 were prepared for two percentages of lime, 3% and 6% by weight and that for clay 2 was treated with 6% lime.

3.3.2.2 Clay + lime + sodium sulphate

To portions of thoroughly mixed moist representative sample predetermined quantity of Na_2SO_4 was added and thoroughly mixed. Estimated amount of lime as percentage of dry weight of the soil was then mixed with the moist soil. The treated soil samples were then cured in PVC rings as described in 3.3.2.1.

Rajasekaran et al. (1999) conducted fabric studies on 11 samples of marine clays. Out of the 4 samples collected from the West coast of India, location of 2 samples designated as sample 8 and sample 9 is reported as Kerala 1 and Kerala 2. Fig 3.1 depicts the locations of the sampling points considered for study. The paper further reports the percentage of sulphate present in all the 11 samples. Samples collected from Cochin and Mangalore (sample 8 and 9) are reported to have a sulphate content of 1.5% and 3.30% respectively. The maximum sulphate content reported is 4.10% for sample collected from Madras (Chennai) and designated as sample 2 and marked in

Fig. 3.1 as Madras 2. A variation from 0.21% to 4.10% is observed in the 11 samples reported.

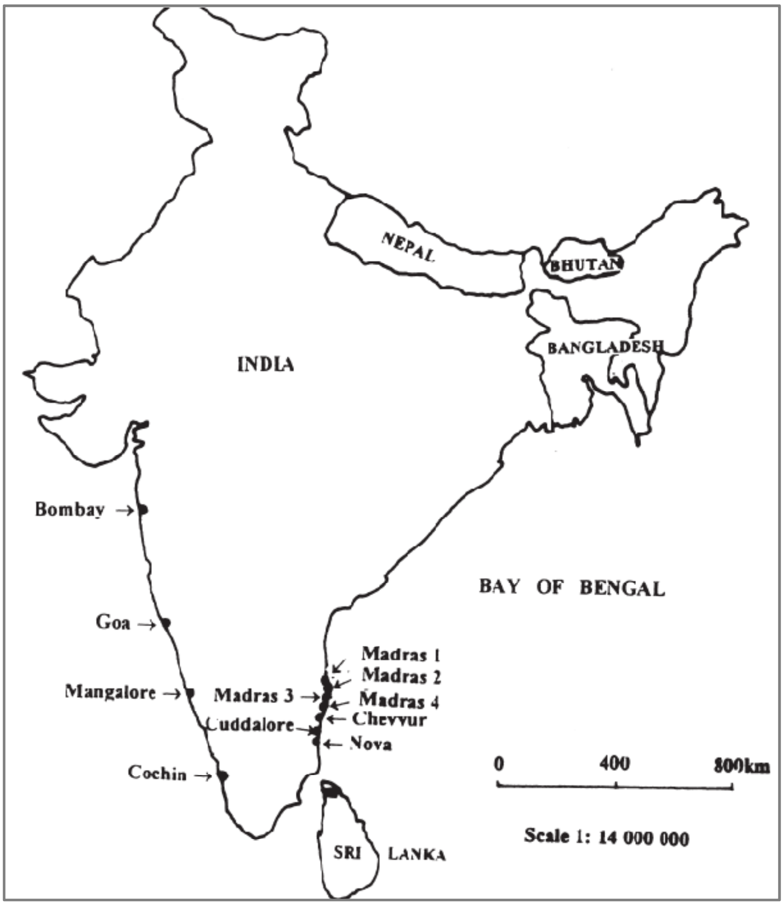

Fig. 3.1 Location of sampling points (Rajasekaran et al. 1999)

Hence the present study focuses on a maximum sulphate content of 4%. Amount of sodium sulphate added to clay 1 are 0.0, 0.5, 1.5 and 3.5 as percentage of dry weight of soil and for clay 2, it is 0.0, 3.9%.

3.3.2.3 Clay + lime + sodium sulphate + barium compound

To thoroughly mixed moist clay predetermined quantity of Na_2SO_4 was added and mixed thoroughly. Enough quantity of barium compound, was then added based on the chemical formula,

$$Na_2SO_4 + BaCl_2 \rightarrow BaSO_4 + 2\ NaCl \quad \text{..} \quad 3.1$$

$$Na_2SO_4 + Ba(OH)_2 \rightarrow BaSO_4 + 2\ NaOH \quad \text{.......................................} \quad 3.2$$

The molecular weight ratio of sodium sulphate and barium chloride in equation 3.1 is 1: 1.5 and that of sodium sulphate and barium hydroxide as given in equation 3.2 is 1:1.2. Samples made were allowed to cure under humid condition in the PVC rings. The ratio was kept as 1:1.5 in both cases.

In lime treated clay 1, experiments were carried out with varying percentages of sulphate and barium chloride. Tests were carried out in lime treated clay 2, to understand the effect of barium chloride versus barium hydroxide under worst condition of 4 % sulphate.

3.3.3 Mineralogical and morphological investigations

3.3.3.1 X – Ray Diffraction Analysis

X-ray diffraction (XRD) is the technique most heavily relied on in soil mineralogical analysis. The engineering behaviour of the soil deposits depends on the mineralogical composition of the samples and it is necessary to identify the minerals present (Barden et al. 1957). It is a powerful tool in the identification of minerals in rocks and soils. The bulk of the clay fraction of many soils is crystalline, but clay particles are too small for optical crystallographic methods to be applied. Therefore, XRD has long been a main say in the identification of clay-sized minerals in soils. Different crystals yield different diffraction patterns. X-ray diffraction analysis can be conducted on single crystals or powders. Small size of most soil particles prevents the study of single crystals and hence X-ray powder diffraction (Reynolds, 1989a), is the technique most applicable to soil mineralogy.

The X-ray diffraction tests were carried out to find out the mineralogical composition of the selected raw soils, clay 1 & clay 2. XRD analysis was carried on radiation generated at 40kV and 40mA using Bruker AXS D8. In the powder method, a small sample containing particles at all orientations is placed in a collimated beam of parallel X-rays and diffracted beams of various intensities are scanned by a Geiger, proportional or scintillation tube and recorded automatically to produce a chart showing the intensity of diffracted beam as a function of range 2θ. Representative sample taken from air dried powdered mix was used for the test. To identify all the minerals present in these samples thoroughly, no attempt was made to screen out any particular fraction from the specimens used (Grim, 1968).

The clay minerals are identified using the generated X-ray diffraction patterns (diffractogram) by the peak's position, intensity, shape and breadth. Peak position is determined using Bragg's law which is written as $n\lambda = 2d\sin\theta$. Most of the important clay peaks are at the 2θ values of 40^{o} or less; therefore, θ is 20^{o} or less.

Comparing the observed X-ray diffraction patterns with International Centre for Diffraction Data (ICDD 2008 PDF-4/Minerals database) X-ray

Powder Data Files (formerly Joint Committee on Powder Diffraction Standards JCPDS) the mineralogical analysis was carried out. The identification of clay minerals was accomplished by careful consideration of peak positions and intensities. The qualitative identification procedure began by searching for a mineral that explains the strongest peak or peaks, then confirming the choice by finding the positions of weaker peaks for the same mineral. Once a set of peaks was confirmed as belonging to a mineral, these peaks were eliminated from consideration. From the remaining peaks, a mineral that will explain the strongest remaining peak or peaks was searched and then confirmed by looking for its peaks of lesser intensity. This method was repeated until all peaks were identified.

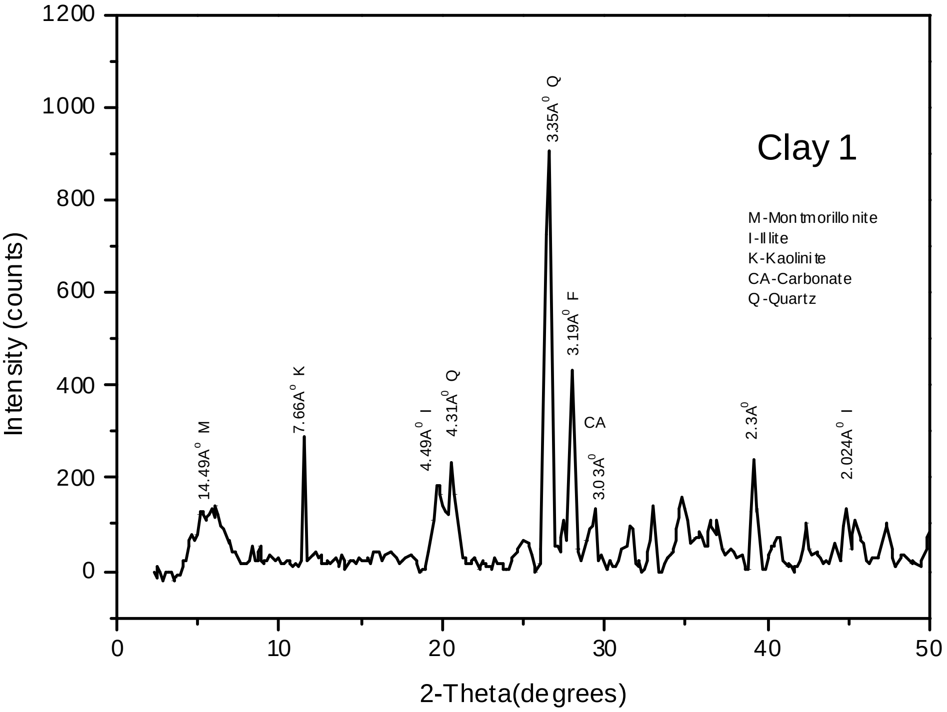

Fig. 3.2 X-ray diffraction pattern of clay 1 (Panampilly Nagar clay)

The X-ray diffraction pattern of the soil indicated the presence of clay minerals, montmorillonite, illite, kaolinite, along with non - clay mineral quartz and Feldspar. Calcium carbonate presence is also indicated. Carbonates present in marine clay deposits partially influencing the behaviour of these soils (Rajasekaran et al. 2005). XRD patterns of raw samples of clay 1 and clay 2 are as shown in Fig 3.2 and Fig. 3.3.

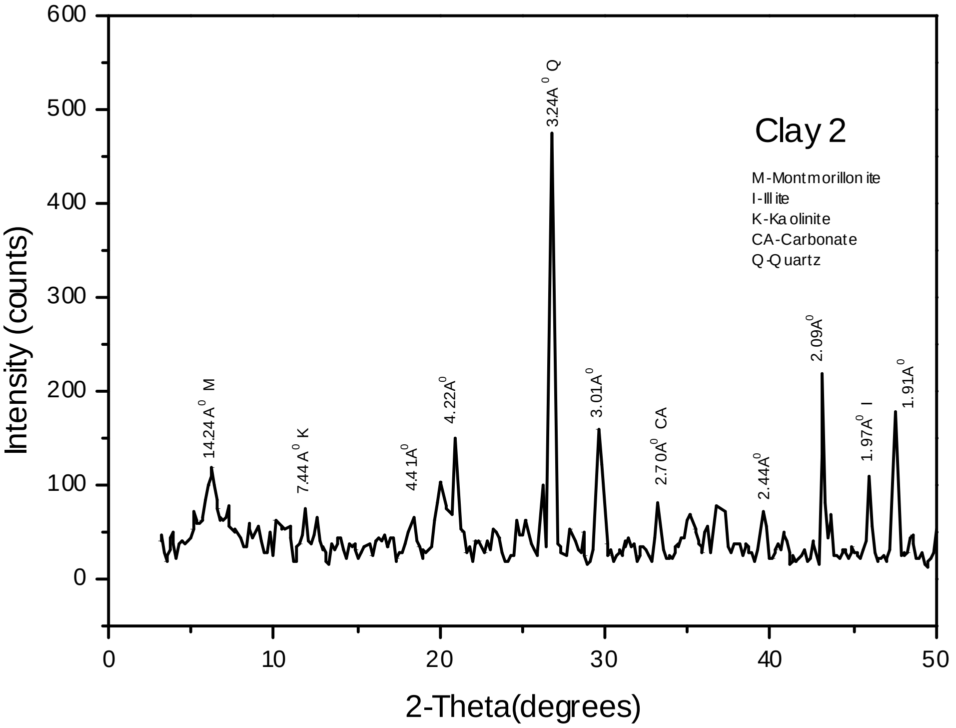

Fig. 3.3 X-ray diffraction pattern of clay 2 (Kaloor clay)

Narasimha Rao and Rajasekaran (2005) reported the presence of day minerals such as montmorillonite and chlorite in appreciable amounts with traces of kaolinite, illite and vermiculite in marine clays.

3.3.3.2 Scanning Electron Microscopy

The scanning electron microscope (SEM) is one of the most versatile instruments available for the examination and analysis of the microstructure morphology and chemical composition characterizations. The SEM utilizes a focused electron beam to scan across the surface of the specimen systematically, producing large numbers of signals. These electron signals are eventually converted to a visual signal displayed on a cathode ray tube (CRT).

Image formation in the SEM is dependent on the acquisition of signals produced from the electron beam and specimen interactions. In most cases when incident electron strikes the specimen surface, instead of being bounced off immediately, the energetic electrons penetrate into the sample for some distance before they encounter and collide with a specimen atom. In doing so, the primary electron beam produces what is known as a region of primary excitation, from which signals are produced. The most widely used signal produced by the interaction of the primary electron beam with the specimen is the secondary electron emission signal. When the primary beam strikes the sample surface causing the ionization of specimen atoms, loosely bound electrons may be emitted and these are referred to as secondary electrons. As they have low energy they can only escape from a region within a few nanometers of the material surface. So secondary electrons accurately mark the position of the beam and give topographic information with good resolution.

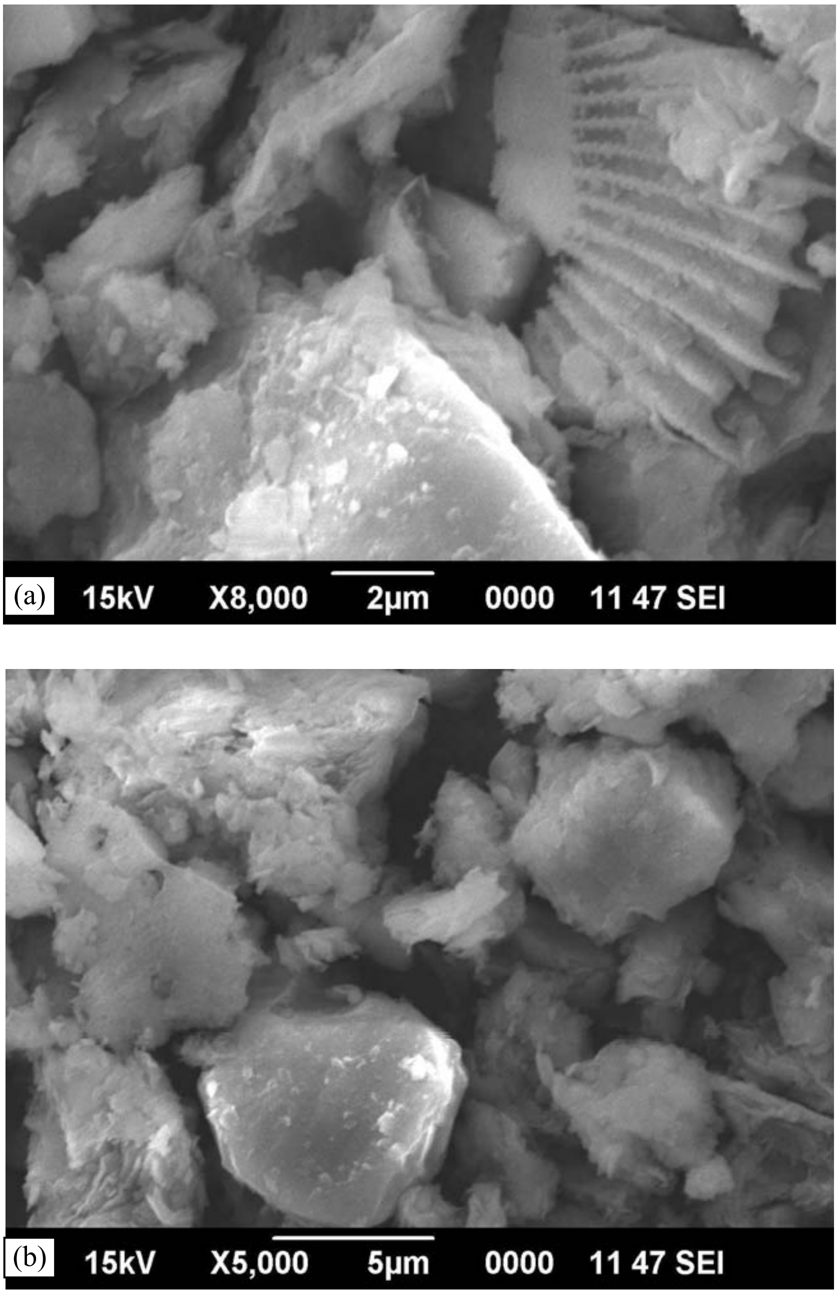

Fig. 3.4 (a) & (b) Micrographs of clay 1

JEOL Model JSM - 6390LV was used to study the morphology and elemental composition of untreated and treated soil samples at a voltage range of 0.5 to 15kV. Undisturbed cubical specimens, 10 mm x 10 mm were prepared and dried in the oven at 40°C and subsequently subjected to vacuum. The specimen was then glued on aluminium holders for scanning. The fractured surfaces of the specimens were coated with carbon to maintain conductivity.

Figs. 3.4 (a) and (b) show the micrographic features of the clay 1. Distinct particulate arrangement due to apparent intergrowth of particles or possible aggregation can be seen. Both crumpled and planar clay flakes can be seen in the micrograph of the samples and some flakes are aggregated within packets whereas others show apparent edge to face bonding.

3.3.4 Atterberg limits

The liquid limit and plastic limit were determined as per IS 2720 (Part 5) – 1985 for fine grained soils (the method adopted is Casagrande cup method for liquid limit and thread rolling method for plastic limit). Since drying significantly reduces the Atterberg limits of marine clays, tests for liquid limit and plastic limit were done on the moist soil itself.

Jose et al. (1988) and Jose (1989) has proved conclusively that drying of Cochin marine clays significantly affects its physical and engineering properties. Oven dried samples are reported to have liquid limit in the range 40% - 60% of the natural moist sample and air drying have shown to reduce liquid limit by 20% - 30%. This behaviour has been attributed to aggregation of particles on air drying and oven drying. Similar reduction in plastic limit and free swell index values has been reported. Jagdish Narain and Iyer (1967) have reported significant reduction in the liquid limit of Kuttanad clays on air drying. Rao et al. (1999) has attributed the reduction in liquid limit of Cochin marine clays on the irreversible aggregation due to the attractive forces between particles and also has pointed out that organic matter and other salts present in the pore water system may cause the formation of new cementing compounds on air drying of the clay. Hence extreme care was taken to use marine clays in their moist condition itself for all the tests.

The liquid limit tests were conducted using Casagrande's apparatus, starting from a water content which required around 10 blows only for the groove to close. The paste was then spread over glass plate to allow evaporation. This was then mixed thoroughly for the next test. Thus all tests were started on the wetter side of liquid limit. Liquid limit tests were carried out to secure a minimum of five points for plotting the flow curve. For each soil specimen the average of two liquid limit values is reported.

The plastic limit reported is an average of two determinations.

The shrinkage limits were obtained as per the IS: 2720 (Part 6) – 1972, first revision, amendment – 1, reaffirmed 1990. The shrinkage limit test, while working with wet soil in the shrinkage dish, care was taken to expel entrapped air. Cracking during drying was a serious problem, especially so, for lime treated soils, and it was prevented by first allowing the soil pat to dry very slowly in the air controlled condition followed by oven drying to a constant mass. The shrinkage limit reported is an average of three determinations.

Samples prepared at liquid limit consistency, moulded in PVC rings and cured for predetermined periods was used for determining the index properties, free swell index and for determining grain size distribution. Throughout the curing period the samples were cured at 100% relative humidity atmosphere.

3.3.5 Free swell index test

IS 2720 (Part 40): 1977 defines the free swell index as the increase in the volume of a soil, without any external constraints, on submergence in water. As per the code, the free swell index is calculated by,

$$\text{Free swell index} = \frac{v_d - v_k}{v_k} \times 100$$

Where v_d - volume of 10 g of oven dry soil passing through 425 micron sieve, in distilled water

v_k - volume of 10 g of oven dry soil passing through 425 micron sieve, in kerosene.

This method of determination of free swell index has some inherent limitations as pointed out by Sridharan et al. (1985). They proved that pure kaolinite mineral occupies a higher sediment volume in a non - polar solvent like kerosene than in water thus resulting in negative values of free swell index. Hence the method proposed by Sridharan et al. was used for the determination of free swell index, in this study.

For this purpose, a moist sample of equivalent dry weight of 10g was taken in a 100 ml graduated cylinder containing about 40 ml of distilled water.

The suspensions were stirred repeatedly and then made up to 100 ml mark with addition of distilled water and was thoroughly mixed with a glass rod. The soil was allowed to settle. The sediment volume per unit weight of dry soil is expressed as free swell index in cc/g.

Accordingly,

$$\text{Free swell index} = \frac{v_d}{10}\ \text{cc/g}$$

Where v_d - volume of 10 g of soil specimen read from the 100 ml graduated cylinder containing distilled water.

As per this equation free swell index is defined as the volume occupied by a unit weight of soil in water without any external constraint.

3.3.6 Grain size distribution

Grain size distribution is the most obviously affected index property of marine clays during drying. Due to aggregation, a portion of the clay fraction is changed to silt size and a portion of the silt size becomes sand size. Hence grain size distribution tests on dried samples give anomalous results.

Even though IS 2720 (Part 4) – 1985 recommends the use of soil oven dried at 105-110^{0}C for sedimentation analysis, because of the reason mentioned above, only moist samples were used for the sedimentation analysis in this study.

The sedimentation analysis was done using hydrometer. Compared to the normally encountered clayey soils, the need of a deflocculating agent was more keenly felt for marine soils (Jose, 1989; Sridharan et al. 1991). Hence the standard dispersing agent recommend by the IS code (sodium hexametaphosphate + sodium carbonate) and proved to be the most ideal one for Cochin marine clays, was used for the hydrometer analysis.

Grain size distribution curves of clay 1 and clay 2 are given in Fig. 3.5.

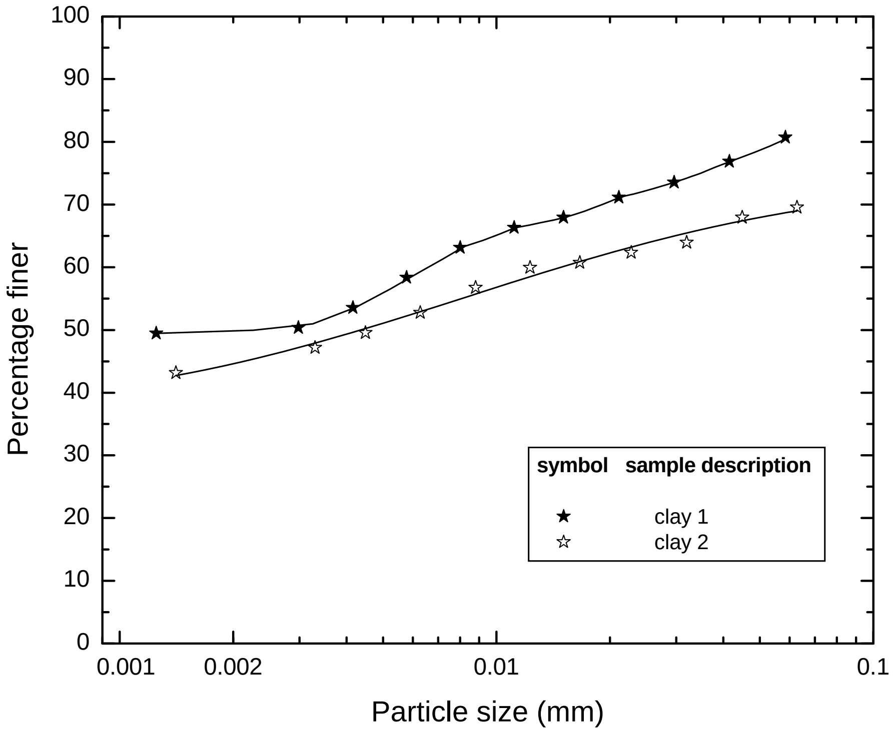

Fig. 3.5 Grain size distribution curves of clay 1 and clay 2

Typical properties of clay 1 & clay 2 are given in Table 3.3. These clays possess natural moisture contents very high and close to liquid limit values (Jose et al. 1988). High values of liquid limit indicate that these sediments were deposited at high water contents (Rajasekaran et al. 1994). The plastic limit values indicate that these soil deposits are highly plastic in nature. The fabric of these deposits consists of an assemblage of silt, clay size rock fragments and clay minerals. The randomly oriented clay platelets are aggregated with coarser fractions to form an open network resulting in high void ratio. The open type of fabric is believed to have been formed during sedimentation in saline water, resulting in a flocculated structure of clay particles (Yong and Warkentin, 1966). The adjacent particles tend to aggregate during sedimentation because the interparticle repulsive forces are low when they are brought into close proximity (Rajasekaran et al. 1994). Jose et al. (1988) also have reported that major portion of clay content of Cochin marine clays is in the form of flocs under natural conditions.

Table 3.3 Physical properties

Sl. No.	Soil property	Clay 1	Clay 2
1	Specific gravity	2.64	2.65
2	Natural moisture content (%)	157.3	115.4
3	Liquid limit (%)	155.6	139.5
4	Plastic limit (%)	58.4	54.5
5	Plasticity index (%)	97.2	85
6	Shrinkage limit (%)	14.4	18.6
7	Grain size distribution		
	Clay size (%) (<0.002mm)	50	45
	Silt size (%) (>0.002mm <0.075mm)	45	42
	Sand size (%) (>0.075mm <4.75mm)	5	13
8	pH value	7.71	7.83
9	Free swell index (cc/gm)	4.45	3.90

3.3.7 Consolidation test

Several series of consolidation tests were carried out on untreated and treated marine clays. After curing the specimens for known periods in PVC rings in an environment preventing loss of moisture, the assembly was taken out and the PVC foam sheets were removed. Samples were extracted into oedometer rings 60mm diameter and 20mm height, by pushing the bevelled edge into the sample in the PVC ring. The sample was then trimmed neat, in level with the edges of the oedometer ring. (The remaining sample in the PVC ring was also used for determining the index properties, free swell index etc.). The ring is then introduced into the consolidation test assembly with porous stones on either side. Filter papers were placed between the porous stones and the soil specimen to prevent the soil from being forced into the pores of the stones. The consolidation assembly was then positioned in the loading frame and the specimen was loaded with a seating load of 6.25 k Pa. The sample was then inundated with water from a reservoir with a head of 50 cm.

The load increment ratio for the routine tests was kept as one. It was found that about two days were required for a complete dissipation of pore pressure and for reaching an equilibrium void ratio for a particular loading stage. Hence the duration for each load increment was kept at two days. A loading sequence of 6.25, 12.5, 50, 100, 200, and 400 k Pa was adopted for the numerous consolidation tests performed on untreated and treated specimens of marine clays.

For each loading, dial gauge readings were taken at 0, 1/4 , 1, 2, 3, 4, 5, 8, 11, 14, 17, 20, 30, 40, 50, 60, 80, 100, 120, 140, 160, 180, 210, 240, 270, 300, 330, 360, 1440, 2880 minutes from the time of loading.

3.3.8 Unconfined compression test

Unconfined compression tests were carried out in accordance with IS 2720 Part 10-1973. While conducting the unconfined compressive strength test under natural conditions it was observed that the soil sample was not taking any load at all. With liquid limit values close to natural moisture content Cochin marine clays possess very low shear strength values (Jose et al. 1987)

3.3.8.1 Sample preparation and curing

For tests on lime admixed samples, lime content of 6% was used for both clay 1 and clay 2.

Varying percentages of sulphate content, 0.0, 0.5, 1.5 and 3.5 as percentage of dry weight of soil was added to clay 1 and for clay 2, the added percentages were 0.0, 3.9%.

Additive barium chloride was used with lime treated clay 1 and tests were conducted on clay 2 to understand the effect of barium chloride vs. barium hydroxide.

UCC test samples were prepared at liquid limit consistency and sealed in polyethylene bags and cured under humid conditions (Fig. 3.6). Unconfined compression tests were then conducted on the cured samples.

Fig. 3.6 Sealed UCC samples kept for curing

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Chapter 4

PHYSICAL PROPERTIES OF LIME STABILISED CLAYS CONTAINING SULPHATE AND TREATED WITH BARIUM COMPOUNDS

Contents

4.1 Introduction

The beneficial effects of soil-lime stabilization in improving the soil properties of weak terrestrial deposits have been reviewed and reported by several investigators (Eades and Grim, 1960; Eades et al., 1962; Diamond et al., 1963 and Somayazulu, 1987).

Lime stabilization started as an aid in roadway maintenance and now covers all highway construction (Eades 1966). This method reduces the soil's plasticity and its ability to undergo volume change when wetted or dried. Lime improves the plasticity, workability, and strength properties of a soil (Thompson 1966).

Lime stabilization increases the soil's bearing strength and permeability, while reducing potential volume changes (Hunter 1988), therefore rendering a stronger soil mixture that will react less, or not at all, to changing moisture conditions. Adding lime converts the soil to a rigid or granular mass where the particles are strongly bound by pozzolanic cementitious compounds that are formed by reactions with soil silica and lime in the presence of water (Sivapullaiah et. al. 2006). Three reasons for stabilizing natural soils beneath pavements include providing a working table for construction equipment during wet weather, reducing roughness due to expansive clay subgrades, and to provide a permanent layer in the pavement structure that is stiffer than the natural soil (Rajasekaran et al. 1997). When lime or cement is mixed with soft clay it changes the physical properties of soil due to reaction of lime or cement with the clay minerals (Ghosh et al. 2005).Treatment of soils with lime has brought many beneficial effects, such as improvements in the plasticity characteristics and strength behaviour with time (Kamon, 1992; Narasimha Rao and Rajasekaran, 1996).

Calcium-based stabilizers including lime and/or cement have been used to increase strength and decrease plasticity index (PI), swell and shrinkage strain potentials of expansive soils and thereby improve the performance of structures built on those soils (Hausmann, 1990).

As mentioned in literature, section 2.5, Jose (1989) has reported using 17 stabilizing agents on moist samples of Cochin marine clays. Out of the seventeen additives tried, lime and cement showed impressive gains in strength. Even though stabilization with cement showed promising results, it is pointed out that consistent results with cement can be obtained only after successful standardization of the additive. Lime, therefore was assessed as having the highest potential as a stabilizing agent. Physical properties of marine clays are reported to have increased considerably by lime treatment. Liquid limit was found to behave erratically but plastic limit was found to exhibit significant increase after one week. The reduction in plasticity index makes the samples less compressible but more friable. The findings also suggest that only small percentages of lime are required to bring these changes in physical properties. Shear strength tests on samples treated with different percentages of lime showed that 6% was the optimum lime content. Within one week of curing the shear strength is reported to have improved tenfold and by about eighteen times in one month. Shrinkage limit also shows an increase, with addition of lime, but registers phenomenal increase with higher lime content and curing period and has been attributed to flocculation and agglomeration. The free swell index increases on mixing with lime, but on curing, the value slowly decreases.

Arabani (2007) observed that any increase in lime content beyond 6 % had a negligible effect on the compressive strength of treated clay soil. However, an increase in lime content up to 6% resulted in a noticeable increase in compressive strength. In fact, it has been shown that with the additions of over 6% lime, the decrease in strength can be quite significant (Al-Rawi 1981).

Incremental additions of lime result in a progressive decrease in liquid limit, increase in shrinkage and plastic limit, decrease in maximum dry density and increase in optimum moisture content of kaolinitic soils when Proctor test was carried out. Curing the soil with lime also has a distinctive influence on its properties (Prakash et al. 1989).

Lime reduces plasticity index, I_p and makes the soil more workable as the lime reacts with the clay surface. The reaction is mineralogy dependent, but almost all plastic soils show a plasticity reduction and work ability increase (Little, 1999).

Calcium-based stabilizers including lime and/or cement have been used to increase strength and decrease plasticity index, swell and shrinkage strain potentials of expansive soils and thereby extend the life of structures built on those soils (Hausmann, 1990). Lime reduces PI and makes the soil more workable as the lime reacts with the clay surface. The reaction is mineralogy dependent, but almost all plastic soils show a plasticity reduction and work ability increase (Little, 1999).

Lime is thus an appropriate stabilizer for most cohesive soils, but high salt concentrations may interfere with, or affect stabilization. The most important salts are sulphate salts (sodium, magnesium or calcium sulphates). Thus natural sulphate rich soils found in many parts of the world are considered a challenge in engineering projects (Hunter, 1988; Mitchell and Dermatas, 1992; Petry and Little, 1992; Kota et al. 1996; Rollings et al. 1999; Puppala et al. 2002).

Currently, one of the most economical and accepted means to stabilize expansive soils is to add lime to the soils before compaction. However, treating soils that contain natural sulphate with lime or other cementitious material may lead to a problem that is as bad as or worse than leaving the soil untreated in its natural state (Burkart et al. 1999).

Presence of sulphate can alter the physical and engineering behaviour of lime treated soils. The effects are pronounced depending upon concentration, form of sulphate and curing period (Ramesh, 1993).

The increasing sulphate heave problems in construction projects, with lime treatment, calls for developing better treatment methods. These methods should mitigate the formation of ettringite minerals in sulphate soils and thereby decrease heave potentials of sulphate soils (Puppala et al. 2004).

4.2 Experimental program

Literature survey conveys that critical conditions are likely to arise when the lime treatment of soil is carried out in the presence of sulphate. Hence study of the effect of curing of lime treated sulphatic soils will give an idea about the changes that are likely to occur to lime-soil mixtures in the field.

The effect of curing on the plasticity, shrinkage and sediment volume of Cochin marine clays in the presence of sulphates has not engaged the attention of the researchers much. In the present investigation, an attempt has been made to study the effect of curing on the Atterberg limits, shrinkage and sediment volume of soil – sulphate – lime mixtures. The study will help to assess the change in the workability of lime-soil mixtures over a period of time in the presence of sulphates as well as with the addition of barium compounds to mitigate the effect of sulphates.

The physical properties of clay 1 and clay 2 treated with 3% and 6% lime, containing various concentrations of sulphate have been studied for immediate effect as well as with the curing period. The effect on basic properties by addition of barium compounds to the sulphate containing soils for mitigating its effect is also presented.

The experimental program to study the basic properties of the selected soils with various percentages of lime and required quantity of barium compounds, as affected by curing period is detailed in Table 4.1.

Sodium sulphate was added and thoroughly mixed to bring the sulphate concentrations in clay 1 to 0.5%, 1%, 2% and 4% and in case of clay 2 to raise the sulphate concentration to 4%. Required quantity of lime also was also mixed. The mixtures were brought to liquid limit consistency and the index properties were determined immediately and after curing for known periods as explained in section 3.3.4 of chapter 3.

Additional samples with enough quantity of barium compounds incorporated, to mitigate the effect of sulphate were prepared. These samples were also prepared at liquid limit consistency such that molecular weight ratio of sodium sulphate and barium compounds were maintained at 1:1.5 as described in section 3.3.2.3 of chapter 3.

Table 4.1 Experimental Program for study of basic properties for clay 1 & clay 2

Soil	Additives (%)			Tests conducted	Curing period
	Lime	$Na_2 SO_4$	Barium compound		
Clay 1	0%	0%	0%	Liquid limit, Plastic limit, Shrinkage limit, Grain size analysis, Free swell index	0, 7, 30, 90, 180, 365, 730 days
	3% & 6%	0%	0%		
		0%	Barium Chloride		
		0.5%	0%		
			Barium Chloride		
		1.5%	0%		
			Barium Chloride		
		3.5%	0%		
			Barium Chloride		
Clay 2		0%	0%		0, 7, 30, 90, 180, 365 days
	3%	0%	0%		
	6%	0%	0%		
		3.9%	Barium Chloride		
		3.9%	Barium Hydroxide		
	0%	0%	6% Barium Chloride		
	0%	0%	6% Barium Hydroxide		

4.3 Results and discussions

4.3.1 Liquid limit

The workability of a soil is closely related to its plasticity characteristics that primarily depend on the water holding capacity of the soil and is quantified through index properties such as liquid limit, plastic limit and plasticity index. Among them, liquid limit is an important physical property used in classification and correlations with engineering properties of soils. The index properties of clay 1 treated with 3% lime and containing various percentages of sulphate is given in Table 4.2. Variation in concentration of sulphate does not produce much of an effect in this decrease with curing period.

It is observed that with 3% lime at all percentages of sulphate, liquid limit exhibits an immediate increase continued for up to one week and then decreases in all cases as shown in Fig. 4.1. A similar trend is observed with the plasticity indices.

With the incorporation of barium compounds the trend remains more or less the same as presented in Tables 4.3 and Fig. 4.2. Lime–soil reactions can be classified into short term and long term reactions. Short term reactions include flocculation, lime migration, pH and cation exchange reactions and carbonation. The above reactions affect the physical properties of the soil system such as Atterberg limits and particle size distribution. Whereas the long term pozzolanic reactions include the formation of various new reaction products, which result in the growth of aggregates and affect the strength and compressibility of clays (Rajasekaran, 2005)

There are several factors that influence the lime treated soil properties such as cations, concentration of sulphates and clay minerals composition (available alumina and silica). The anions of sulphates combine with the available calcium and alumina, and form insoluble ettringite in the soil system. The formation of ettringite increases the porosity and simultaneously decreases the free moisture content during ettringite nucleation and its subsequent growth. The formation of calcium silicate hydrate and calcium aluminate hydrate in crystalline or semi-crystalline phases can be seen in lime stabilized clays (Croft, 1964; Wild et al., 1993, 1995). But the presence of sulphates in the mixing water and ground water caused adverse effects in the soil systems (Sherwood, 1962; Obika and Freer-Hewish, 1990; Snedker and Temporal, 1990a). In view of cation exchange, the broken bonds of soil particle edges and unbalanced ionic substitution within the clay mineral lattice result in increasing negative charges of soil system (Grim, 1968). Lime dissociates into Ca^{2+} and OH^- ions in the presence of water, and results in reduction of inter particle repulsive forces and increases the soil alkalinity (George et al., 1992; Smith et al., 1994).

The effect of different cations such as Na^+, K^+, Ca^{2+} and Mg^{2+} on lime treated kaolinite clay containing sulphates has been studied by Kinuthia et al. (1999). His test results indicated that Ca^{2+} and Mg^{2+} enhance the beneficial effects, whereas Na^+ and K^+ induced adverse effects in treated soil systems. The addition of lime to soil results in several reactions including flocculation and aggregation, increases pore volume and optimum moisture content, and lowers dry density. The long term reactions result in the formation of several cementitious products which results in aggregates of different sizes with time

(Wild et al., 1996, 1998). Cation exchange reactions influence the Atterberg limits and compaction characteristics of lime treated kaolinite clay containing sulphates (Leroueil and Le Bihan, 1996). The penetration of cations into the soil system results in neutralizing the negative charges of soil particles, and change the soil particles flocculated structure to parallel arrangement. This phenomenon results in decreasing rate of water flow as well as increasing liquid limit of clay.

Higher cation concentration increases soil particles inter-particle spacing due to cations hydrolysis and reduces the liquid limit due to depression of diffuse double layer (Grimshaw, 1971; Yong and Warkentin, 1975; Vyalov, 1986; Kinuthia et al., 1999).

Rajasekaran (2005) also reports that compared with sodium ions, potassium ions can be more strongly held into the hexagonal holes of the tetrahedral faces of clay particles, and result in the reduction of consistency limits close to divalent cations. The presence of divalent ions in the soil system increases the shear resistance between the particles stronger than monovalent ions. The inherent repulsion between clay particles with large hydro-sphere results in interparticle separation, in the presence of monovalent ions. However, the increasing concentration of monovalent ions in the soil system results in the reduction of diffused double layer thickness (due to inadequate negative charge neutralization when compared with divalent ions), and prevents further reduction in liquid limit. However, the formation of ettringite in the sulphates enriched soil systems affects the cation exchange, consistency and compaction characteristics with time. The addition of gypsum and magnesium sulphates lowers the liquid limit as well as plasticity index of lime treated kaolinite system. Even though the presence of sodium sulphate initially lowers the liquid limit and plasticity index values of treated soil systems, the trend was stable over a period of time. In the case of potassium sulphate treated soil system, the initial trend is similar to the above except that there is a slight increase in liquid limit and plasticity values with time. The magnitude of the effect of sulphates on consistency values follows the series such as $Ca2^{+}$ $>Mg2^{+}>K^{+}>Na^{2+}$, as in the case of iyotropic (or Hofmesister) series (Rajasekaran et al. 2005).

The observed decrease in liquid limit with time for lime treated clay 1 containing sulphates and further decrease in liquid limit for sulphatic soil treated with barium chloride may be attributed to this.

Table 4.4 gives the effect on index properties of clay 1 treated with 6% lime and containing various percentages of sulphate. The effect produced due to incorporation of barium chloride is given in Table 4.5.

Table 4.2 Physical properties of clay 1 treated with 3% lime and sulphate

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 1 (Sulphate Content = 0.5%)	0 day	155.6 ±2%	58.4 ±2%	97.2 ±2%	14.4 ± 1%	50 ±2%	4.45 ±0.2
		1week						
		1 month						
		3 months						
		6 months						
		12 months						
		24 months						
2	Clay 1 + 3% lime	0 day	151.7	47.9	103.8	26.9	43	5.39
		1week	163.6	53.7	109.9	19.3	41	4.96
		1 month	161.0	51.8	109.2	19.4	41	4.77
		3 months	146.8	48.8	98.0	15.9	45	4.03
		6 months	144.8	50.5	94.3	18.8	45	4.67
		12 months	142.9	59.6	83.3	16.7	39	4.04
		24 months	135.5	51.5	84.0	15.4	45	3.99
3	Clay 1 + 3% lime + 0.5% Sulphate	0 day	152.5	42.7	109.8	17.5	46	5.50
		1week	166.9	40.2	126.7	17.7	43	5.44
		1 month	163.3	43.6	119.7	18.6	45	5.40
		3 months	136.9	46.9	90.0	18.0	43	5.34
		6 months	134.4	46.7	87.7	18.0	48	4.72
		12 months	135.9	45.5	90.4	18.2	44	4.47
		24 months	128.8	45.2	83.6	16.6	44	4.38
4	Clay 1 + 3% lime + 1.5% Sulphate	0 day	151.2	42.7	108.5	22.3	45	5.70
		1week	165.3	41.5	123.8	18.8	43	5.68
		1 month	157.8	42.8	115.0	20.5	44	5.75
		3 months	133.6	46.4	87.2	15.1	46	5.76
		6 months	131.7	46.3	85.4	17.1	49	5.72
		12 months	126.3	44.8	81.5	15.0	44	4.74
		24 months	125.8	44.3	81.5	15.4	43	4.88
5	Clay 1 + 3% lime + 3.5%sulphate	0 day	152.8	45.8	107.0	22.2	50	6.02
		1week	160.3	44.1	116.2	18.9	-	5.87
		1 month	158.3	43.5	114.8	21.1	-	5.85
		3 months	134.9	40.5	94.4	16.4	46	5.95
		6 months	133.8	40.2	93.6	15.9	45	5.75
		12 months	132.8	46.0	86.8	18.1	41	5.57
		24 months	133.7	45.4	88.3	14.4	41	5.47

Table 4.3 Physical properties of clay 1 treated with 3% lime, sulphate and barium chloride

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 1 + 3% lime + $BaCl_2$	0 day	160.9	53.9	107.0		45	5.3
		1week	153.5	64.7	88.8	19.9	42	5.17
		1 month	147.8	54.7	93.1	20.3	42	4.48
		3 months	143.5	55.7	87.8	15.2	46	4.40
		6 months	143.3	56.5	86.8	15.7	43	4.32
		12 months	138.4	58.5	79.9	16.1	41	4.71
		24 months	131.0	57.7	73.3	14.9	46	3.63
2	Clay 1 + 3% lime + 0.5% sulphate + $BaCl_2$	0 day	166.5	44.3	122.2	22.3	45	5.60
		1week	159.0	61.5	97.5	20.9	43	5.28
		1 month	155.6	60.5	95.1	21.0	42	4.45
		3 months	145.2	53.4	91.8	15.1	42	4.35
		6 months	139.3	54.3	85.0	20.1	43	3.52
		12 months	139.1	54.5	84.6	16.9	44	3.50
		24 months	131.7	54.8	76.9	14.6	43	3.29
3	Clay 1 + 3% lime + 1.5% sulphate + $BaCl_2$	0 day	159.0	47.8	111.2	18.5	47	5.51
		1week	156.5	54.3	102.2	17.1	44	4.72
		1 month	151.5	53.2	98.3	21.4	-	4.47
		3 months	138.4	42.5	95.9	20.7	45	4.45
		6 months	137.3	43.9	93.4	15.0	40	4.26
		12 months	134.2	52.5	81.7	17.7	42	4.03
		24 months	126.8	51.4	75.4	15.9	47	3.48
4	Clay 1 + 3% lime + 3.5% sulphate+ $BaCl_2$	0 day	145.4	49.5	95.9	13.6	45	5.13
		1week	142.8	47.5	95.3	17.8	46	4.46
		1 month	139.8	51.2	88.6	15.2	-	4.27
		3 months	121.2	40.4	80.8	13.2	40	3.24
		6 months	115.0	45.1	69.9	18.0	42	3.54
		12 months	113.6	49.9	63.7	14.2	41	3.46
		24 months	111.5	50.9	60.6	16.0	41	3.55

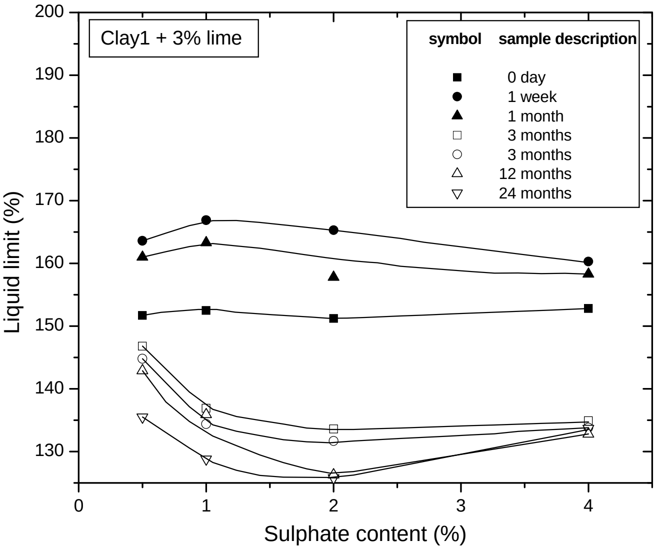

Fig. 4.1 Variation of liquid limit with sulphate content for clay1 treated with 3% lime

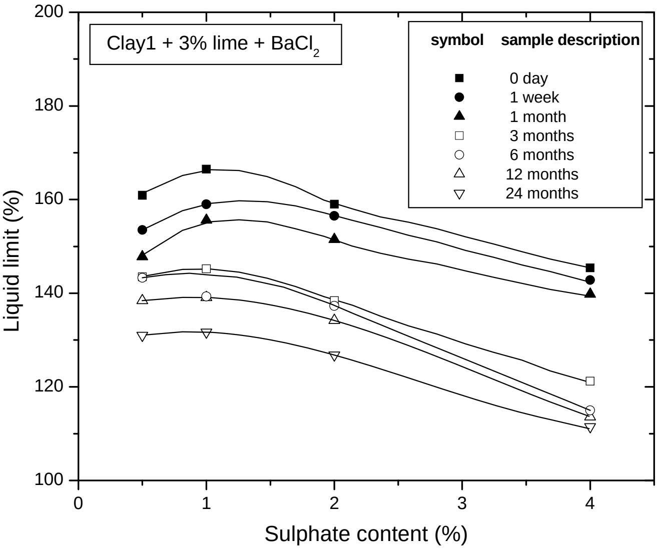

Fig. 4.2 Variation of liquid limit with sulphate content for clay 1 with treated 3% lime and $BaCl_2$

Variation of liquid limit with sulphate content as affected by curing time for clay 1 treated with 6% lime and with 6% lime and barium chloride is illustrated in Fig. 4.3 and Fig. 4.4 respectively.

In the presence of $Na_2\ SO_4$, both with 3% and 6% lime, the liquid limit is seen to increase up to a certain curing period. The increase of liquid limit continues for longer curing periods for increased percentage of lime and with 6% lime, higher the concentration of sulphate, higher is the increase. Rajasekaran et al. (2005) reports presence of sodium ions in the soil retards the diffusion of lime through the soil. It is also stated that presence of sodium sulphate leads to a system dominated with exchangeable sodium ions affecting the adsorption of calcium ions by the soil particles. Also the presence of monovalent sodium sulphate encourages the formation of ettringite in lime treated marine clay under favourable conditions. This is confirmed by the reduction in strength of lime treated clays cured for long periods in the presence of sulphates as presented in Chapter 6. In addition, some of the Na_2SO_4can get converted into sparingly insoluble $CaSO_4$ and thus effectively reduce the available lime. This can lead to decreased flocculation in the presence of sodium sulphate compared with lime alone (Ramesh, 2003).

4.3.2 Plastic limit

The increase in plastic limit in lime treated soils is attributed to increase in shear strength. A flocculated structure also yields higher plastic limit. A flocculated fabric which results from lime stabilization requires more water for thread formation and the same will be reflected in higher plastic limit.

In all the cases as given in Table 4.2 through 4.5, the plastic limit, though does not give a definite trend clearly shows that after curing for longer periods the decrease in plastic limit is more for soil – sulphate – lime system than that for the system where barium chloride has been incorporated.

Table 4.4 Physical properties of clay 1 treated with 6% lime and sulphate

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 1 (Sulphate Content = 0.5%)	0 day	155.6 ±2%	58.4 ±2%	97.2 ±2%	14.4 ± 1%	50 ±2%	4.45 ±0.2
		1week						
		1 month						
		3 months						
		6 months						
		12 months						
		24 months						
2	Clay 1 + 6% lime	0 day	166.8	65.4	101.4	31.9	51	5.70
		1week	163.5	61.4	102.1	28.5	45	5.91
		1 month	161.0	60.5	100.5	28.6	37	5.91
		3 months	169.2	72.5	96.7	30.4	-	5.73
		6 months	167.1	65.4	101.7	30.2	44	4.97
		12 months	172.0	83.4	88.6	31.7	43	4.80
		24 months	140.2	62.4	77.8	25.6	38	4.67
3	Clay 1 + 6% lime + 0.5% Sulphate	0 day	167.4	62.0	105.4	25.8	38	6.70
		1week	169.5	73.1	96.4	28.5	33	6.19
		1 month	173.6	73.2	100.4	32.1	37	6.19
		3 months	177.3	70.7	106.6	31.1	40	6.12
		6 months	169	70.2	98.8	25.9	44	5.45
		12 months	160.4	70.4	90.0	24.8	40	5.00
		24 months	134.4	63.9	70.5	18.8	35	4.99
4	Clay 1 + 6% lime + 1.5% Sulphate	0 day	167.0	61.1	105.9	32.7	-	6.34
		1week	164.0	68.0	96.0	-	-	-
		1 month	170.0	72.7	97.3	-	-	-
		3 months	173.1	72.0	101.1	26.8	43	5.74
		6 months	162.4	76.6	85.8	27.0	46	5.77
		12 months	154.6	72.3	82.3	29.9	44	5.74
		24 months	126.7	62.7	64.0	17.3	38	5.66
5	Clay 1 + 6% lime + 3.5% Sulphate	0 day	168.8	58.7	110.1	26.6	-	6.95
		1week	172.1	74.5	97.6	28.8	-	6.16
		1 month	175.1	79.2	95.9	27.5	-	6.19
		3 months	179.4	78.7	100.7	25.7	43	6.05
		6 months	160.0	74.0	86.0	23.0	44	6.07
		12 months	156.4	74.8	71.6	23.9	-	6.06
		24 months	127.8	64.6	63.2	14.8	40	5.99

Table 4.5 Physical properties of clay 1 treated with 6% lime, sulphate and barium chloride

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 1 + 6% lime + $BaCl_2$	0 day	154.3	51.8	102.5	28.8	48	6.02
		1week	151.2	56.1	95.1	28.2	32	5.54
		1 month	147.8	57.8	90.0	26.5	38	4.54
		3 months	146.3	60.1	86.2	24.0	39	4.15
		6 months	132.8	63.4	69.4	25.7	42	4.03
		12 months	136.0	62.9	73.1	26.1	39	4.01
		24 months	129.6	65.7	63.9	25.4	36	4.00
2	Clay 1 + 6% lime + 0.5% sulphate+ $BaCl_2$	0 day	161.1	67.0	94.1	30.6	-	6.30
		1week	156.7	72.2	84.5	29.4	37	4.33
		1 month	152.8	71.3	81.5	30.5	35	4.33
		3 months	143.8	66.9	76.9	21.8	39	3.24
		6 months	135.2	56.4	78.8	20.1	42	3.27
		12 months	129.0	63.0	66.0	24.1	36	3.18
		24 months	124.6	67.8	56.8	23.1	35	3.08
3	Clay 1 + 6% lime + 1.5% sulphate + $BaCl_2$	0 day	154.9	61.8	93.1	26.1	36	6.42
		1week	150.8	72.9	77.9	29.5	40	4.78
		1 month	147.0	72.2	74.8	28.4	40	4.48
		3 months	138.8	69.1	69.7	22.9	38	4.38
		6 months	132.8	53.7	79.1	23.8	34	3.07
		12 months	120.6	67.5	53.1	26.9	34	3.32
		24 months	116.9	70.2	46.7	25.9	34	3.07
4	Clay 1 + 6% lime + 3.5% sulphate + $BaCl_2$	0 day	153.6	61.7	91.9	26.1	-	6.03
		1week	148.5	72.8	75.7	-	-	-
		1 month	144.0	72.0	72.0	-	-	-
		3 months	133.5	64.4	69.1	28.8	41	4.41
		6 months	132.6	61.6	71.0	28.4	34	3.96
		12 months	119.0	66.7	52.3	28.8	-	3.42
		24 months	114.0	68.2	45.8	28.4	32	3.42

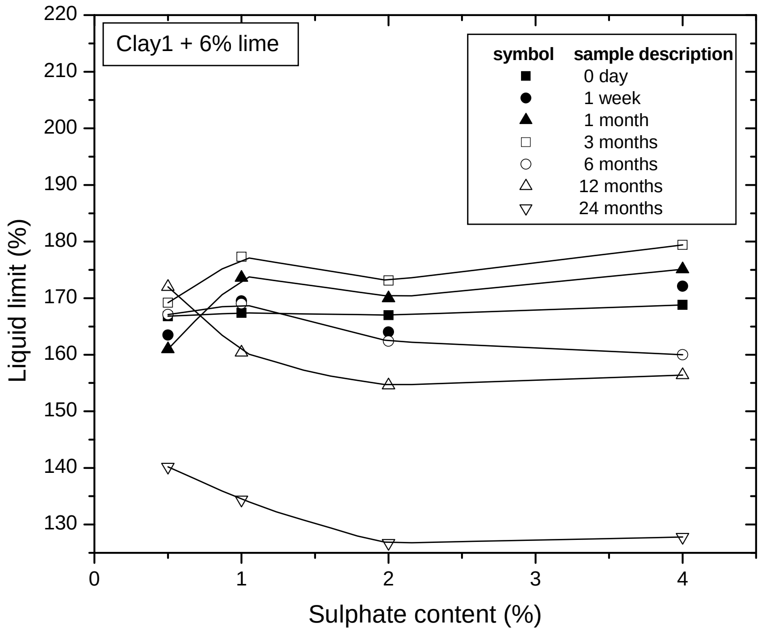

Fig. 4.3 Variation of liquid limit with sulphate content for clay 1 with 6% lime

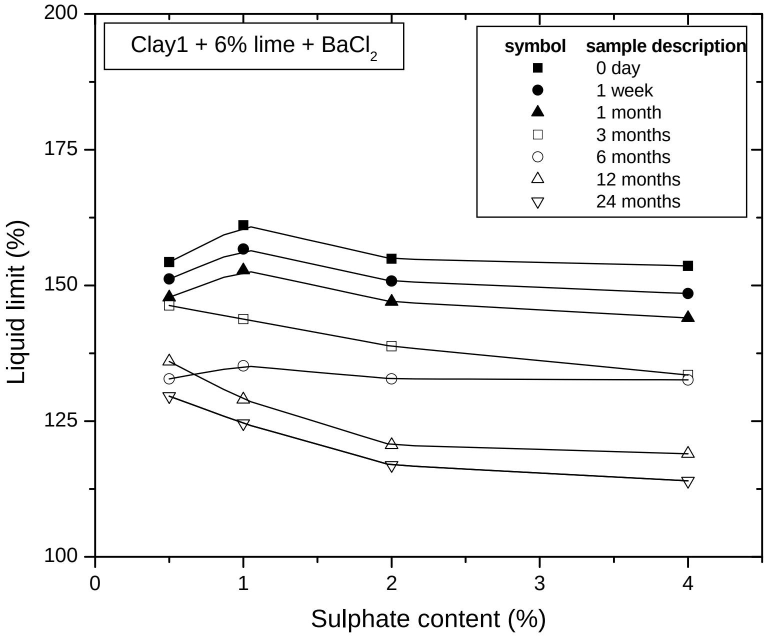

Fig. 4.4 Variation of liquid limit with sulphate content for clay 1 with 6% lime and $BaCl_2$

4.3.3 Plasticity index

Presence of any concentration of sulphate increases the plasticity index of lime treated clay 1, immediately. The increase in plasticity index increases with increasing concentration especially so in the case where soil has been treated with 6% lime. The plasticity index in all cases is found to reduce with curing period and is lowered more in case where barium chloride has been used as an additive. Where barium chloride has been used as an additive the plasticity index has decreased instantaneously, which is desirable as it increases workability (Tables 4.3 and 4.5).

Figs. 4.5 to 4.8 shows the plot between liquid limit and plasticity index for clay 1 treated with lime containing varying concentrations of sulphate and with and without additive. Even in the presence of various chemicals good correlation coefficients not less than 0.91 was observed in all cases. A statistical fit of the data yielded equations as noted down in the corresponding figures.

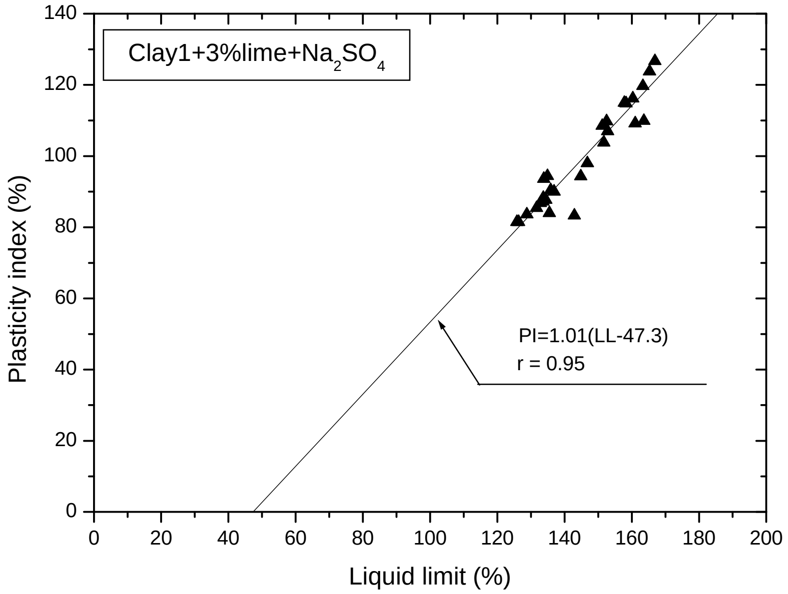

Fig. 4.5 Liquid limit vs. plasticity index for 3% lime treated clay 1with varying sulphate contents

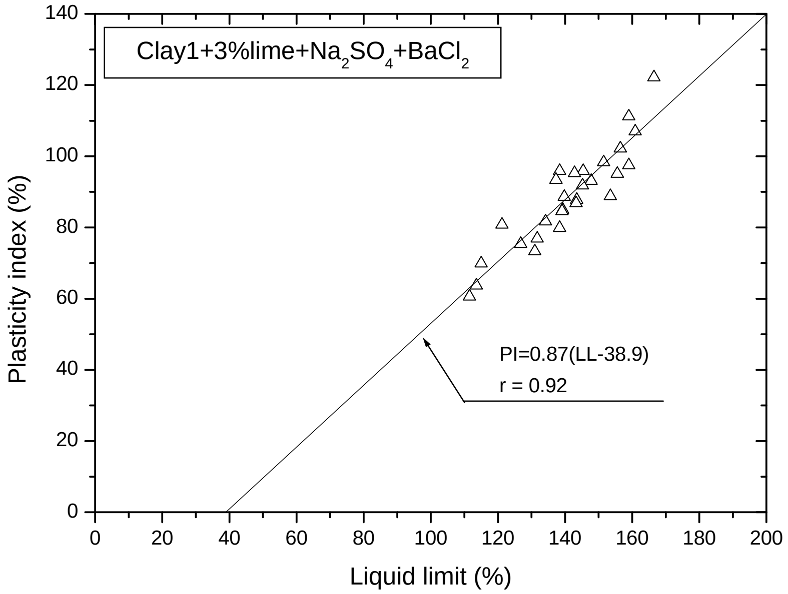

Fig.4.6 Liquid limit vs. plasticity index for 3% lime treated clay 1 with varying sulphate contents and barium chloride

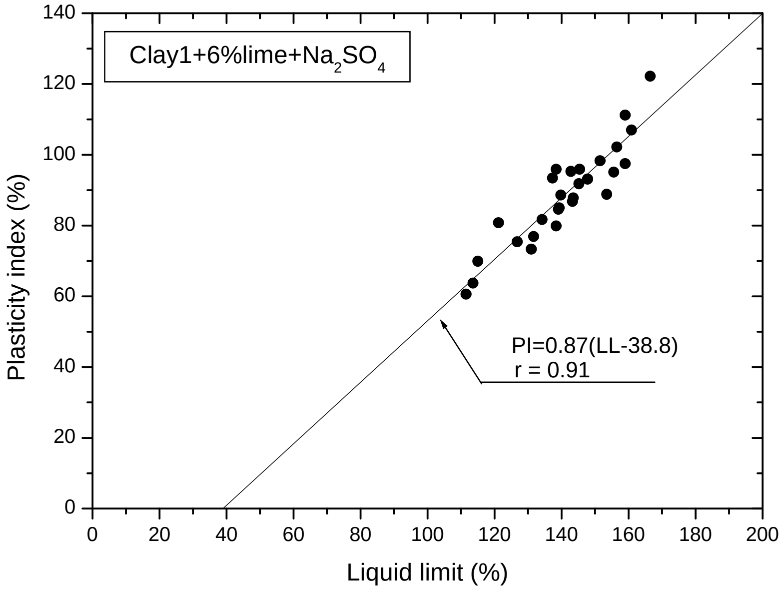

Fig. 4.7 **Liquid limit vs. plasticity index for 6% lime treated clay 1 with varying sulphate contents**

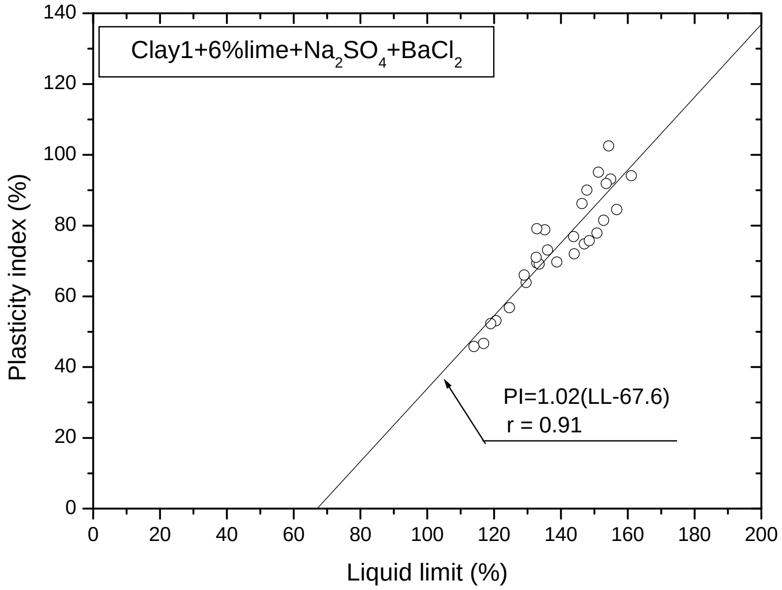

Fig. 4.8 **Liquid limit vs. plasticity index for 6% lime treated clay 1 with varying sulphate contents and barium chloride**

4.3.4 Shrinkage limit

Lime stabilization contributes to decrease in the double layer thickness and increase in the attractive forces at the inter-particle level. The increased attractive force induces higher shearing strength and thereby low volume reduction and hence higher shrinkage limit. The steep increase in shrinkage limit on curing of lime treated soils is due to formation of pozzolanic compounds, which are time dependent (Lambe, 1958b).

It can be seen from Tables 4.2 and 4.4 that curing in the presence of sulphate reduces shrinkage limit considerably. The decrease is prominent in 6% lime treated clay. This may be due to further reduction in strength and /or increased concentration of deleterious compounds formed. Presence of sulphate has thus ruled out the possibility of well flocculated arrangement of particles.

But with usage of barium chloride as additive shrinkage limit has increased in most cases. This may be due to lesser reduction in strength in the presence of these additives.

4.3.5 Grain size distribution

Typical grain size distribution plots for clay 1 and clay 2 treated with various additives is given in Figs. 4.9 to 4.16.

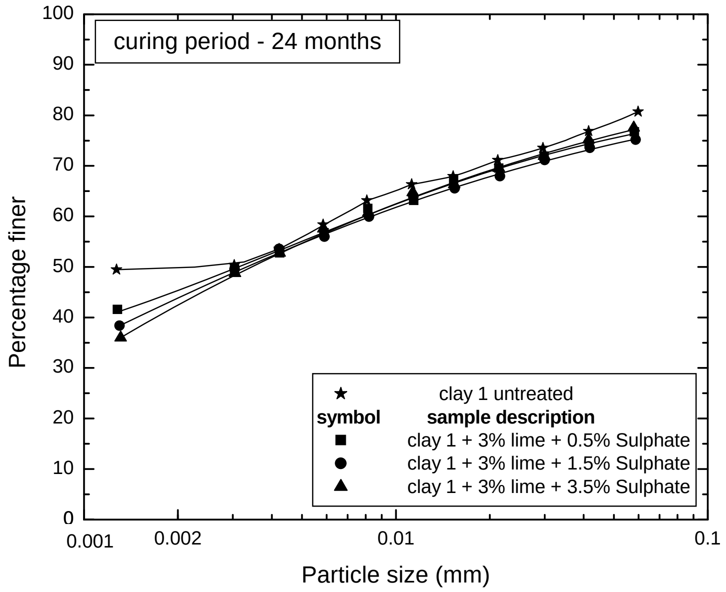

Fig. 4.9 Grain size distribution curves for 3% lime treated clay 1 with varying sulphate contents

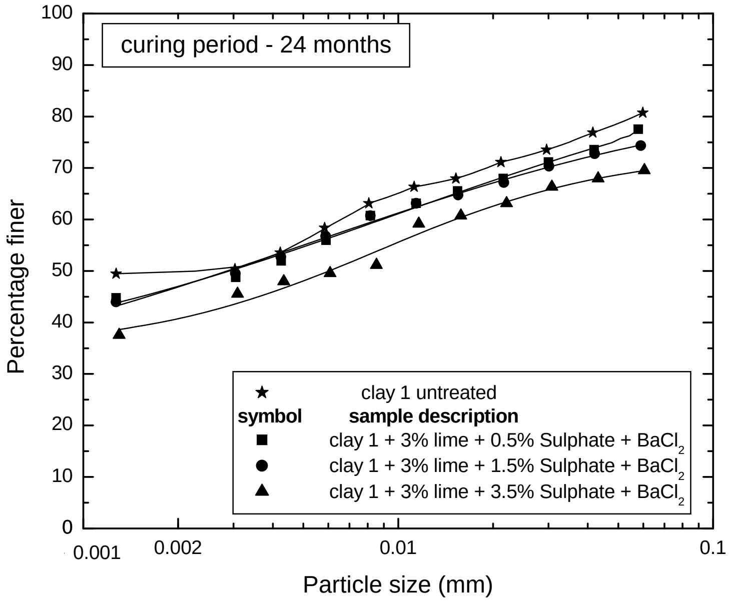

Fig. 4.10 Grain size distribution curves for 3% lime treated clay 1 with varying sulphate contents and barium chloride

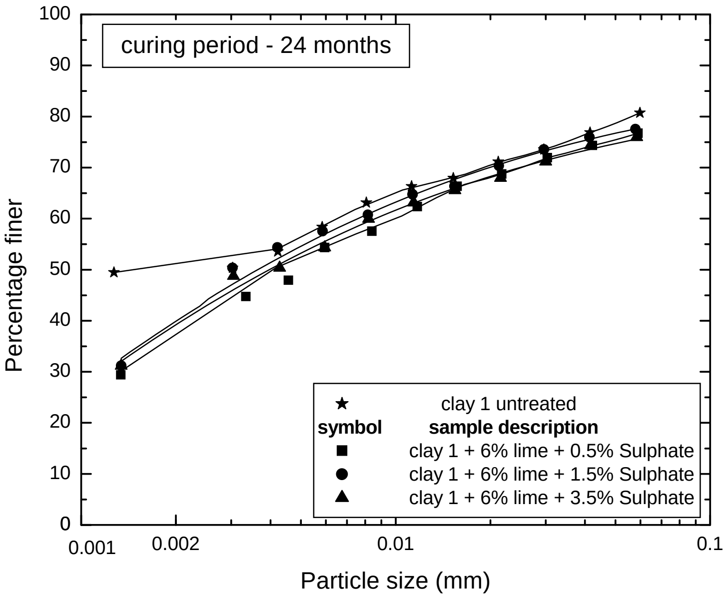

Fig. 4.11 Grain size distribution curves for 6% lime treated clay 1 with varying sulphate contents

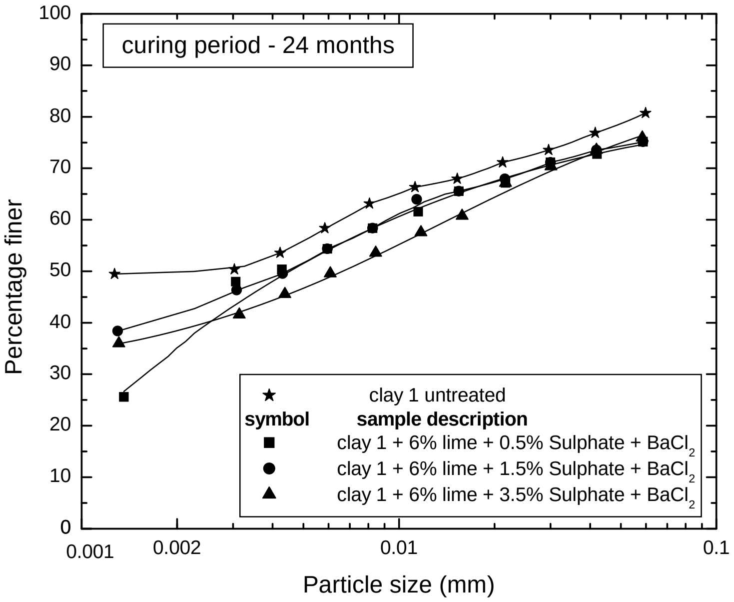

Fig. 4.12 Grain size distribution curves for 6% lime treated clay 1 with varying sulphate contents and barium chloride

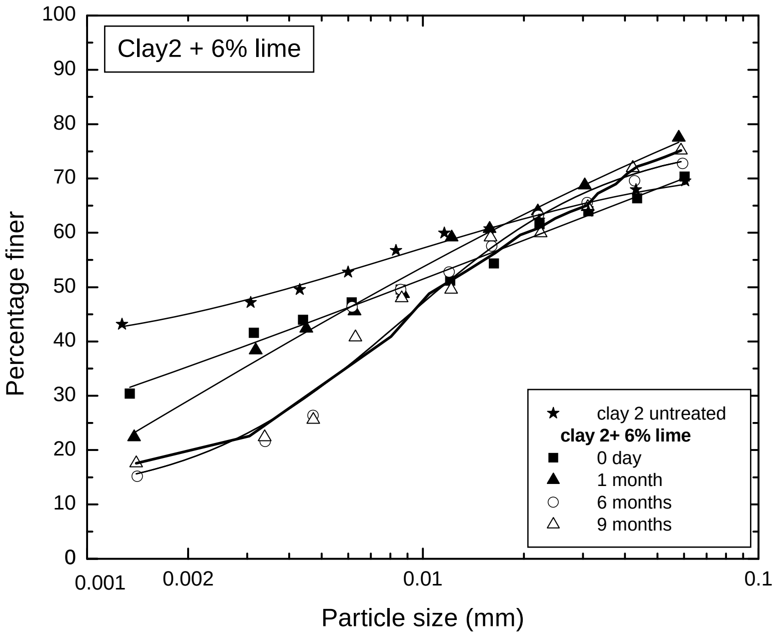

Fig. 4.13 Grain size distribution curves for 6% lime treated clay 2

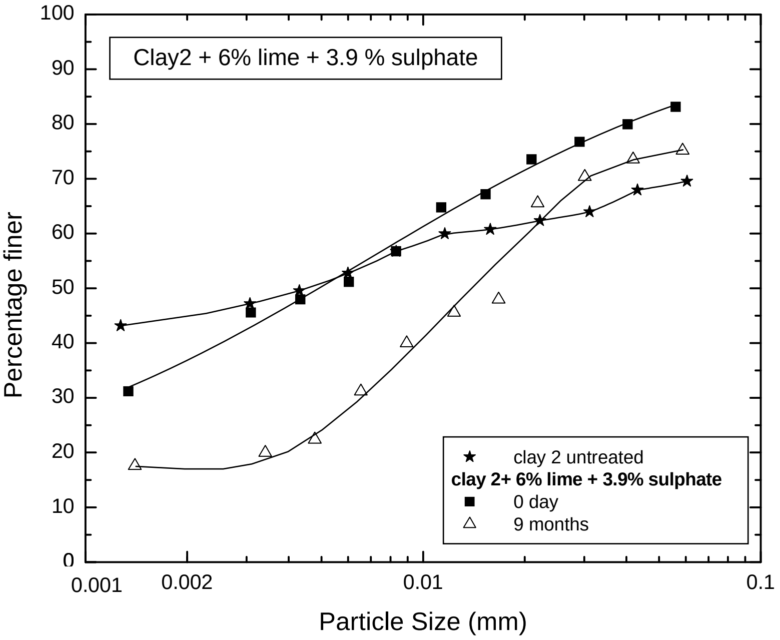

Fig. 4.14 Grain size distribution curves for 6% lime treated clay 2 with 4% sulphate

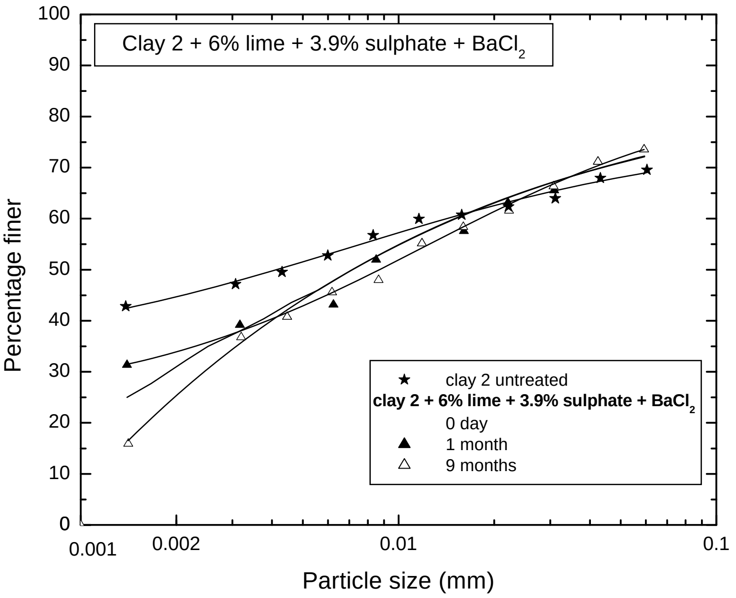

Fig. 4.15 Grain size distribution curves for 6% lime treated clay 2 with 4% sulphate and barium chloride

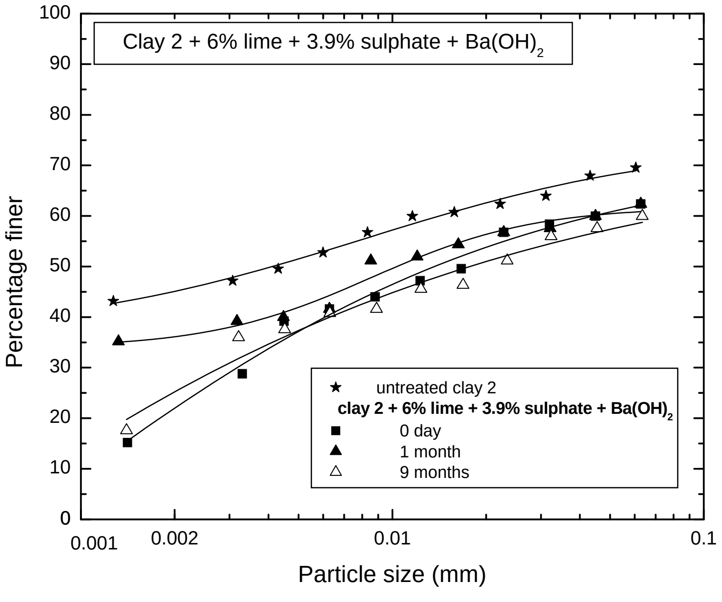

Fig. 4.16 Grain size distribution curves for 6% lime treated clay 2 with 4% sulphate and barium hydroxide

4.3.6 Free swell index

Addition of lime initially increases the free swell volume and this is attributed to flocculation of clay particles (Ingles and Metcalf, 1972). Along with flocculation the decrease in the repulsive forces may also occur due to depression of the diffuse double layer due to increase in concentration of cations and change of monovalent ions by divalent ions. The effect of replacement of original monovalent ions present in clay by calcium ions and resulting excess ion concentration of cations is to decrease the thickness of diffuse double layer thereby reducing the volume of the sediment suspension occurs.

The free swell volume of the lime treated soil will generally be greater than the soil alone, showing that the effect of flocculation is predominant than the effect of cation exchange. With increase in curing period, pozzolanic compounds formed cement the soil particles together and aggregation takes place. The aggregated particles consolidate due to their self - weight and the free swell volume decreases. After a certain curing period the free swell volumes remain more or less a constant indicating that further cementation of particles does not cause any perceptible volume changes.

This is seen true in the cases where barium chloride has been used as an additive where in the free swell index has reached more or less a constant value within three months curing as shown in Tables 4.3 and 4.5.

Whereas, the tabulated values in Tables 4.2 and 4.4 clearly show that presence of sulphate has a tendency to keep the free swell volumes at increased levels.

4.3.7 Comparative study of the effect of barium chloride and barium hydroxide

Similar trends as given in Tables 4.4 and 4.5 have been observed for clay 2 as shown in Tables 4.6 and 4.7.

The variation of liquid limit, plasticity index, shrinkage limit and free swell index with curing of lime treated clay 2 with 4% sulphate as well as in the presence barium chloride and barium hydroxide as additive is illustrated in Figs. 4.17 to 4.20. Figs. 4.17 and 4.19 indicate that barium hydroxide additive is capable of creating a more open fabric. Higher values of liquid limit and shrinkage limit is indicative of development of flocculant fabric. Water accumulation tends to be more in open fabric. Free swell index values for clay 2 + 3.9% sulphate at any curing period is higher when compared to samples where either barium chloride or barium hydroxide has been used to counteract the effect of sulphates (Fig. 4.20). Barium chloride helps to lower free swell volumes with curing period and barium hydroxide has a tendency to still lower the values.

In spite of the various additives added, good correlation with a correlation coefficient not less than 0.94 was obtained between liquid limit and plasticity index was obtained for clay 2 treated with various additives. The same is depicted in Figs. 4.21 to 4.24.

Table 4.6 Physical properties of lime treated clay 2 with sulphate and treated with barium chloride and barium hydroxide additive

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 2 (Sulphate Content = 0.1%)	0 day	139.5 ± 2%	54.49 ± 2%	85 ± 2%	18.62 ± 1%	45 ± 2%	3.9 ± 0.2
		1week						
		1 month						
		3 months						
		6 months						
		9 months						
		12 months						
2	Clay 2 + 6% lime	0 day	-	-	-	-	35.0	-
		1week	140.8	60.7	80.1	32.1	-	4.75
		1 month	136.8	66.4	70.4	30.6	28.0	4.64
		3 months	127.8	67.0	60.8	35.3	25.5	4.41
		6 months	125.2	68.9	56.3	37.2	17.0	4.42
		9 months	124.3	68.1	56.2	41.4	19.0	4.20
		12 months	122.9	65.7	57.2	46.5	-	4.18
3	Clay 2 + 6% lime + 3.9% sulphate	0 day	-	-	-	-	37.0	-
		1week	144.5	56.4	88.1	31.5	-	4.98
		1 month	143.0	68.7	74.3	32.1	31.0	4.74
		3 months	128.9	62.8	66.1	33.9	31.0	4.55
		6 months	127.1	62.5	64.6	31.2	23.0	4.59
		9 months	125.4	62.9	62.5	27.8	23.0	4.56
		12 months	125.1	63.3	61.8	25.4	-	4.56
4	Clay 2 + 6% lime + 3.9% sulphate + BaCl$_2$	0 day	-	-	-	-	27.0	-
		1week	128.1	66.5	61.6	30.7	-	4.49
		1 month	127.8	68.9	58.9	30.2	35.0	4.40
		3 months	113.9	60.0	53.9	36.7	39.0	4.05
		6 months	109.3	60.6	48.7	39.1	23.0	4.15
		9 months	109.9	62.5	47.4	42.6	23.0	3.85
		12 months	108.0	60.0	48.0	47.6	-	3.77
5	Clay 2 + 6% lime + 3.9% sulphate + Ba(OH)$_2$	0 day	-	-	-	-	20.0	-
		1week	130.6	63.4	67.2	32.4	-	4.21
		1 month	130.4	69.4	61.0	35.7	37.0	4.17
		3 months	121.8	64.5	57.3	41.9	35.0	3.90
		6 months	115.9	63.7	52.2	42.7	36.0	*
		9 months	115.7	66.9	48.8	46.7	24.0	*
		12 months	114.9	65.5	49.4	51.2	-	*

Table 4.7 Physical properties of clay 2 treated with 6% additives

Sl. No.	Sample description	Curing period	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Shrinkage limit (%)	Clay size (%)	Free swell index (cc/g)
1	Clay 2 + 6% lime	0 day	-	-	-	-	35	-
		1week	140.8	60.7	80.1	32.1	-	4.75
		1 month	136.8	66.4	70.4	30.6	28	4.64
		3 months	127.8	67.0	60.8	35.3	25	4.41
		6 months	125.2	68.9	56.3	37.2	17	4.42
		9 months	124.3	68.1	56.2	41.4	19	4.20
		12 months	122.9	65.7	57.2	46.5	-	4.18
2	Clay2 + 6% $BaCl_2$	0 day	126.7	46.9	79.8	15.5	39	4.18
		1week	126.1	47.7	78.4	15.7	32	4.07
		1 month	125.0	47.4	77.6	17.32	39	3.59
		3 months	125.2	50.4	74.8	17.6	36	3.42
		6 months	122.8	48.1	74.7	17.7	42	3.16
		9 months	122.4	51.0	71.4	17.9	-	3.15
3	Clay2 + 6% $Ba(OH)_2$	0 day	149.1	55.2	93.9	15.5	43	4.49
		1week	132.1	52.4	79.7	15.8	40	3.94
		1 month	123.5	52.0	71.5	15.9	41	3.34
		3 months	118.3	50.0	68.3	17.1	43	3.19
		6 months	117.9	50.2	67.7	17.7	42	2.99
		9 months	113.7	50.2	63.5	18.0	-	2.97

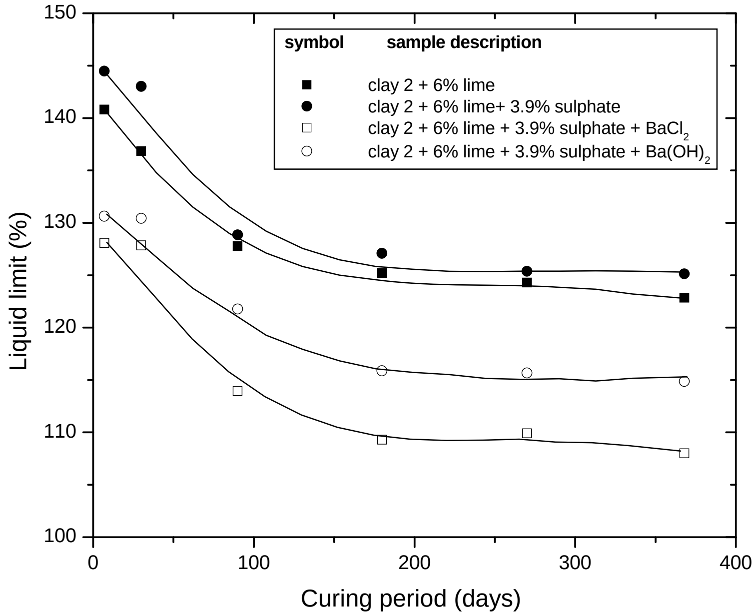

Fig. 4.17 Variation of liquid limit with curing period for clay 2

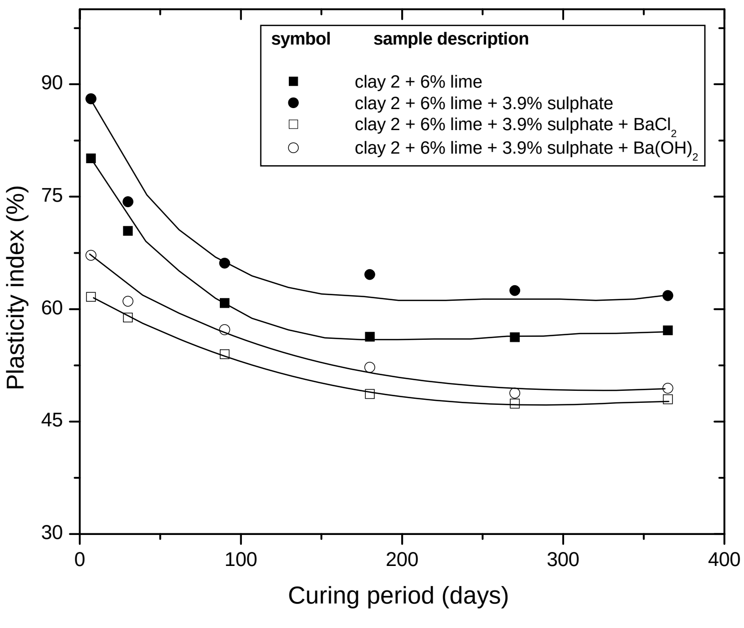

Fig. 4.18 Variation of plasticity index with curing period for clay 2

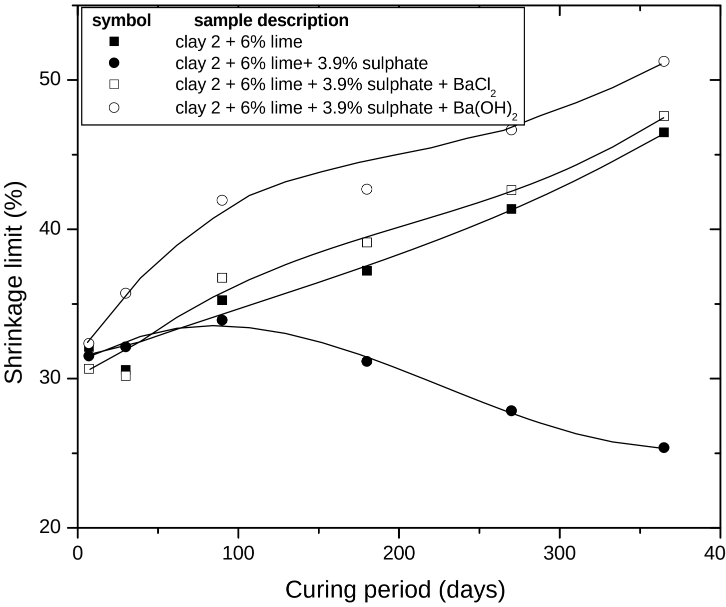

Fig. 4.19 Variation of shrinkage limit with curing period for clay 2

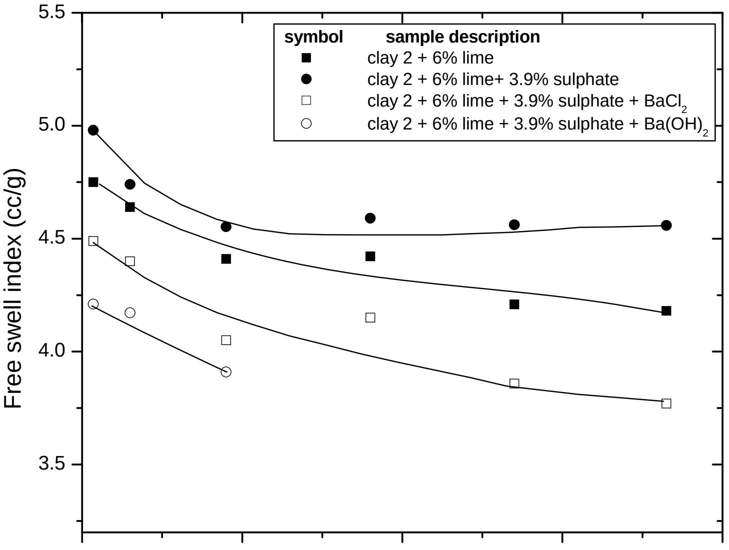

Fig. 4.20 Variation of free swell index with curing period for clay 2

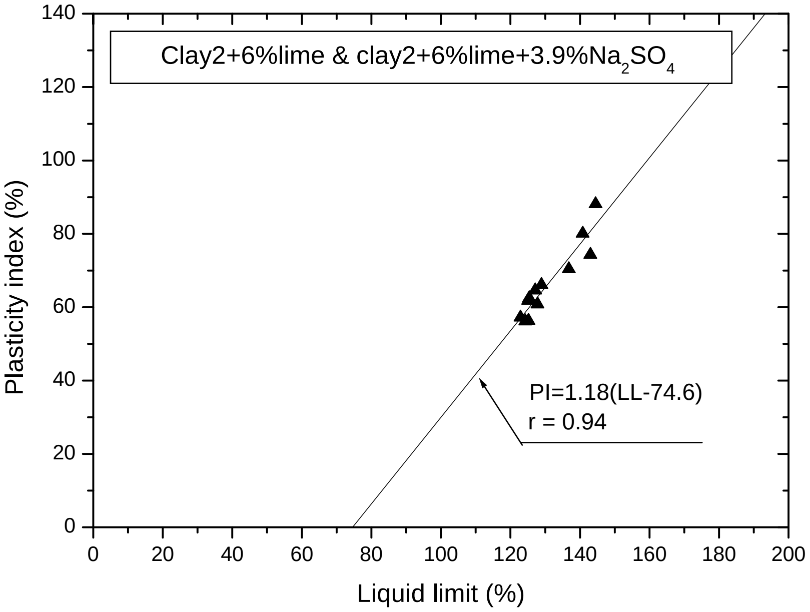

Fig. 4.21 Liquid limit vs. plasticity index for 6% lime treated clay 2 with 4% sulphate

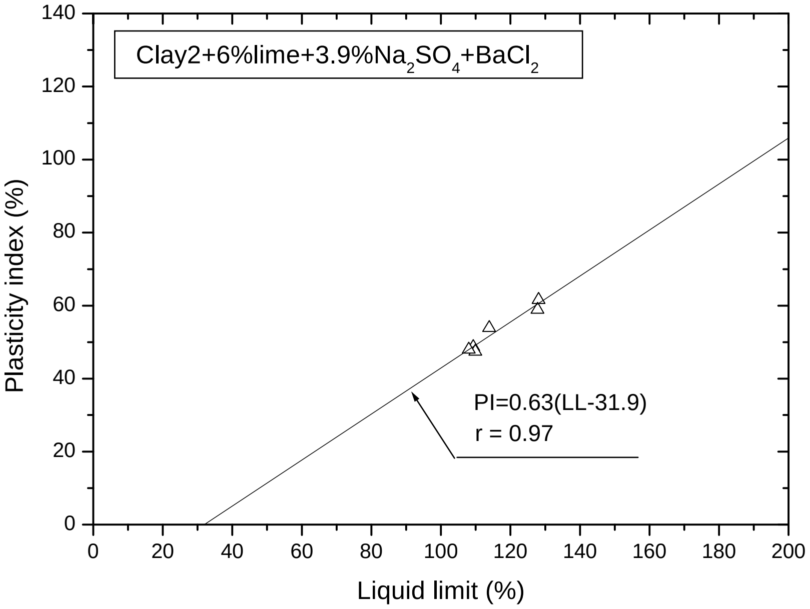

Fig. 4.22 Liquid limit vs. plasticity index for 6% lime treated clay 2 with 4% sulphate and barium chloride

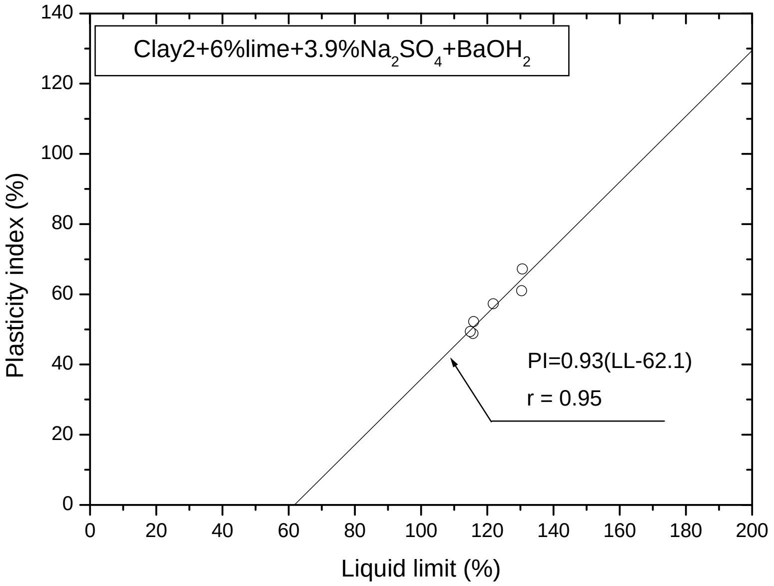

Fig. 4.23 Liquid limit vs. plasticity index for 6% lime treated clay 2 with 4% sulphate and barium hydroxide

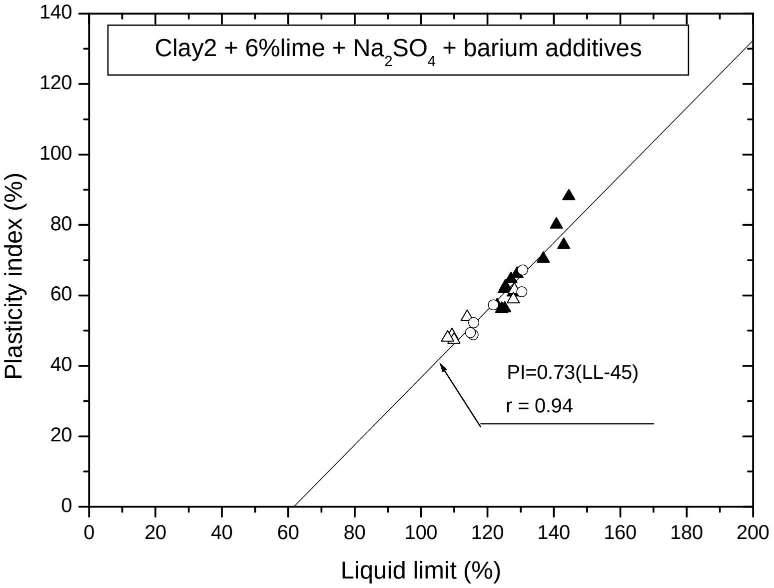

Fig. 4.24 Liquid limit vs. plasticity index for 6% lime treated clay 2 with 4% sulphate and barium additives

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Chapter 5

COMPRESSIBILITY BEHAVIOUR OF LIME STABILISED CLAYS CONTAINING SULPHATE AND TREATED WITH BARIUM COMPOUNDS

Contents

5.1 Introduction

Soft clay is encountered in geotechnical engineering practice all over the world. In general, the soils which exist in the coastal corridors are soft marine clays, formed by the deposits and these are generally weak and highly compressible in nature. These soils possesses low stiffness, low shear strength and high compressibility, and thus presents a great challenge to geotechnical engineers, as both the strength requirement and serviceability requirement of upper structures may not be satisfied. Many offshore structures and coastal structures are required to be built on clayey soils. The main drawbacks of clayey soils when required to carry structural loads are their low bearing capacities and tendency to undergo large settlements in course of time. Problems of stability and settlement of structures constructed over such deposit persists even under small loads. Barring a few heavily loaded structures, large numbers of lightly loaded structures (2 - 3 storey, load at foundation level 8 t/m^2 to 12 t/m^2) are constructed for various purposes including the normal dwelling houses for the general public living in the coastal areas. To overcome the difficulty of large post construction settlement due to low bearing capacity and high compressibility foundations are conventionally constructed on wooden or concrete piles. As a result, relatively a large sum of money is spent for the construction of foundation even for the lightly loaded structures as mentioned above. In view of the above, a need exist to improve the bearing capacity of the soft coastal clay so that at least the lightly loaded structures can be founded on the ground of improved bearing capacity without resorting to deep foundations or any other special measures.

Compressibility property of soil is also pivotal part in the building of roads and airport, and embankments. In order to minimize settlement in the geotechnical structures such as embankments, structural backfills, other compacted fills and roadways, the compressibility properties of soil should be controlled.

Lime is frequently used to improve the volume change behaviour of soils (Thompson, 1966; Broms and Boman, 1979; Transportation Research Council, 1987; Blacklock and Pcngelly, 1988; Petry and Armstrong, 1989 to name a few). Volume change behaviour of clay – water – electrolyte system is significantly influenced by the attractive and repulsive forces. Addition of lime increases the attractive forces between clay particles and thereby reduces the volume changes (Somayazulu, 1987). Curing with lime further reduces the volume changes because of cementation of the clay particles due to pozzolanic compounds formed by the reaction between clay and lime.

It has been brought out in chapter 4 that the physical properties of lime treated Cochin marine clays are altered in the presence of sulphate. These variations in properties are an indication of alterations in the normal pozzolanic reactions which should have otherwise taken place in the absence of sulphates. Presence of sulphate is reported to prevent cementation of particles and thereby cause a reduction in shear strength of lime treated black cotton soils (Sivapullaiah, et al. 2000). Sridharan et al. (1995) showed that the presence of sulphate led to an increase in the compressibility of lime-treated black cotton soil after curing for long periods.

Since only limited data are available concerning the volume change behaviour of lime treated Cochin marine clay containing sulphate, further investigations are desirable. A detailed study on sulphate induced undesirable changes on the compression and consolidation characteristics of lime treated Cochin marine clay is therefore attempted in this chapter.

5.2 Experimental program

In an attempt to determine the effectiveness of lime stabilisation techniques in the presence of sulphate and to investigate the sulphate induced variations in long term compressibility characteristics of lime – soil systems with time, standard consolidation tests were carried out as per the experimental program detailed in Table 5.1. Preparation of samples consisted of mixing soil with the various additives in concentrations given in Table 5.1, bringing them to liquid limit consistency by adding required amount of water and curing them for various periods as explained in section 3.3.2 of chapter 3. The specimens cured for period ranging from 0 day to 2 years were subjected to consolidation test under different pressures ranging from 6.25 k Pa to 400k Pa. In this study, the changes in, compression index, coefficient of consolidation, preconsolidation pressure and secondary compression coefficient of 6% lime treated clay specimens with varying sulphate contents and barium compounds sufficient to counteract their effect were investigated and reported.

Table 5.1 Experimental program for consolidation tests

Soil	Additives (%)			Curing period
	Lime	$Na_2 SO_4$	Barium compound	
Clay 1	0%	0%	0%	0, 7, 30, 90, 180, 365, 730 days
	3% & 6%	0%	0%	
		0%	Barium Chloride	
		0.5%	-	
			Barium Chloride	
		1.5%	-	
			Barium Chloride	
		3.5%	-	
			Barium Chloride	
Clay 2	0%	0%	0%	0, 30, 90, 180, 270 days
	3%	0%	0%	
	6%	0%	0%	

5.3 Results and discussions

5.3.1 Void-ratio pressure relationships

Figure 5.1 shows the effective pressure (p) – void ratio (e) curves commonly referred to as the ‘‘e–log p curves’’ for lime treated clay 1 containing 0.5% natural sulphate and cured for various periods. Fig. 5.1 brings out that the void ratios of sample cured for 6 months at any pressure are lower than samples cured for 3 months. This decrease in void ratio due to increase in compressibility can be attributed to decrease in bond strength consequent to alteration of the pozzolanic reaction compounds formed by soil – lime interactions in the presence of sulphate. A further decrease in void ratio is not predominant in the case of sample cured for one year or two years compared to sample cured for 180 days showing that once the sulphate present in soil is consumed in alteration of the soil - lime reaction products, the normal soil - lime reactions takes place increasing the bond strength leading to no further decrease in void ratio.

Fig. 5.2 illustrates the effect of curing on void ratio-pressure relationships for lime treated clay 1 treated, with barium chloride, sufficient enough to counteract the sulphate present. It can be seen that inclusion of barium chloride can reduce compressibility quite effectively. With the incorporation of barium chloride, the system can resist the compression loading much better and consequently shows lesser compressibility.

Figs.5.2 (a) to (g) shows the compressibility curves for lime treated clay 1 samples cured for various periods with and without barium chloride. It is seen that cured samples in the presence of barium chloride resist the external load very effectively resulting in flatter load–compression curves. The negative effect of sulphate might have been counteracted by barium chloride which is capable of reacting with sodium sulphate resulting in its conversion into insoluble $BaSO_4$.

Figs. 5.3 (a) to (c) illustrates the effect of barium chloride on 6% lime treated clay 1 with 1% sulphate and cured for 3, 6 and 24 months. These results also support the above conclusions.

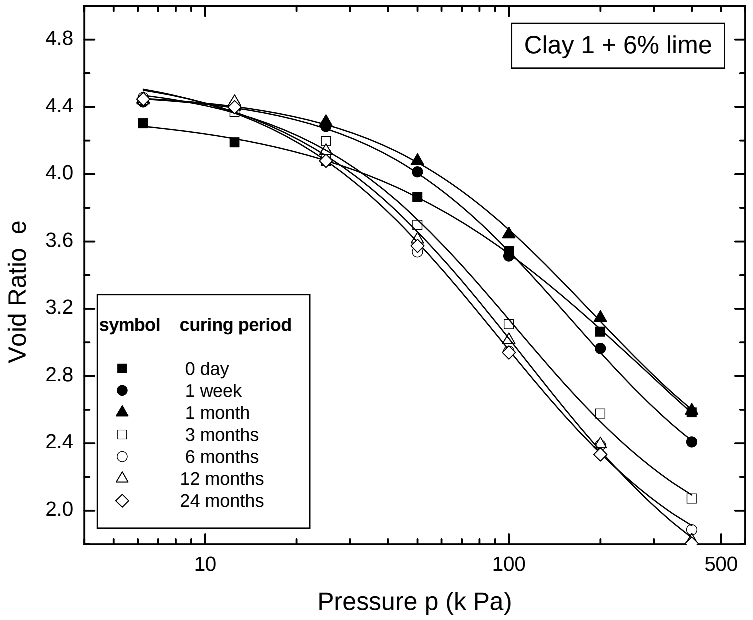

Fig. 5.1 e - log p curves for 6% lime treated clay 1 (containing 0.5% natural sulphate)

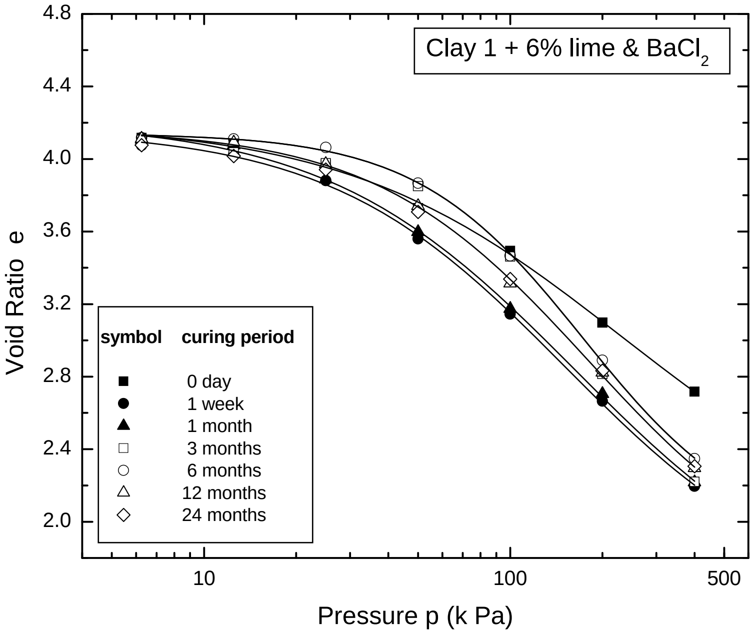

Fig. 5.2 e - log p curves for 6% lime treated clay 1 with barium chloride

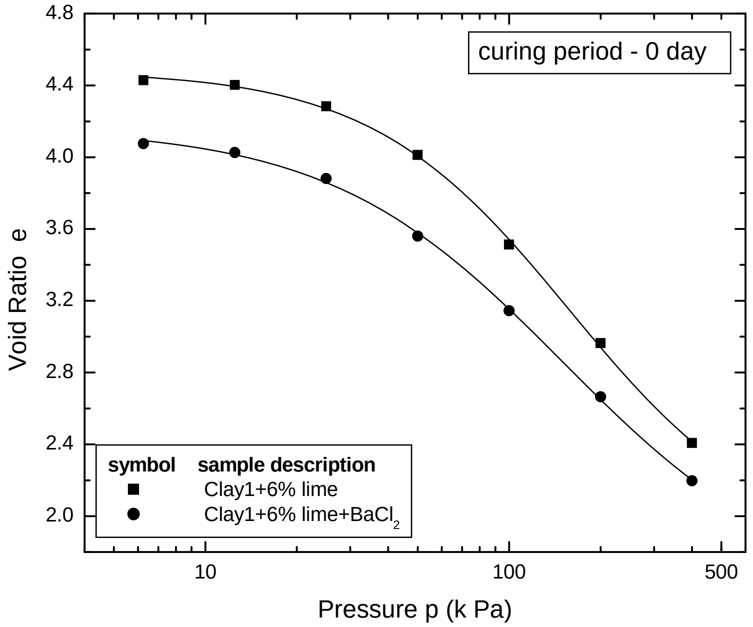

Fig. 5.2 (a) Effect of barium chloride on 6% lime treated clay 1 (immediate)

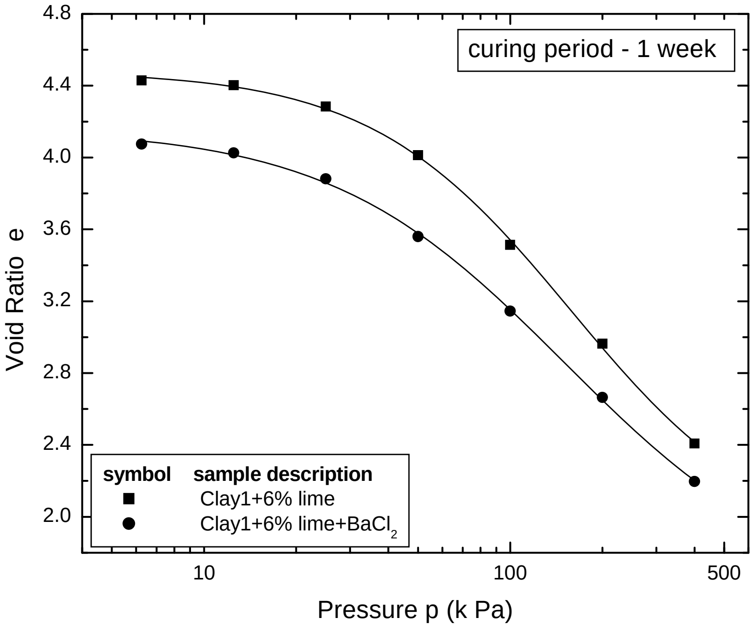

Fig. 5.2 (b) Effect of barium chloride on 6% lime treated clay 1 cured for one week

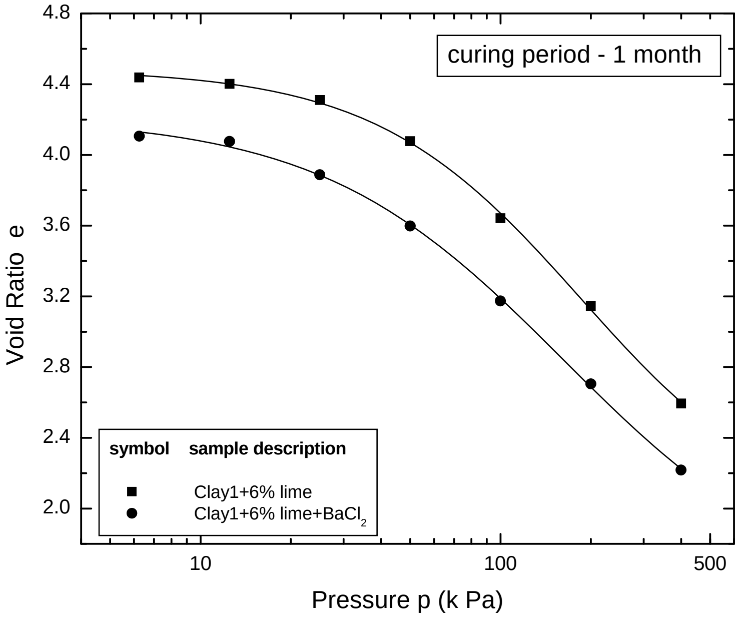

Fig. 5.2 (c) Effect of barium chloride on 6% lime treated clay 1 cured for one month

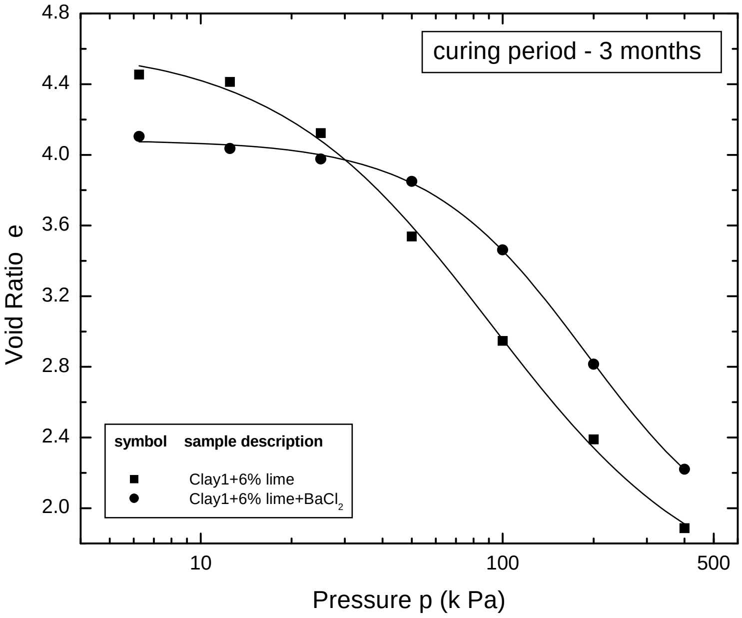

Fig. 5.2 (d) Effect of barium chloride on 6% lime treated clay 1 cured for three months

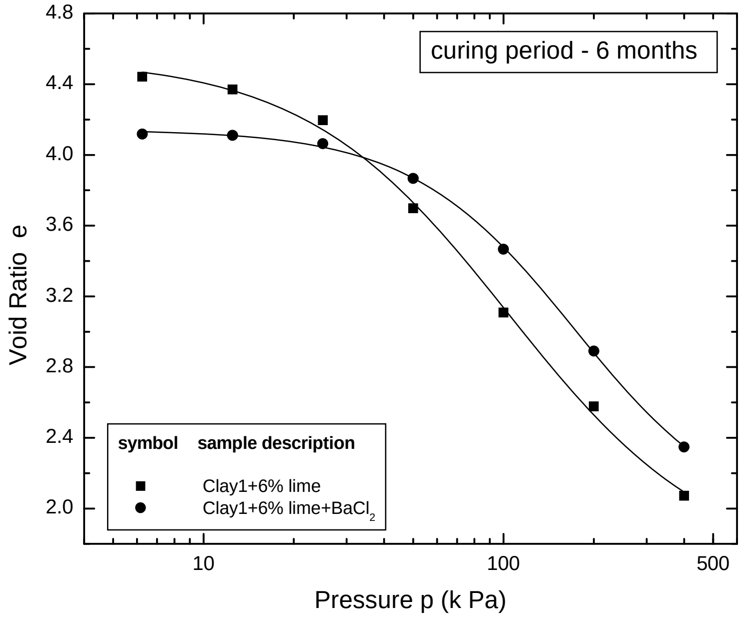

Fig. 5.2 (e) Effect of barium chloride on 6% lime treated clay 1 cured for six months

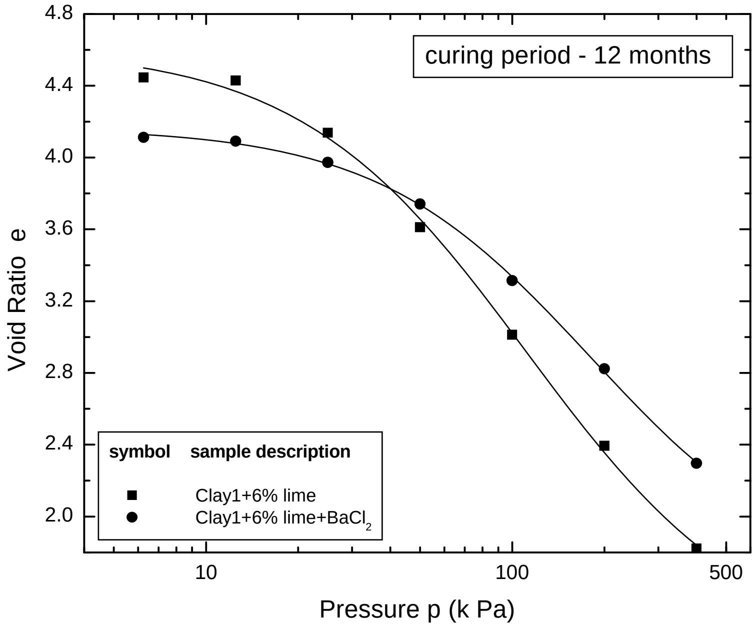

Fig. 5.2 (f) Effect of barium chloride on 6% lime treated clay 1 cured for 12 months

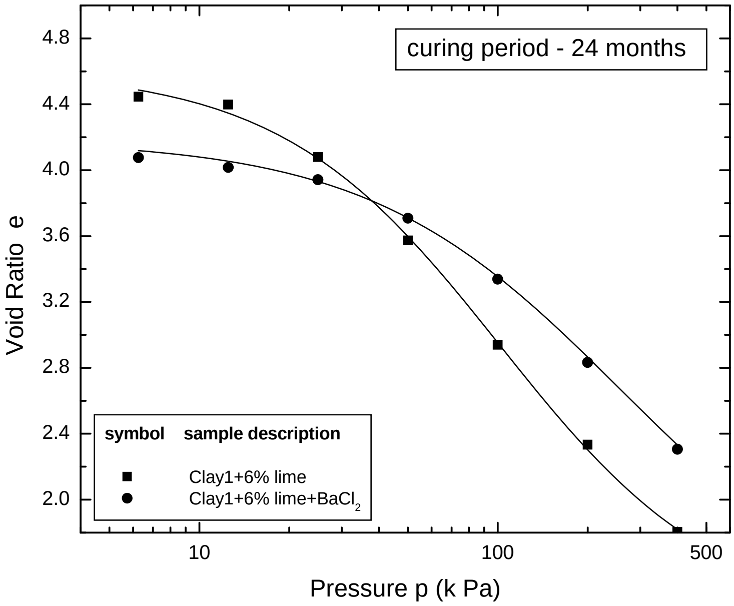

Fig. 5.2 (g) Effect of barium chloride on 6% lime treated clay 1 cured for 24 months

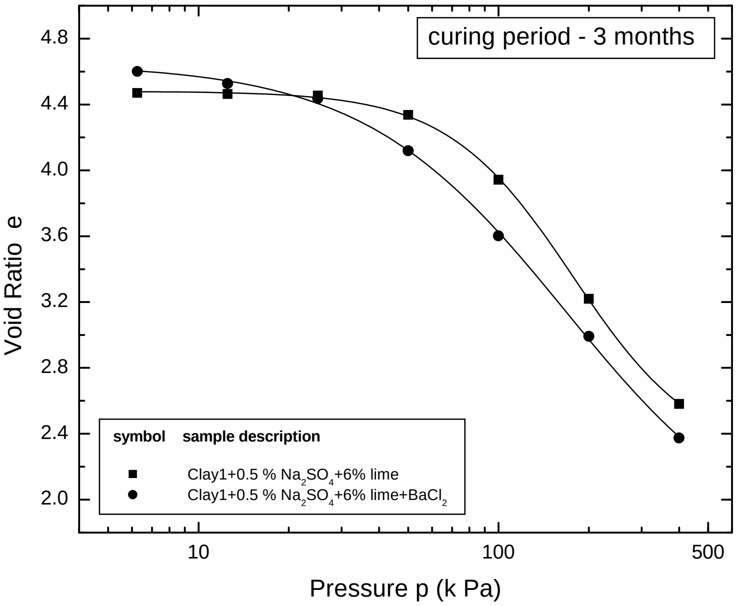

Fig. 5.3 (a) Effect of barium chloride on 6% lime treated clay 1 with1% sulphate and cured for 3 months

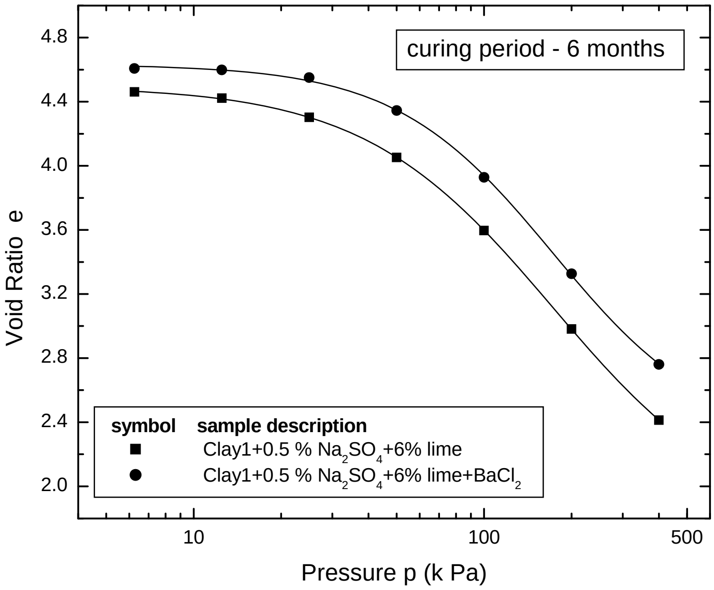

Fig. 5.3 (b) Effect of barium chloride on 6% lime treated clay 1 with 1% sulphate and cured for 6 months

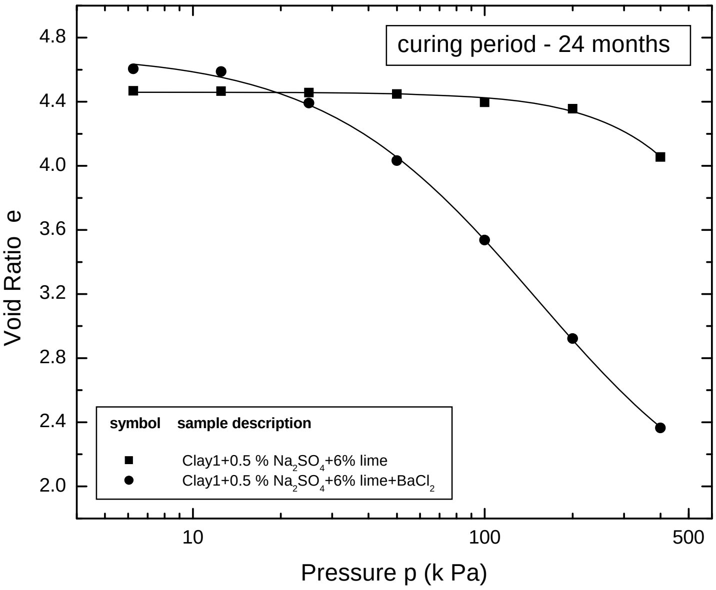

Fig. 5.3 (c) Effect of barium chloride on 6% lime treated clay 1 with 1% sulphate and cured for 24 months

Fig. 5.4 (a) depicts the e-log p curves for lime treated clay 1 samples containing 2% sulphate cured for various periods. It can be observed that the void ratio at any pressure generally decreases with increase in curing period. The decrease continues steadily up to one year. The inconspicuous decrease in void ratio after one year in spite of curing for another 365 days, may indicate that the sulphate content is capable enough of causing further alteration in pozzolanic reactions is not present in the system. The results of strength tests on cured lime treated clays with sulphate content presented in chapter 7, lends support to this view. These results clearly establish that soil-lime reactions affect the compressibility behaviour of the system. The diffused sodium ions definitely affect the lime-induced changes in soil. This phenomenon weakens the soil system and affects its behaviour with time.

Fig 5.4 (b) shows the e log p curves for 6% lime treated clay 1 with 2% sulphate and the same treated with barium chloride and cured for twelve months. The decrease in compression clearly brings out the role of barium chloride in counteracting the negative effect of sulphates resulting in increased bond strength and corresponding reduction in the volume change of the lime – soil – sulphate system.

The effect of barium chloride is again brought out in the dial gauge reading vs. log t plot for 6% lime treated clay 1 with 2% sulphate. The dial gauge reading vs. log plot of load range 50 – 100 k Pa, for the same is compared with a system wherein barium chloride has been introduced and with 6% lime treated clay 1 having 0.5% natural sulphate (fig. 5.4(c)).

The compression is maximum for lime treated clay 1 with 2% natural sulphate, followed by lime treated clay 1 with 0.5 % sulphate. Compression is least wherein lime treated clay 1 with 2% sulphate has been treated with barium chloride sufficient enough to counteract the effect of sulphate present.

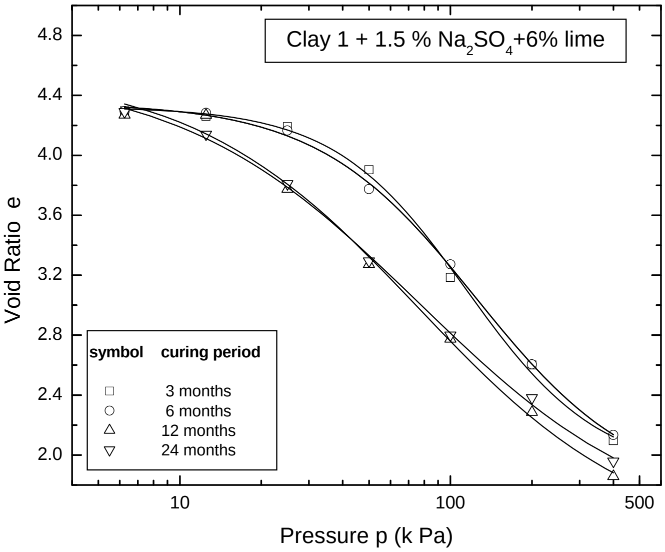

Fig. 5.4 (a) e-log p curves for 6% lime treated clay 1 with 2% sulphate

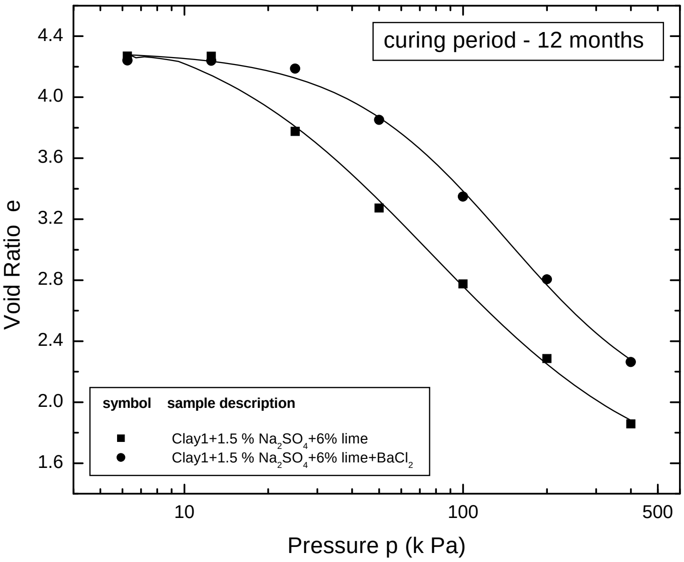

Fig. 5.4 (b) Effect of barium chloride on 6% lime treated clay 1 with 2% sulphate and cured for 12 months

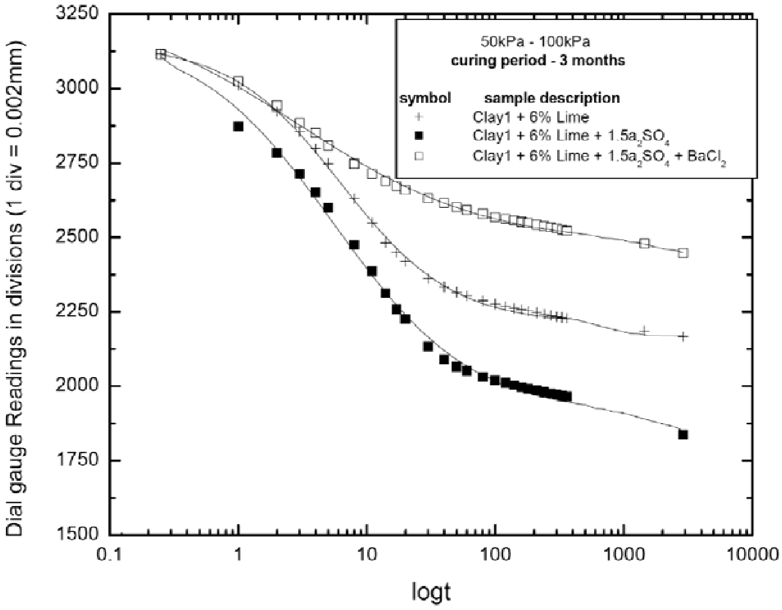

Fig. 5.4 (c) Dial gauge reading vs. log time (t) curves

Fig. 5.5 illustrates void ratio pressure relationship for lime treated clay 1 with varying sulphate contents, 0.5%, 1%, 2% and 4% and cured for 2 years.

It can be visualised that with increase in sulphate concentrations compressibility increases. This increase in compression might be due to conversion of part of $Ca(OH)_2$ into $CaSO_4$ reducing the availability of lime for normal soil lime reactions. It is evident that with increase in sulphate content the compressibility turns out to be more. This may be due to decreased availability of lime for formation of normal pozzolanic products as a result of increased sulphate concentration. Tsatos and Dematos (1998) have reported the ettringite formation and the calcium silicate hydrate (CSH) phase are associated with each other in sulphate enriched lime - treated soil systems.

According to Sridharan and Venkatappa Rao (1973), volume change behaviour of clays is mainly governed by two mechanisms: shearing resistance at the interparticulate level in the case of non – expanding lattice type minerals such as Kaolinite and diffused double – layer – induced repulsive forces in the case of expanding lattice – type monmorillonite mineral. The extensive diffused double layer formation saturated with sodium ions in the system may be the result of decrease in interparticle strength and increase in compressibility with time.

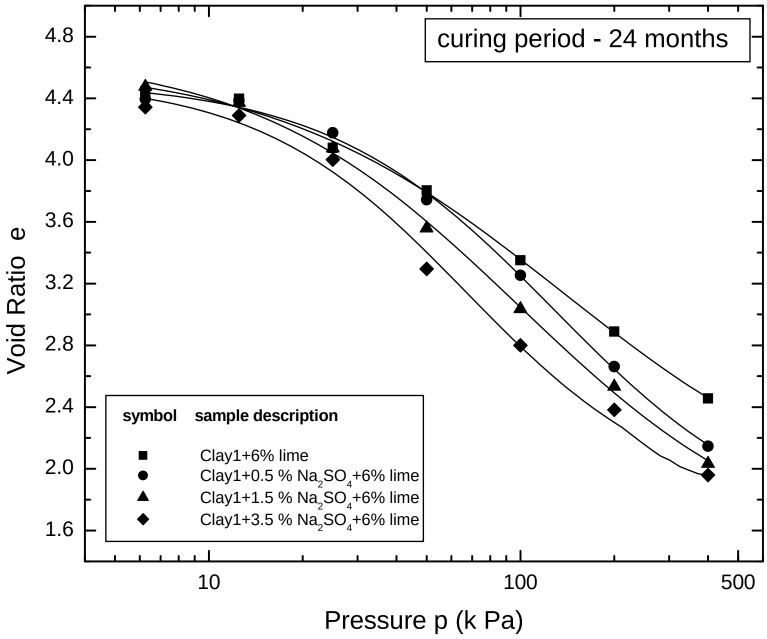

Fig. 5.5 Effect of varying sulphate content on 6% lime treated clay 1

Even though the effect of 3% lime was considered for understanding the influence of sulphates as well as the role of barium chloride in mitigating the changes likely to be caused by sulphates on compressibility characteristics, the results were not encouraging. This might be because 3% lime brings in only modification to the properties of clay and does not play significant role in improving the engineering properties of soil. The effect of varying concentrations of sulphate on 3% lime treated clay 1 could not be thus understood from the results obtained and thereby the effect of barium chloride also could not be brought out. Fig. 5.6 shows the effect of curing on e-log p curves for clay 1 (containing 0.5% natural sulphate) treated with 3% lime.

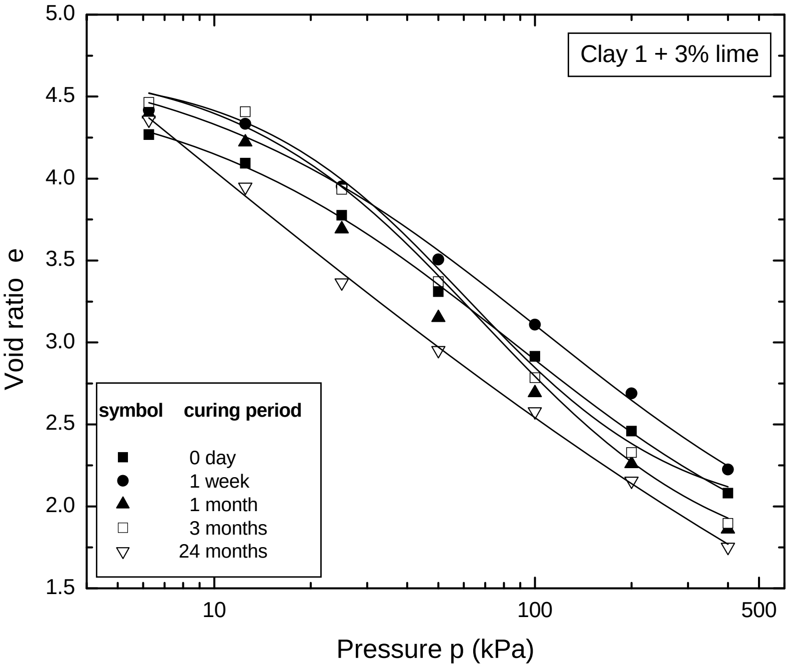

Fig 5.6 e - log p curves for 3% lime treated clay 1 containing 0.5% natural sulphate

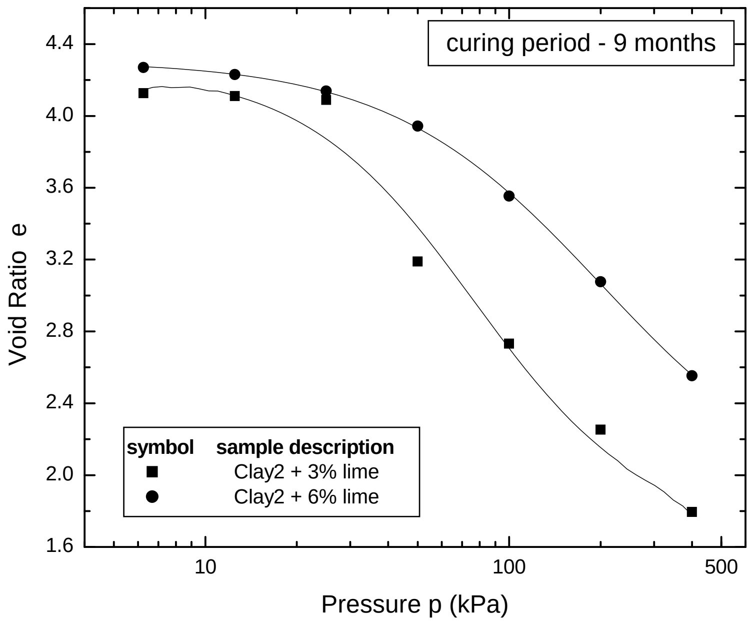

Fig. 5.7 Effect of lime content on clay 2

Fig. 5.7 establishes the effect of increased lime content in decreasing the compressibility of clay 2. As seen from the figure, 6% lime treated clay 2 shows remarkable increase in bond strength. The same is visible in the results presented in chapter 4 with respect to grain size distribution plots illustrated therein as well corresponding strength gain as explained in chapter 6.

Fig. 5.8 shows the effect of curing time on 6% lime treated clay 2. It is seen that the compressibility decreases with curing. Increasing bond strength with time is proof for the fact that 0.1% natural sulphate is not of concern for lime treating Cochin marine clays.

Results obtained from experimental studies conducted on clay 1 at the same time reflects the negative effects that can be induced in 6% lime stabilised Cochin marine clays by the presence of 0.5% sulphate.

Fig. 5.9 shows the effect of a higher percentage of sulphate viz., 4%, as this is also not an uncommon sulphate percentage in the southern region of India as has been presented in the literature review. Four percent sulphate is seen to affect the compressibility characteristics drastically with time. This suggests that there is a reduction in lime available for pozzolanic reactions in clays in the presence of sodium sulphate (Mitchell, 1986).

Fig. 5.10 shows the decrease in compressibility with curing period brought about by addition of barium chloride in 6% lime treated clay 2 with 4% sulphate. The increase in bond strength brought about with curing and presented in chapter 6 lends support to these results.

Fig. 5.11 illustrates the same beneficial changes brought about in the lime treated clay with 4% sulphate by use of barium hydroxide to counteract the effect of sulphates. The effect in reducing compressibility in more pronounced here.

Figs. 5.12 (a) and (b) bring out the comparison between barium chloride and barium hydroxide in effectively modifying the volume change behaviour exhibited by lime treated clays containing sulphate, clearly bringing out the beneficial effect of barium hydroxide in comparison to barium chloride. This is again in line with the shear strength results presented in chapter 6. Total compression on nine months curing for 6% lime treated clay 2 for 400 k Pa pressure is 3269 divisions. With 4% sulphate the total compression increased to 3879 divisions. Barium chloride when used to mitigate the effect of this 4% sulphate could reduce total compression to 3219 divisions and with use of barium hydroxide the same was reduced to 2043 divisions underlining the increasing effectiveness of barium hydroxide.

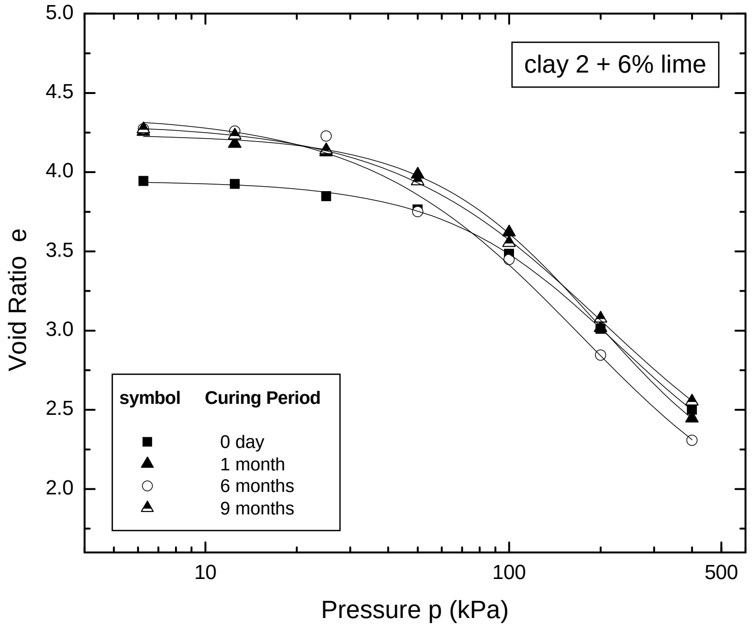

Fig. 5.8 Effect of curing period on 6% lime treated clay 2

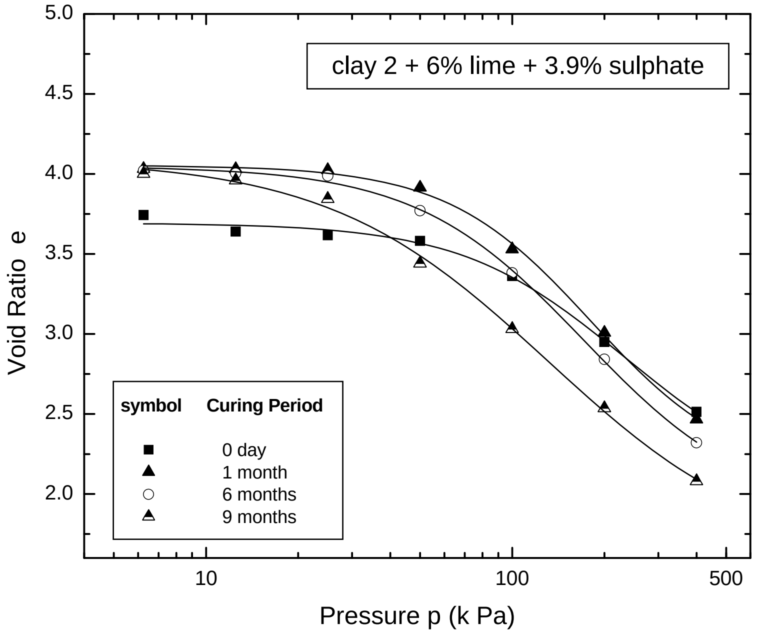

Fig. 5.9 e - log p curves for 6% lime treated clay 2 with 4% sulphate

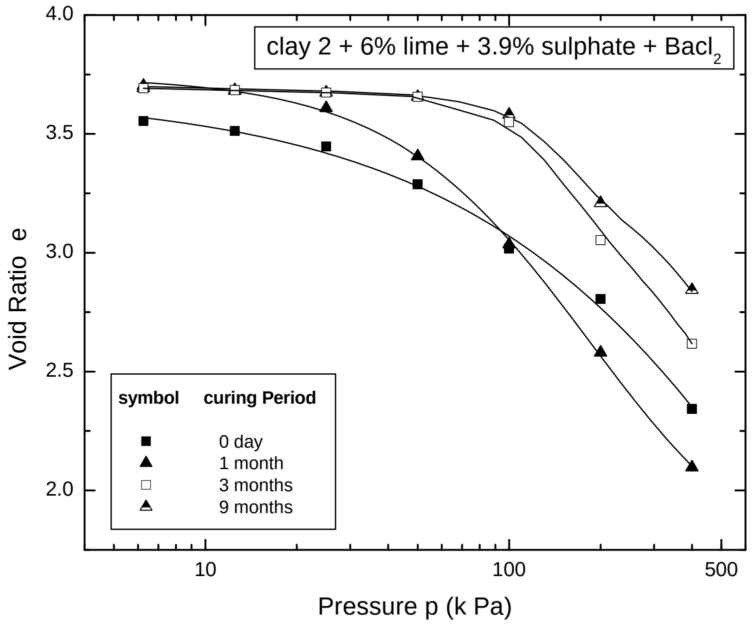

Fig. 5.10 e - log p curves for 6% lime treated clay 2 with 4% sulphate and barium chloride

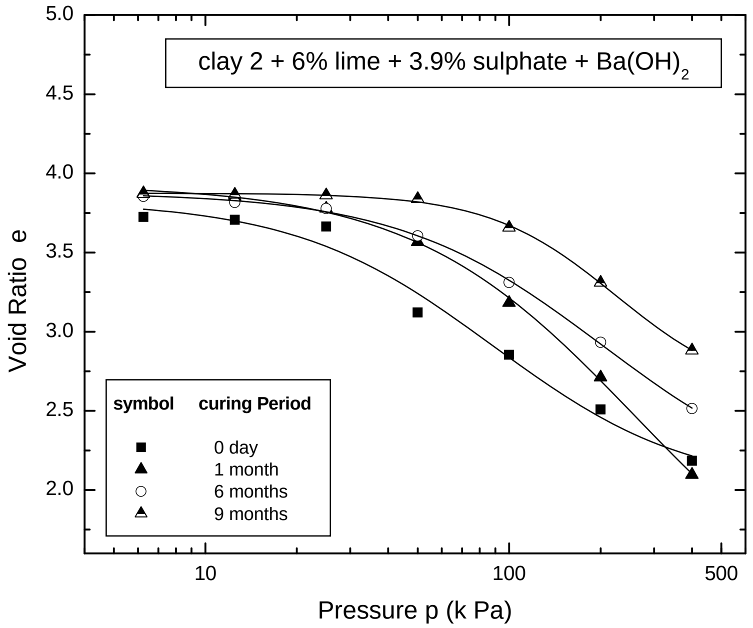

Fig. 5.11 e - log p curves for 6% lime treated clay 2 with 4% sulphate and barium hydroxide

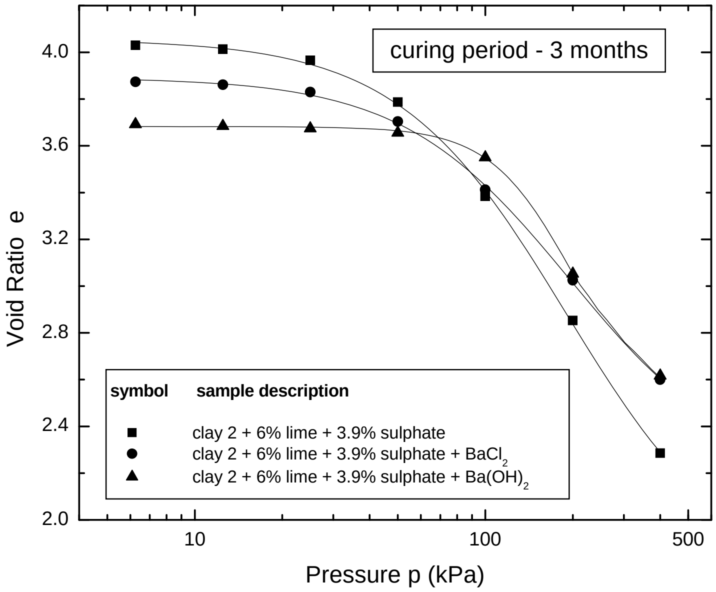

Fig. 5.12 (a) Comparison of effect of barium chloride and barium hydroxide (curing period 3 months)

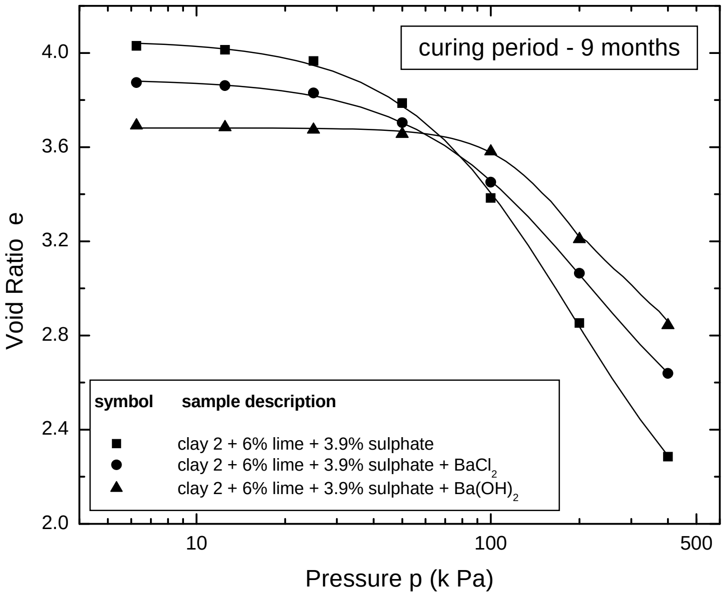

Fig. 5.12 (b) Comparison of effect of barium chloride and barium hydroxide (curing period 9 months)

The compressibility is decreased when barium chloride is used. A drastic decrease in compressibility is felt in comparison to barium chloride when barium hydroxide is used in place, to mitigate the effects of 4% sulphate in the lime treated clay.

It is established that sulphate anions gets adsorbed on the surface of the clay minerals. The mode of attachment of sulphate varies depending upon sulphate content and positive charge on the edges of the clay minerals (Rao and Sridharan, 1984). Consequent to attachment of sulphate, the basic and engineering properties of different types of minerals are altered due to changes caused in the fabric of the soil. Sridharan et al. (1986) have predicted edge to edge flocculation of clay particles as possible reason of change of properties.

5.3.2 Compressibility characteristics

The compressibility characteristics, namely compression index, which is used to determine the magnitude of settlement and the coefficient of consolidation, c_v, which is used to calculate the rate of settlement are determined by standard procedures.

5.3.2.1 Compression index

The compressibility parameter, namely, compression index, C_c, which is the slope of the linear portion of ‘‘e - log p curve’’ indicates the amount of compression undergone by the soil or treated soil as the case may be.

Compression index was calculated for every pressure increment in the following manner from the e - log p curves. For each pressure increment the change in void ratio was calculated. Then the compression index is given by '{change in the void ratio divided by (log p2 – log p1)}'. This is nothing other than (de/d (log p)).

As had been brought out earlier 3 % lime treated clay 1 could not clearly bring out the effect of varying sulphate content and gave erratic results. The de/d(log p) values are presented in Tables 5.2 and 5.3.

Table 5.4 gives the de/d(log p) values for clay 1 treated with 6% lime in the presence of varying sulphate contents and Table 5.5 gives the same when treated with barium chloride.

Table 5.6 shows the de/d(log p) values for clay 2 treated with lime in the presence of 4% sulphate and also the decrease in the same when treated with barium compounds.

de/d(log p) values of lime treated clays with any sulphate content is seen to increase with increase in pressure and de/ d(log p) increase in presence of sulphate at higher pressures is more conspicuous.

The addition of barium compounds in general seems to decrease de/d(log p). The same is found to have increased values in the presence of sulphates.

de/d(log p) values for samples treated with barium chloride are very low for pressure increments of 6.25 to 12.5 k Pa and 12.5 to 25 k Pa as shown in Figs. 5.13 (a) & (b) and 5.14 (a) & (b) .

From the same figures, for samples treated with barium chloride, higher values of de/d(log p) values can be observed when no curing is allowed. It might be higher because there was no time for bond strength to build up. Once p_c values are built up with curing period, the values of de/d(log p) drops down to steady low values. But once the pressure increment is higher than the maximum p_c that can be developed, de/d(log p) shows a steady value irrespective of the curing period as shown in Fig. 5.13 (c) & 5.14 (c).

From these figures one can also understand the variation in de/d(log p) values with curing period for lime treated samples with sulphates. The amount of compression undergone by the samples is significantly higher and goes on increasing with increasing pressure and curing period.

Similar behaviour is observed for all percentages of sulphate in 6% lime treated clay 1 as shown in Table 5.4.

The beneficial effect of barium chloride in decreasing compression can be observed from Table 5.5 in comparison, at any percentage of sulphate.

Table. 5.2 de/d(log p) values for 3% lime treated clay 1 treated with varying sulphate contents

Sl. No.	Sample description	Curing period	$de/d(log\ p)$ values for pressure ranges (k Pa)					
			6.25-12.5	12.5-25	25-50	50-100	100-200	200-400
1	Clay 1 + 3%lime	0 day	0.58	1.05	1.55	1.31	1.51	1.26
		1 week	0.27	1.27	1.48	1.32	1.39	1.54
		1 month	0.57	1.76	1.80	1.52	1.44	1.33
		3 months	-	1.57	1.87	1.95	1.52	1.43
		6 months	0.29	0.75	1.91	1.32	1.18	1.60
		12 months	0.15	0.38	0.30	4.88	1.86	1.26
		24 months	1.36	1.94	1.37	1.24	1.41	1.34
2	Clay 1 + 0.5%sulphate+ 3%lime	0 day	1.14	2.28	1.50	1.36	1.46	1.31
		1 week	0.10	1.80	1.95	1.49	1.47	1.35
		1 month	1.01	1.43	1.63	1.39	1.42	1.31
		3 months	0.71	1.29	1.42	1.72	1.93	1.65
		6 months	0.60	1.26	1.71	1.47	1.53	1.17
		12 months	0.84	1.15	1.58	1.28	1.56	1.45
		24 months	0.72	1.55	1.20	1.53	1.47	1.39
3	Clay 1 + 1.5% sulphate+ 3%lime	0 day	1.25	1.40	1.39	1.40	1.32	1.30
		1 week	0.70	1.33	1.40	1.35	1.20	1.45
		1 month	0.13	1.36	1.37	1.42	1.32	1.38
		3 months	1.36	1.40	1.42	1.49	1.47	1.35
		6 months	1.33	1.95	1.74	1.45	1.44	1.11
		12 months	1.36	1.21	1.33	1.19	1.37	1.10
		24 months	1.01	1.04	1.66	1.82	1.18	1.52
4	Clay 1 + 3.5% sulphate+ 3%lime	0 day	1.30	1.53	1.39	1.21	1.16	1.23
		1 week	0.94	1.08	1.49	1.24	1.27	1.31
		1 month	0.36	1.44	1.48	1.30	1.39	1.33
		3 months	0.76	1.22	1.21	1.18	1.23	1.15
		6 months	0.94	1.78	1.75	1.21	1.38	1.18
		12 months	0.59	1.26	1.64	1.48	1.26	1.22
		24 months	0.06	0.23	4.62	1.29	1.48	1.42

Table. 5.3 de/d(log p) values for 3% lime treated clay 1 treated with varying sulphate contents and barium chloride

Sl. No.	Sample description	Curing period	$de/d(log\ p)$values for pressure ranges (k Pa)					
			6.25-12.5	12.5-25	25- 50	50-100	100-200	200-400
1	Clay 1 + 3%lime+$BaCl_2$	0 day	0.68	1.00	1.49	1.33	1.56	1.42
		1 week	0.51	1.45	1.25	1.49	1.42	1.22
		1 month	0.69	1.33	1.45	1.56	1.46	1.39
		3 months	1.00	1.37	1.28	1.37	1.49	1.39
		6 months	0.66	1.59	1.53	1.48	1.38	1.04
		12 months	0.32	2.04	1.51	1.62	1.70	1.60
		24 months	0.05	2.07	1.42	1.35	1.29	1.25
2	Clay 1 + 0.5% sulphate+ 3%lime+$BaCl_2$	0 day	1.13	0.96	1.31	1.38	1.48	1.28
		1 week	0.56	2.11	0.92	1.44	1.34	1.26
		1 month	0.05	1.51	1.92	1.30	1.68	1.64
		3 months	1.21	1.44	1.47	1.42	1.36	1.26
		6 months	1.08	2.00	1.44	1.56	1.47	1.24
		12 months	0.07	1.19	1.61	1.76	2.09	1.44
		24 months	0.11	1.21	1.99	1.57	1.39	1.29
3	Clay 1 + 1.5% sulphate+ 3%lime+$BaCl_2$	0 day	1.21	1.62	1.20	1.41	1.49	1.23
		1 week	0.62	1.51	1.59	1.35	1.17	1.19
		1 month	0.36	1.44	1.48	1.30	1.39	1.33
		3 months	1.21	1.94	1.73	1.52	1.40	1.25
		6 months	1.35	1.67	1.48	1.31	1.37	1.20
		12 months	0.49	1.69	1.08	1.49	1.37	1.29
		24 months	0.75	0.92	1.23	1.28	1.36	1.24
4	Clay 1 + 3.5% sulphate+ 3%lime+$BaCl_2$	0 day	0.20	0.61	0.99	1.63	1.36	1.35
		1 week	0.25	0.59	0.68	1.18	1.16	1.06
		1 month	0.14	0.64	1.50	1.54	1.26	1.50
		3 months	0.91	1.54	1.34	1.26	1.31	1.18
		6 months	0.35	1.27	1.93	1.37	1.38	1.30
		12 months	0.04	1.96	1.88	1.32	1.28	1.30
		24 months	0.91	1.54	1.40	1.23	1.29	1.19

Table. 5.4 de/d(log p) values for 6% lime treated clay 1 treated with varying sulphate contents

Sl. No.	Sample description	Curing period	$de/d(logp)$ values for pressure ranges (k Pa)					
			6.25-12.5	12.5-25	25-50	50-100	100-200	200-400
1	Clay 1 + 6%lime	0 day	-	0.37	0.71	1.07	-	1.59
		1 week	-	0.40	0.90	1.66	-	1.85
		1 month	-	0.41	0.97	1.45	-	1.84
		3 months	-	0.46	1.54	1.96	-	1.97
		6 months	-	0.58	1.66	1.96	-	1.98
		12 months	-	0.96	1.75	1.95	-	1.99
		24 months	0.16	0.86	1.71	1.94	1.53	1.99
2	Clay 1 + 0.5% sulphate+ 6%lime	0 day	0.17	0.36	0.55	1.00	1.43	1.44
		1 week	0.18	0.39	0.51	1.09	1.58	1.61
		1 month	0.20	0.42	0.64	1.18	1.50	1.67
		3 months	0.22	0.53	0.79	1.31	1.68	1.69
		6 months	0.23	0.57	0.83	1.51	1.74	1.79
		12 months	0.21	0.63	0.83	1.57	1.73	1.80
		24 months	0.21	0.78	1.10	1.60	1.80	1.89
3	Clay 1 + 1.5% sulphate+ 6%lime	0 day	-	-	-	-	-	-
		1 week	-	-	-	-	-	-
		1 month	-	-	-	-	-	-
		3 months	0.22	0.63	0.95	1.39	1.94	1.97
		6 months	0.24	0.69	1.30	1.66	1.88	1.98
		12 months	0.31	0.74	1.67	1.86	1.92	1.97
		24 months	0.36	0.79	1.73	1.87	1.99	1.99
4	Clay 1 + 3.5% sulphate+ 6%lime	0 day	0.13	0.38	0.39	1.14	1.63	1.37
		1 week	0.22	0.39	0.37	1.51	1.63	1.40
		1 month	0.21	0.47	1.36	1.56	1.62	1.66
		3 months	0.24	0.57	1.58	1.77	1.82	1.94
		6 months	0.31	0.66	1.66	1.69	1.89	1.98
		12 months	0.31	1.28	1.79	1.67	1.96	1.99
		24 months	0.44	1.68	1.82	1.74	1.97	2.00

Table. 5.5 de/d(log p) values for 6% lime treated clay 1 treated with varying sulphate contents and barium chloride

Sl. No.	Sample description	Curing period	$de/d(logp)$ values for pressure ranges (k Pa)					
			6.25-12.5	12.5-25	25-50	50-100	100-200	200-400
1	Clay 1 + 6%lime+$BaCl_2$	0 day	0.11	0.38	0.80	0.98	1.32	1.47
		1 week	0.12	0.38	0.86	0.91	1.29	1.36
		1 month	0.10	0.33	0.86	0.99	1.28	1.32
		3 months	0.09	0.20	0.42	0.95	1.31	1.39
		6 months	0.03	0.15	0.41	0.75	1.30	1.38
		12 months	0.03	0.14	0.41	0.72	1.29	1.38
		24 months	0.03	0.14	0.41	0.72	1.29	1.38
2	Clay 1 + 0.5%sulphate + 6%lime+$BaCl_2$	0 day	0.13	0.46	0.94	1.22	1.36	1.37
		1 week	0.12	0.32	0.92	1.11	1.29	1.34
		1 month	0.09	0.26	0.85	1.11	1.27	1.31
		3 months	0.07	0.20	0.42	0.99	1.33	1.34
		6 months	0.03	0.17	0.41	0.76	1.32	1.33
		12 months	0.03	0.16	0.40	0.64	1.31	1.32
		24 months	0.03	0.16	0.40	0.64	1.31	1.32
3	Clay 1 + 1.5%sulphate + 6%lime+$BaCl_2$	0 day	0.28	0.57	1.15	1.24	1.39	1.43
		1 week	0.25	0.42	1.12	1.18	1.30	1.34
		1 month	0.17	0.39	0.95	1.10	1.29	1.31
		3 months	-	-	0.40	0.78	1.30	1.39
		6 months	0.05	0.19	0.40	0.70	1.30	1.38
		12 months	0.04	0.17	0.39	0.67	1.29	1.38
		24 months	0.04	0.16	0.38	0.67	1.29	1.38
4	Clay 1 + 3.5%sulphate+ 6%lime+$BaCl_2$	0 day	-	-	-	-	-	-
		1 week	-	-	-	-	-	-
		1 month	-	-	-	-	-	-
		3 months	0.10	0.75	0.97	1.31	1.48	1.51
		6 months	0.10	0.68	0.67	1.20	1.46	1.53
		12 months	0.09	0.61	0.64	1.20	1.39	1.45
		24 months	0.06	0.61	0.58	1.18	1.40	1.42

Table. 5.6 de/d(log p) values for lime treated clay 2 treated with varying sulphate contents and barium compounds

Sl. No.	Sample description	Curing period	$de/d(logp)$ values for pressure ranges (k Pa)					
			6.25-12.5	12.5-25	25-50	50-100	100-200	200-400
1	Clay 2 +3%lime	0 day	0.12	0.22	0.64	1.24	1.58	1.68
		1 month	0.07	0.17	0.57	1.09	1.18	1.52
		3 months	0.03	0.16	0.46	1.08	1.16	1.52
		6 months	0.03	0.16	1.44	1.07	1.17	1.36
		9 months	0.03	0.15	1.44	1.05	1.19	1.32
2	Clay 2 + 6%lime	0 day	0.16	0.26	0.57	0.94	1.17	1.40
		1 month	0.15	0.18	0.57	0.91	1.14	1.35
		3 months	0.08	0.13	0.44	0.82	1.15	1.39
		6 months	0.05	0.10	0.39	0.71	1.14	1.38
		9 months	0.05	0.10	0.38	0.70	1.14	1.38
3	Clay 2 + 3.9% sulphate + 6%lime	0 day	0.17	0.27	0.58	0.73	1.37	1.45
		1 month	0.16	0.32	0.66	1.28	1.74	1.80
		3 months	0.25	0.36	0.69	1.34	1.76	1.89
		6 months	0.36	0.45	0.73	1.39	1.79	1.93
		9 months	0.43	0.51	0.75	1.40	1.88	1.94
4	Clay 2 + 3.9% sulphate + 6%lime+$BaCl_2$	0 day	0.14	0.22	0.58	1.14	1.28	1.39
		1 month	0.07	0.21	0.63	0.93	1.21	1.35
		3 months	0.03	0.13	0.66	0.83	1.25	1.37
		6 months	0.02	0.11	0.20	0.72	1.24	1.36
		9 months	0.02	0.11	0.20	0.71	1.24	1.36
5	Clay 2 + 3.9% sulphate + 6%lime+$Ba(OH)_2$	0 day	0.06	0.24	0.80	1.26	1.29	1.38
		1 month	0.05	0.22	0.90	0.99	1.26	1.35
		3 months	0.04	0.12	0.42	0.82	1.24	1.35
		6 months	0.02	0.09	0.38	0.71	1.23	1.34
		9 months	0.02	0.09	0.37	0.70	1.24	1.34

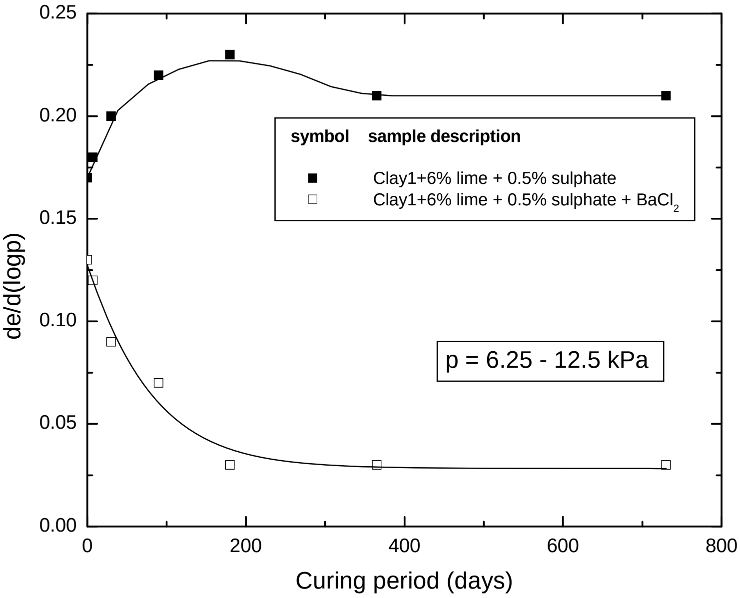

Fig. 5.13 (a) Variation of de/d(log p) with curing period for treated clay 1 (p = 6.25 – 12.5 k Pa)

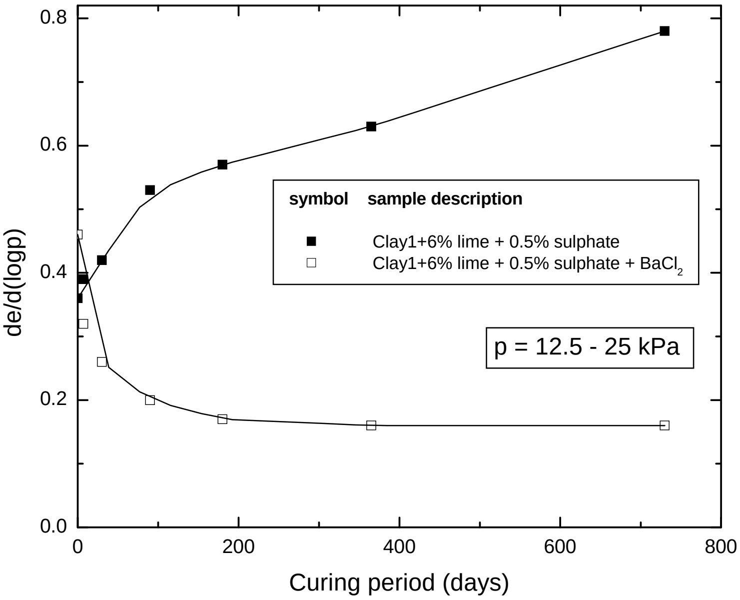

Fig. 5.13 (b) Variation of de/d(log p) with curing period for treated clay 1 (p = 12.5 – 25 k Pa)

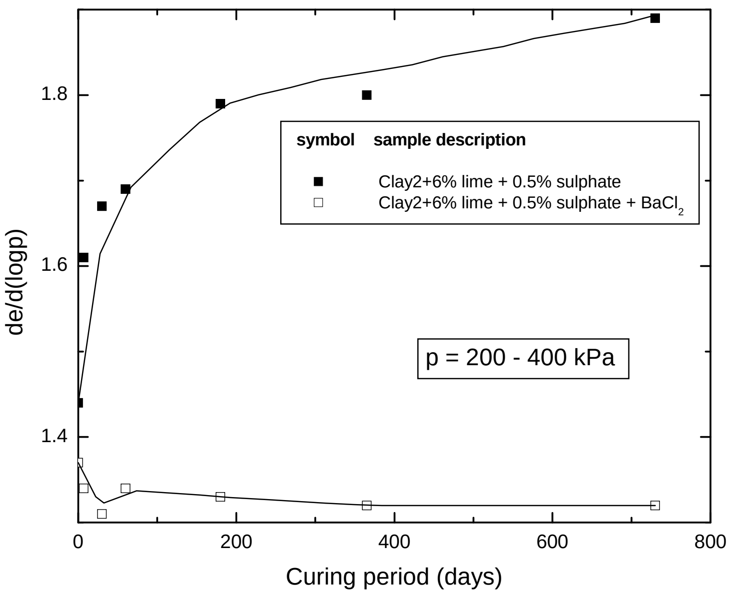

Fig. 5.13(c) Variation of de/d(log p) with curing period for treated clay 1 (p = 200 - 400 k Pa)

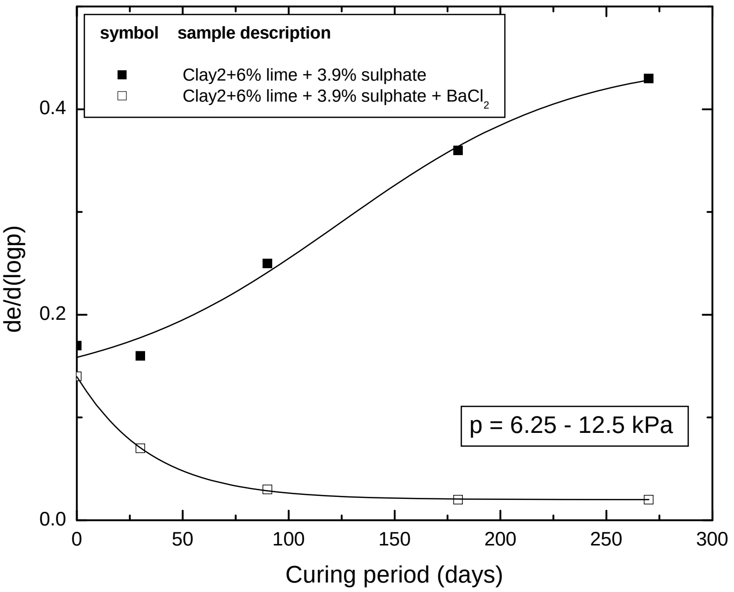

Fig. 5.14 (a) Variation of de/d(log p) with curing period for treated clay 2 (p = 6.25 – 12.5 k Pa)

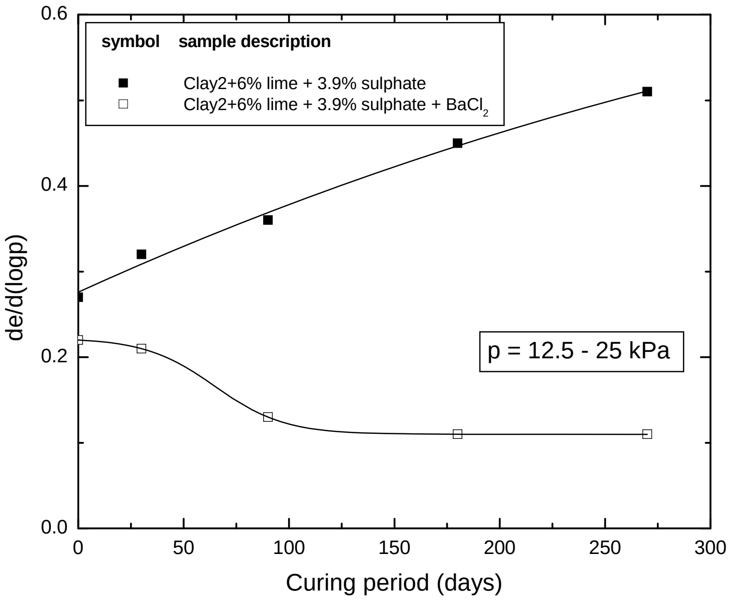

Fig. 5.14(b) Variation of de/d(log p) with curing period for treated clay 2 (p = 12.5 – 25 k Pa)

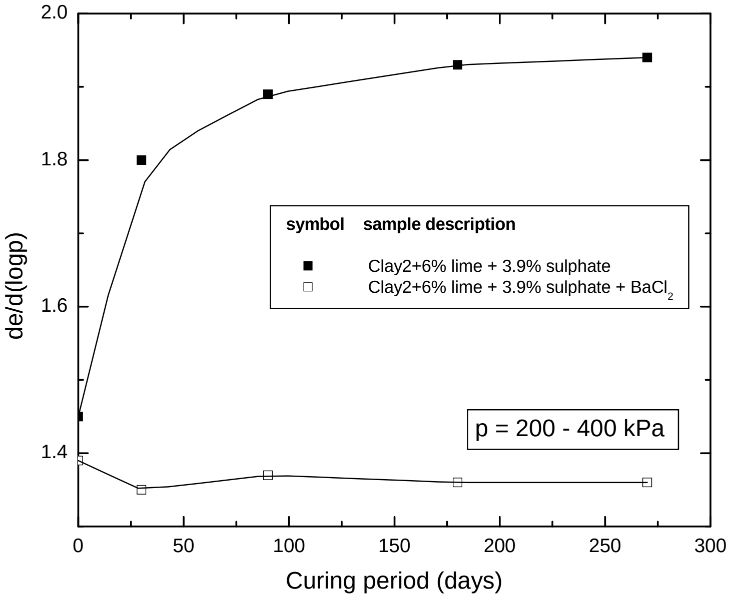

Fig. 5.14 (c) Variation of de/d(log p) with curing period for treated clay 2 (p = 200 - 400 k Pa)

5.3.2.2 Coefficient of consolidation

Coefficient of consolidation, c_v, the parameter governing the time rate of consolidation, has been determined for different pressure ranges. Of the various methods of determining coefficient of consolidation, two common curve-fitting methods are Taylor’s method and Casagrande’s method. Both methods were tried out and Casagrande’s method was opted.

No definite trend could be established for variation of c_v with respect to either pressure or sulphate content. The c_v values of all samples are presented in Tables 5.7 and 5.8.

Table. 5.7 Coefficient of consolidation for 3% lime treated clay 1 with varying sulphate contents and barium chloride

Sl. No.	Sample description	Curing period	With sulphate			On treatment with $BaCl_2$		
			c_v in cm^2/sec ($x10^{-4}$) for p (k Pa) =					
			50 - 100	100 - 200	200 - 400	50 - 100	100 - 200	200 - 400
1	Clay 1 (Sulphate Content = 0.5%)	0 day						
		1week						
		1 month						
		3 months	1.39	2.3	2.70	-	-	-
		6 months						
		12 months						
		24 months						
2	Clay 1 + 3% lime	0 day	2.19	3.49	4.39	2.09	2.97	3.70
		1week	3.67	4.04	5.71	3.02	3.42	3.88
		1 month	2.87	2.81	3.19	3.65	3.42	4.01
		3 months	3.43	4.91	4.52	2.63	3.03	3.65
		6 months	2.21	3.38	3.84	2.04	2.47	2.19
		12 months	2.56	2.41	3.68	1.97	2.63	2.96
		24 months	1.66	2.36	2.41	2.00	3.19	2.96
3	Clay 1 + 0.5% sulphate+ 3% lime	0 day	2.46	3.29	3.59	3.67	4.39	4.60
		1week	2.35	2.95	3.72	3.66	4.41	4.78
		1 month	1.96	3.70	4.31	2.58	4.21	4.36
		3 months	2.26	2.88	3.45	2.40	3.13	3.26
		6 months	1.67	2.35	2.02	2.33	3.09	3.43
		12 months	1.73	2.10	2.17	1.85	2.15	2.31
		24 months	1.30	1.95	2.16	1.66	2.36	3.70
4	Clay 1 + 1.5% sulphate + 3% lime	0 day	2.54	3.01	3.67	3.31	4.73	5.13
		1week	2.23	2.20	4.63	2.17	3.18	4.57
		1 month	2.36	2.73	3.69	2.73	3.41	4.38
		3 months	1.57	2.19	2.56	2.07	2.62	3.31
		6 months	1.25	2.16	3.94	2.20	3.66	4.55
		12 months	1.02	2.71	1.97	2.49	3.48	3.06
		24 months	1.21	2.21	3.38	2.32	2.95	3.16
5	Clay 1 + 3.5% sulphate + 3% lime	0 day	1.98	2.44	3.34	4.00	4.84	5.74
		1week	1.62	2.15	2.75	2.87	3.66	4.05
		1 month	2.16	3.99	3.80	4.06	3.71	4.49
		3 months	1.26	1.63	2.26	2.57	3.57	4.43
		6 months	1.37	1.79	2.47	2.80	3.13	3.25
		12 months	1.24	1.52	1.69	2.02	2.13	2.71
		24 months	1.11	1.77	2.00	2.10	2.40	2.67

Table. 5.8 Coefficient of consolidation for 6% lime treated clay 1 with varying sulphate contents and barium chloride

Sl. No.	Sample description	Curing period	With sulphate			**On treatment with $BaCl_2$**		
			c_v in cm^2/sec ($x10^{-4}$) for p (k Pa) =					
			50 – 100	100 - 200	200 - 400	50 - 100	100 - 200	200 - 400
1	Clay 1 (Sulphate Content = 0.5%)	0 day	1.39	2.34	2.70			
		1week						
		1 month						
		3 months				-	-	-
		6 months						
		12 months						
		24 months						
2	Clay 1 + 6% lime	0 day	3.94	5.16	5.80	-	8.32	9.51
		1week	3.61	3.56	4.24	5.31	7.35	7.34
		1 month	3.32	3.73	4.34	4.81	5.28	6.40
		3 months	4.19	4.11	4.27	-	5.09	4.41
		6 months	3.78	4.19	4.40	6.72	4.36	4.19
		12 months	4.51	4.89	5.73	6.06	5.98	6.91
		24 months	4.61	4.73	5.98	5.04	5.61	5.92
3	Clay 1 + 0.5% sulphate + 6% lime	0 day	4.08	4.49	5.36	4.70	6.01	6.58
		1week	4.70	5.74	6.05	5.63	6.77	7.15
		1 month	6.11	1.80	5.57	5.93	6.37	5.33
		3 months	4.16	4.10	4.28	6.30	5.75	5.34
		6 months	6.61	4.49	3.87	6.15	6.41	4.75
		12 months	-	1.66	9.27	6.34	7.13	7.23
		24 months	3.42	4.31	5.16	6.15	6.06	6.22
4	Clay 1 + 1.5% sulphate + 6% lime	0 day	-	-	-	4.81	6.93	7.52
		1week	-	-	-	4.74	5.27	7.15
		1 month	-	-	-	5.57	6.13	6.61
		3 months	3.28	3.76	-	5.07	7.11	7.64
		6 months	3.02	3.61	4.02	5.53	6.49	7.21
		12 months	3.10	3.57	3.81	5.16	6.94	7.59
		24 months	2.99	3.22	3.87	6.40	6.37	6.88
5	Clay 1 + 3.5% sulphate + 6% lime	0 day	2.41	4.11	5.11	-	-	-
		1week	3.05	4.06	2.09	-	-	-
		1 month	4.01	4.70	4.92	-	-	-
		3 months	2.64	4.19	3.48	5.19	6.35	7.82
		6 months	3.00	3.56	4.12	5.73	6.29	7.47
		12 months	2.91	3.60	4.23	5.01	6.25	7.15
		24 months	3.10	3.53	4.00	9.27	9.42	9.89

5.3.2.3 Secondary compression coefficient

Figs. 5.15 (a) and (b) shows the variation of secondary compression coefficient of 6% lime treated clay 1 in the presence of varying sulphate content. As seen from the figures, secondary compression coefficients decreases with curing period wherein barium chloride has been used to mitigate the effect of sulphates. Whereas, C_α values for samples in presence of sulphate tends to be on the higher side. Thus the variation of secondary compression coefficient is seen to be same as that observed for de/d(log p).

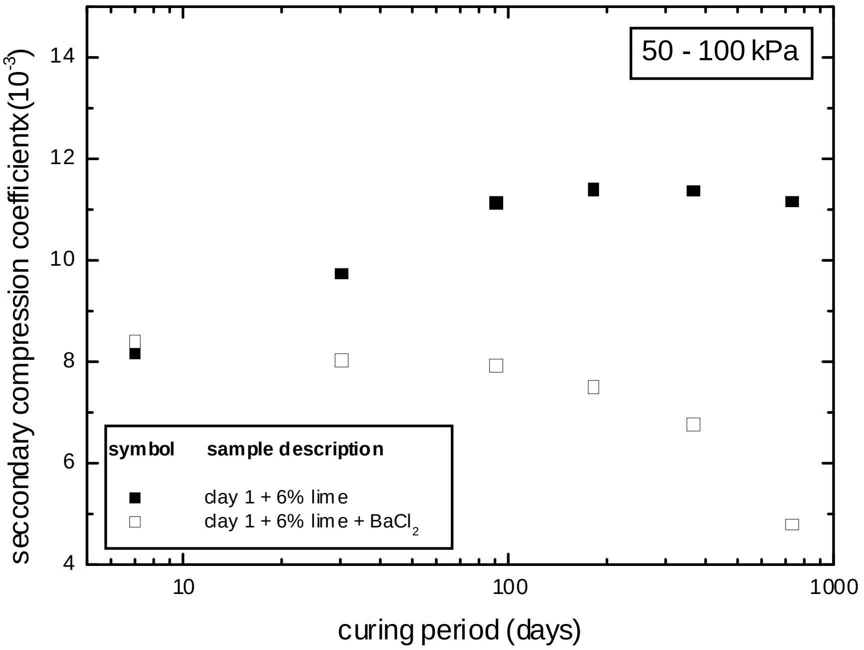

Fig. 5.15 (a) Effect of barium chloride on 6% lime treated clay 1 with 0.5% sulphate

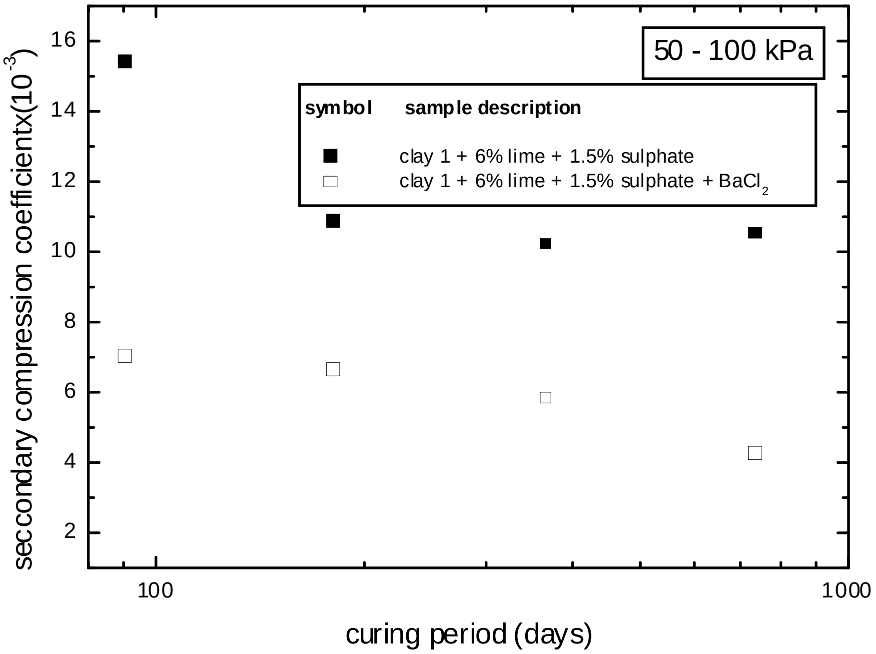

Fig. 5.15 (b) Effect of barium chloride on 6% lime treated clay 1 with 2% sulphate

5.3.3 Development of bond strength

Bond strength (preconsolidation pressure) was determined by log – log method (Jose et al. 1989). A typical log - log plot showing the method of determination of bond strength (p_c) is given in Fig. 5.16.

The development of bond strength with respect to curing period is very evident from the Figs. 5.17 to 5.19, for 6% lime treated samples treated with barium chloride. One can easily infer that irrespective of the variation in the sulphate contents, the trend for development of bond strength is the same. An interesting feature that can be observed in lime treated specimens in the presence of sulphates is that it picks up strength almost instantaneously, and continues to increase to almost one month, but thereafter strength decreases.

The instantaneous increase in strength in lime treated clays is pronounced in the presence of 0.5% and 1% of sulphate. Abnormal increase of bond strength can be observed in the presence of 1% sulphate such that on curing for one month, it reaches a peak value of 74.7 k Pa and thereafter drops to 41.9 k Pa in one year and to 29.5 k Pa at the end of two years. Thus as explained in earlier sections the properties of lime treated clays are significantly altered due to the presence of sulphates.

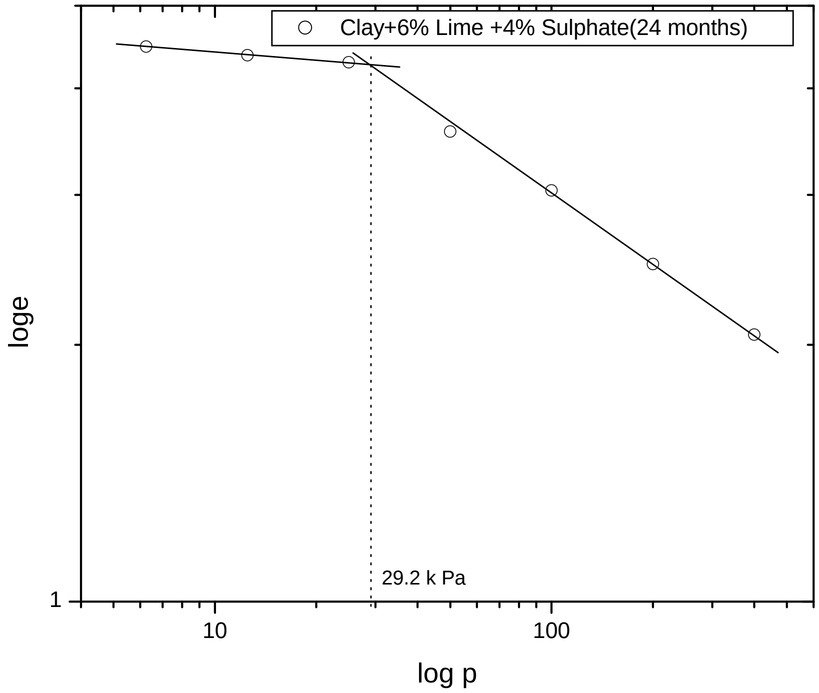

Fig. 5.16 Typical log e-log p plot for determination of p_c

The deleterious effect of sulphate in reducing the bond strength is seen to be counteracted by the use barium chloride as seen from the continuously increasing trend in Figs. 5.17 to 5.19.

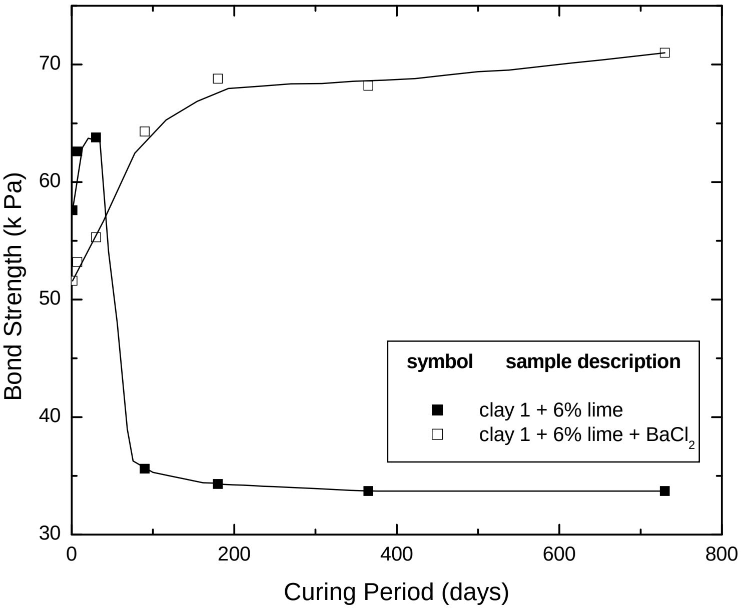

Fig. 5.17 Effect of barium chloride in 6% lime treated clay 1

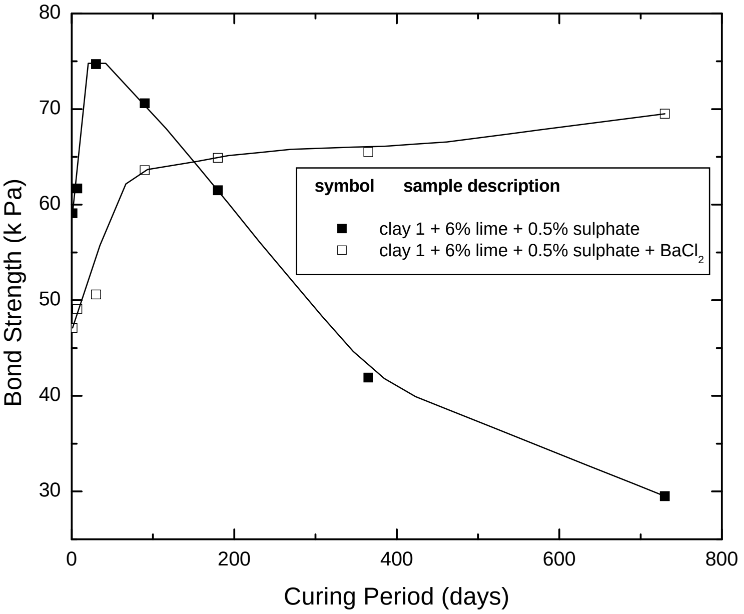

Fig. 5.18 Effect of barium chloride in 6% lime treated clay 1 with 1% sulphate

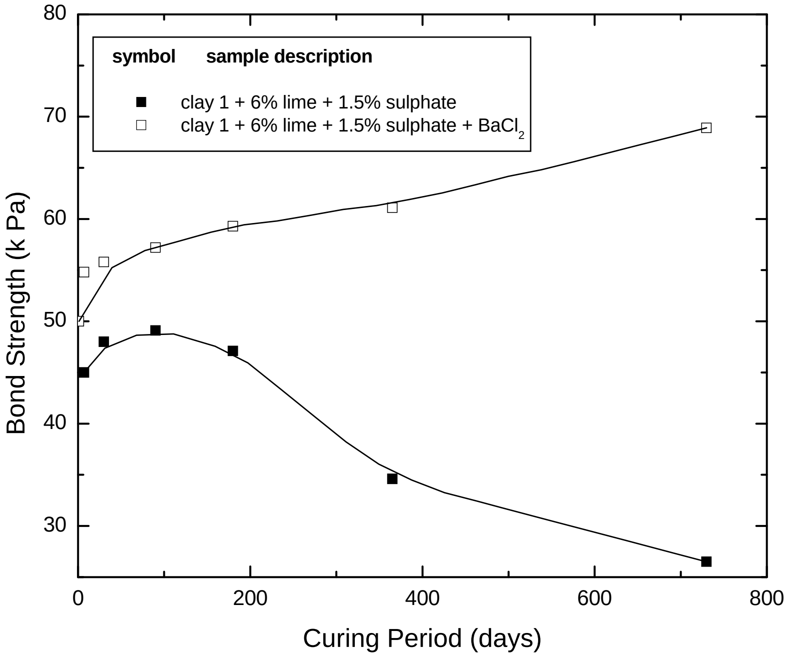

Fig. 5.19 Effect of barium chloride in 6% lime treated clay 1 with 2% sulphate

The variation of bond strength with curing period for 6% lime treated clay 2 is presented in Fig. 5.20. The steadily increasing bond strength indicates that 0.1% sulphate present in clay 2 in no way interferes with the normal pozzolanic reactions.

Fig. 5.21 brings out the effect of 4% sodium sulphate in the same clay treated with 6% lime. Though bond strength initially increases, which might be attributed to the increased lime reactivity of soils in the presence of sulphates, a steady decrease in strength occurs after three months of curing period.

Incorporation of barium chloride into the system has definitely arrested this reduction in bond strength as is evident from the continuously increasing trend as brought out in the figure.

Fig. 5.22 brings out the effect of barium hydroxide in nullifying the effect of 4% sulphate in 6% lime treated clay 2.

Bond strength development at the end of nine months for barium hydroxide treated sample is 90 k Pa as against a value of 77.5 k Pa for barium chloride. 6% lime treated clay 2 with 4% sulphate could yield only a value of 44 k Pa i.e., half the strength that was developed by barium hydroxide treated sample over the same curing period. The effectiveness of barium hydroxide in comparison to barium chloride is clearly brought out here also, as has been also proved in chapter 6.

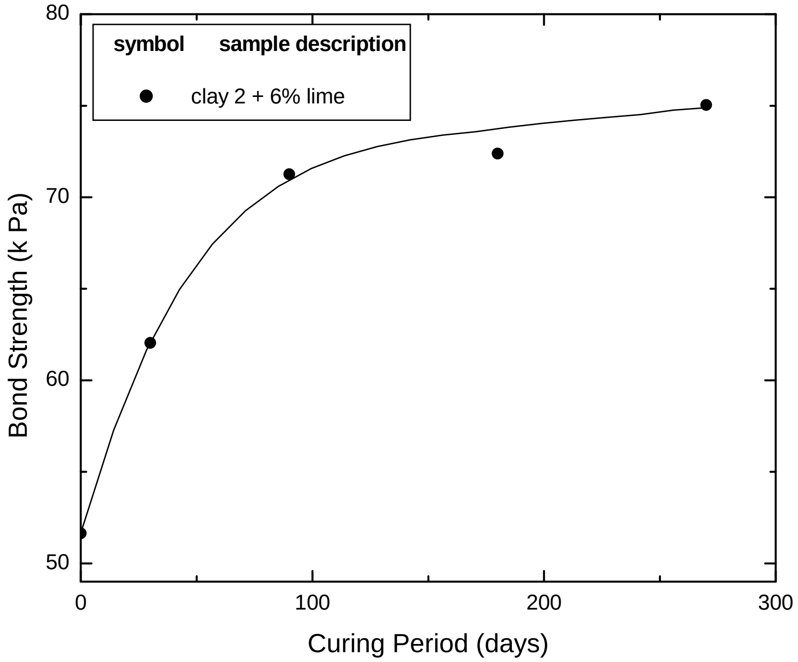

Fig. 5.20 Variation of bond strength with curing period for 6% lime treated clay 2

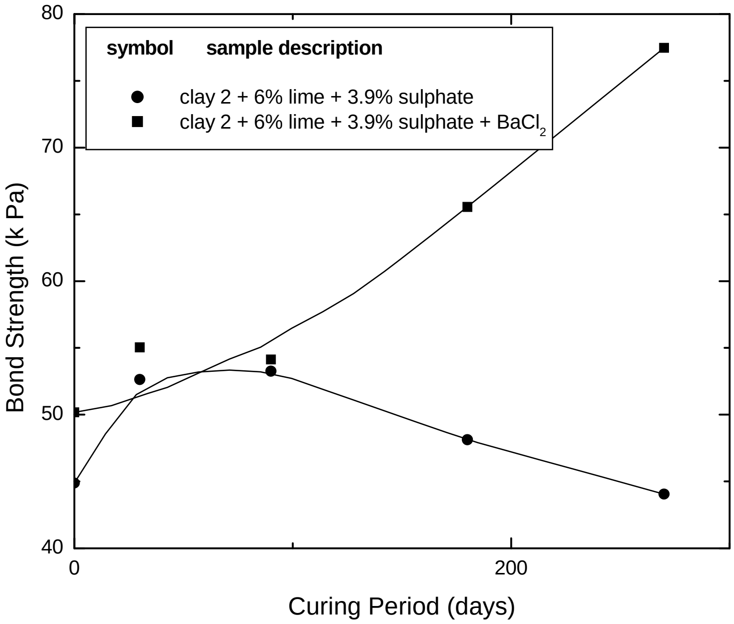

Fig. 5.21 Effect of barium chloride in 6% lime treated clay 2

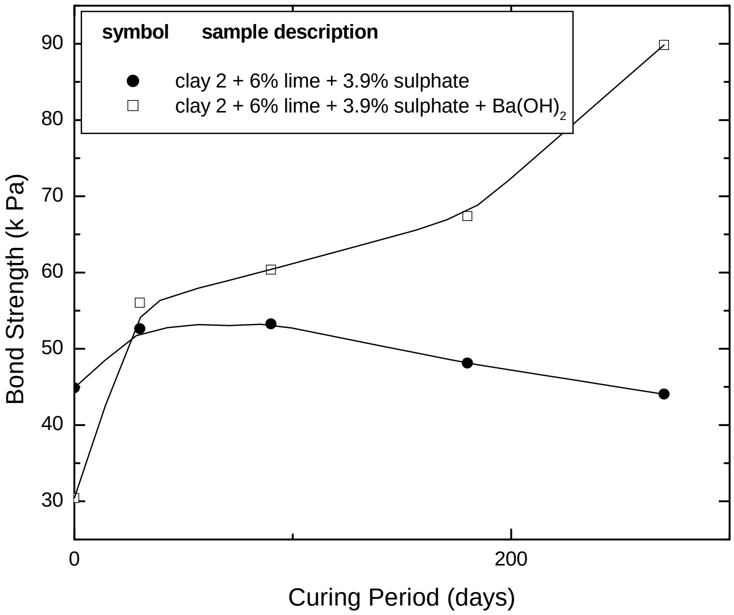

Fig. 5.22 Effect of barium hydroxide in 6% lime treated clay 2

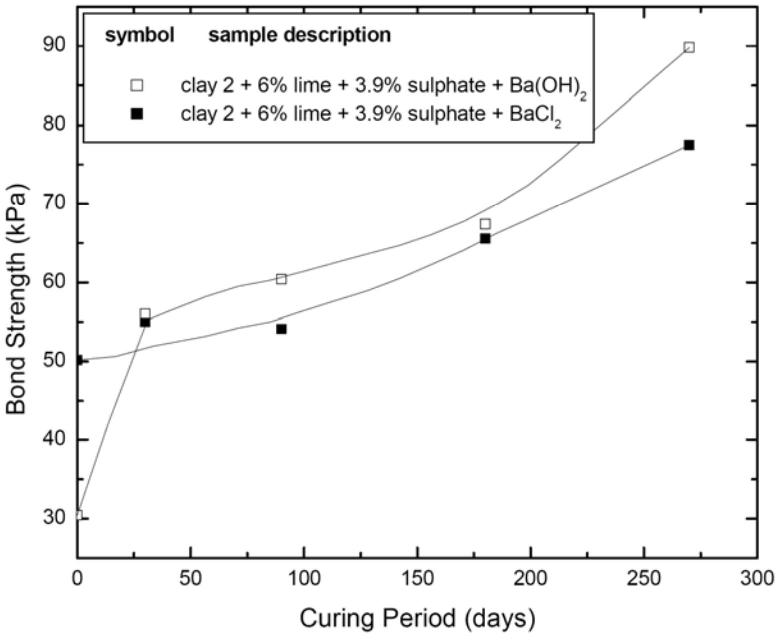

Fig. 5.23 Comparison of effect of barium hydroxide and barium chloride

Barium hydroxide is thus seen to be far more superior to barium chloride in effectively nullifying the effect of even very high percentage of sulphate as illustrated in Fig. 5.23. This is also evident from Fig. 5.12 (b) indicating the significant reduction in compression brought about by barium hydroxide on curing lime treated sulphatic clays.

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Chapter 6

STRENGTH BEHAVIOUR OF LIME STABILISED MARINE CLAYS CONTAINING SULPHATE AND TREATED WITH BARIUM COMPOUNDS

Contents

6.1 Introduction

In place soil treatment using calcium-based stabilizers is an economically feasible solution to address strength deficiencies and problematic shrink/swell behaviour of unstable subgrade soils. Soil instability may originate from the presence of clay or silt whose instability is normally triggered by a change in moisture content. Even though stabilization improves engineering properties, problems can arise when calcium-based stabilizers are used in soils rich in sulphate-bearing minerals. Stabilization of sulphate rich soils in the presence of excess moisture may lead to the formation of minerals such as ettringite and/or thaumasite and can cause distress in or even destruction of pavement structures due to heaving (Mitchell, 1986; Hunter, 1988).

6.1.1 Mechanism(s) involved

As illustrated in the section 2.4 on literature review, even though the use of calcium-based stabilizers is beneficial in most cases, literature as well as practical experience has established that sulphate-bearing soils can develop deleterious reactions when treated with calcium-based stabilizers such as lime or cement. Since it is the presence of lime [CaO or $Ca(OH)_2$] in the stabilizers that provides calcium and raises the pH in the presence of water, the reactions between soil and other calcium-based stabilizers may be considered to be similar to that between lime and soil (Little, 1999).

Little and Nair (2000) has reported that the kinetics of ettringite formation during initial cement hydration is rapid because in cement, the components in dry form are amorphous and uniformly blended. Also, due to the nature of their particle size distribution, they have a very large surface area. When mixed with water to form cement paste, this high surface area translates to a higher rate of reactivity and the reactants immediately become available in solution as soluble ions. Hence ettringite formation in Portland cement concrete is fast and is dependent solely on available sulphate content in the matrix. On the contrary, when soil systems are treated with calcium-based stabilizers, ion availability in solution is defined by mineralogy and dissolution properties of soil minerals. The flocculation/agglomeration during initial reaction periods contributes to reduction in surface area of soil particles. Hence the particles, or what may be better classified as agglomerates of particles, normally have a substantially smaller surface area when compared to Portland cement. Moreover, the soil minerals have a well-defined crystal structure and the effects of weathering and varying environmental conditions make the distribution of soil minerals more heterogeneous when compared to Portland cement. Hence the extent of ions available in solution to form ettringite is limited in stabilized soils when compared to cement pastes.

Therefore, there is no reason to assume that because ettringite occurs rapidly in cement, say within the first day or so of cement hydration, it should occur as rapidly in stabilized soils.

Furthermore, the behaviour of treated soils and the extent of damage have to be considered to be soil specific and dependent on factors other than sulphate content alone. (Mitchell et al., 1992; Kohler et al., 2006; Puppala et al., 2005). Research has proven that ettringite precipitation and the resulting volume changes in stabilized soils are higher in clays when compared to sandy soils under similar environmental conditions.

Presence of sulphates can alter the basic properties as well as the compressibility characteristics of lime treated soils. The extent of alteration depends on the sulphate content and curing period.

Another important engineering property to be addressed is the shear strength. In fact, strength is often the most significant parameter in measuring the effect of soil improvement in geotechnical engineering practice (Little, 1999).

Hence it is proposed to study the strength characteristics of clay 1 and clay 2 treated with optimum percentage of lime, containing various concentrations of sulphate as affected by curing time. Role of barium compounds in limiting ettringite formation has also been analysed.

6.2 Experimental Program

Quality control of the lime and cement stabilized specimens is often assessed in terms of strength improvement that the stabilizers (brought in to the soil specimens. The shear strength of lime-soil mixtures can be measured in the laboratory in a variety of ways: unconfined compressive strength, triaxial shear strength, indirect tensile (diametral tensile) strength, CBR and California R-value. The most common method of strength measurement is the unconfined compression test because of its simplicity (Little, 1999).

Soils were mixed with 6% of lime by weight of soil, predetermined quantity of sodium sulphate and required additives brought to its liquid limit consistency. Unconfined compressive test specimens 38mm dia and 76mm long were prepared and cured as per procedure given in chapter 3 (section 3.3.7.1).

The details of soils used, sulphate contents, additives used and curing period are summarised in Table 6.1.

Table6.1 Experimental program for unconfined compression tests

Soil	Additives (%)			Curing period
	Lime	Na_2 SO_4	Barium compound	
Clay 1	6 %	0%	0%	0, 7, 30, 90, 180, 365,730 days
		0%	Barium Chloride	
		1.5 %	0%	
			Barium Chloride	
		3.5 %	0%	
			Barium Chloride	
Clay 2	6 %	0%	0%	0,7,30,90,180, 270,365 days
		3.9 %	0%	- do -
		3.9 %	Barium Chloride	- do -
		3.9 %	Barium Hydroxide	- do -
	0%	0%	6 % Barium Chloride	0,7,30,90,180 days
	0%	0%	6 % Barium Hydroxide	0,7,30,90,180 days

6.3 Unconfined compressive strength and discussion of results

The most obvious improvement in a soil through lime stabilization is strength gain. Laboratory vane shear tests on undisturbed samples of clay 1 and clay 2, yielded shear strength of 1.4 k Pa and 1.9 k Pa only. Series of unconfined compression tests were performed to evaluate the effect of sulphates and that of barium compound additives. Unconfined compressive strength of various samples is given in Table 6.2.

Table 6.2 Unconfined compressive strength of treated clay 1

Sl. No.	Sample description	Curing Period						
		0 day	1 week	1 month	3 months	6 months	12 months	24 months
		Unconfined compressive strength (k Pa)						
1	Clay 1 +6%lime	17	42	64	58	54	52	52
2	Clay 1 +6%lime +Bacl$_2$	16	34	45	50	52	53	57
3	Clay 1 +6%lime +1.5%sulphate	14	53	76	64	60	58	57
4	Clay 1 +6%lime +1.5%sulphate+ BaCl$_2$	14	47	75	88	95	98	100
5	Clay 1 +6%lime +3.5%sulphate	14	26	46	44	41	38	35
6	Clay 1 +6%lime +3.5%sulphate+ BaCl$_2$	14	27	36	57	60	65	71

Fig 6.1 shows unconfined compressive strength (q_u) of clay 1 containing 0.5% natural sulphate with varying percentages of sodium sulphate plotted against curing period. In general an increase in sulphate content tends to decrease the q_u values. In all cases q_u value shows an initial increase for samples cured up to 30 days and thereafter decreases. Presence of sulphate induces two changes in the soil – lime system a) increases pH of the system due to formation of NaOH, which enhances soil lime reaction and b) decreases the amount of lime available converting lime to $CaSO_4$ as shown in equation 6.1

$$Na_2SO_4 + Ca(OH)_2 \rightarrow 2NaOH + CaSO_4 \quad \text{...} \quad 6.1$$

The decrease is relatively lower in the case of 6% lime treated clay 1 (containing 0.5% natural sulphate) and at the end of 180 days strength becomes almost constant. The decrease in strength may be due to alteration of soil – lime pozzolanic reactions. These alterations require only a definite amount of sulphate after a particular curing period. Since the amount of sulphate is already consumed in the alteration reactions, normal soil reactions may continue in this case.

Test results indicate that with 1.5% Na_2SO_4 the alteration reactions have extended up to two years and with 3.5% Na_2SO_4, the same is continuing. The results also indicate that greater reduction in strength can occur at higher percentages of sulphate.

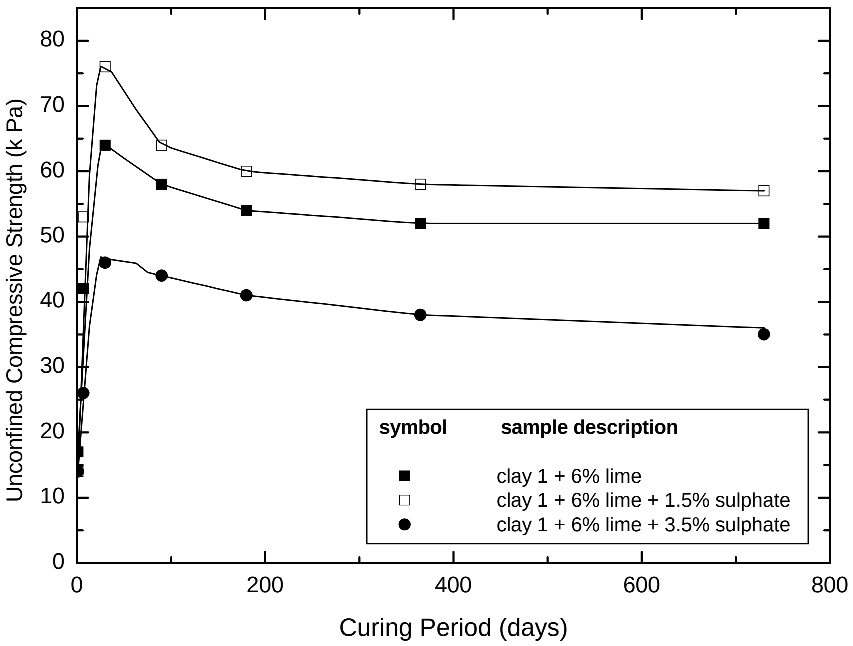

Fig. 6.1 Variation of unconfined compressive strength with curing period for clay 1

Sivapullaiah et al. (2000) have illustrated the effectiveness of lime treated black cotton soil in the presence of sulphate. Similar results indicating the effect of sulphate to be marginal for short curing periods and drastic reduction in shear strength after curing for long periods have been reported.

Figs. 6.2 to 6.5 show the effect of barium chloride in mitigating the effect of presence sulphate in lime stabilised soil. In all the cases it can be seen that the strength in the presence of $BaCl_2$ is higher.

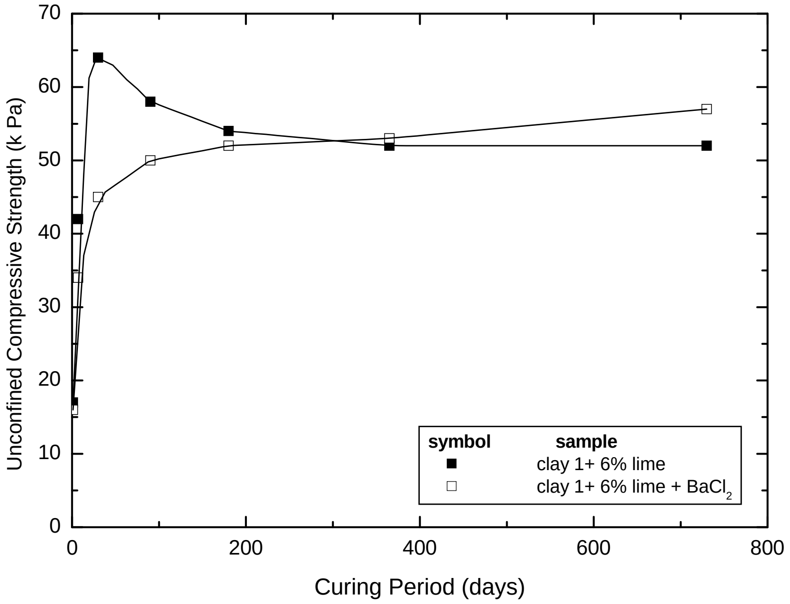

Fig. 6.2 Effect of barium chloride in mitigating the effect of sulphates in lime stabilised clay1 (0.5% sulphate)

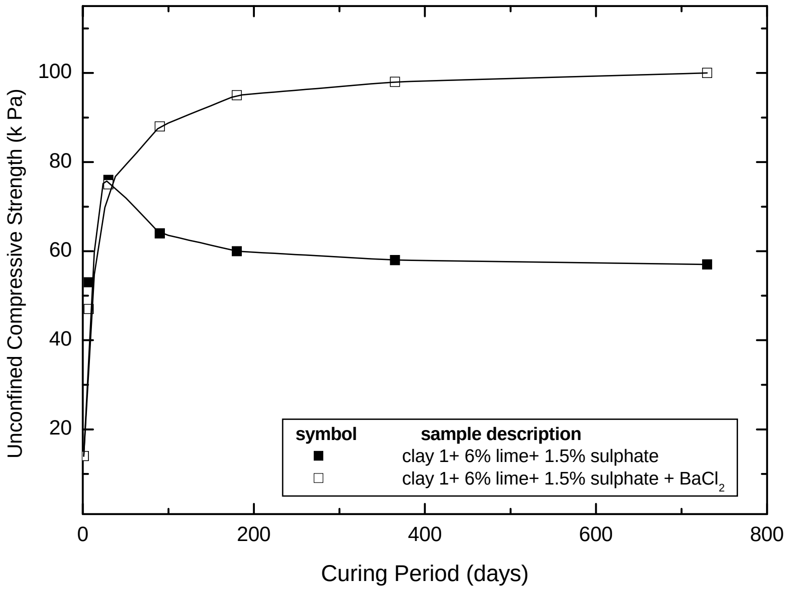

Fig 6.3 Effect of barium chloride in mitigating the effect of sulphates in lime stabilised clay 1 (2 % sulphate)

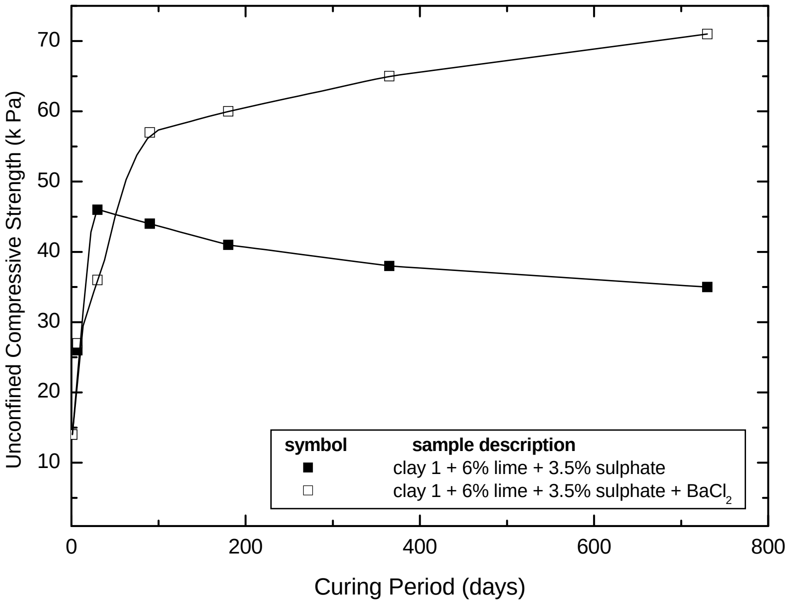

Fig 6.4 Effect of barium chloride in mitigating the effect of sulphates in lime stabilised clay 1 (4 % sulphate)

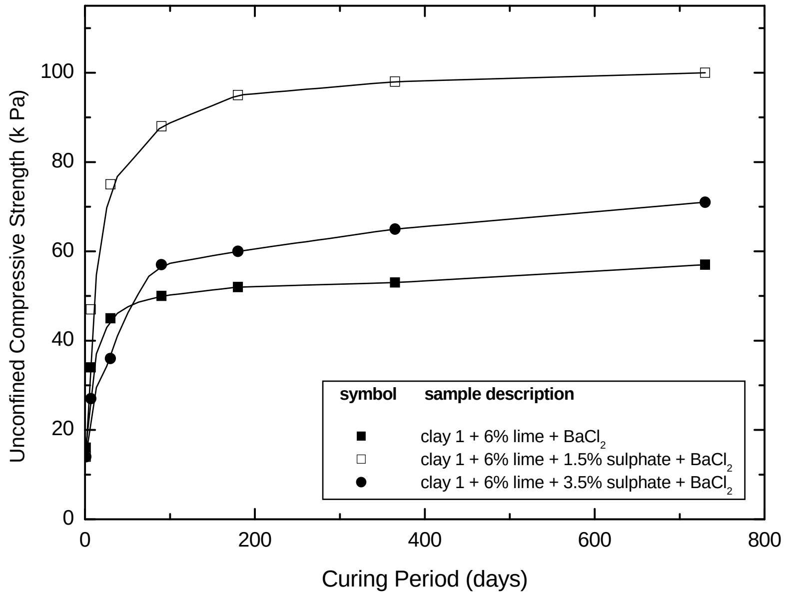

Fig 6.5 Effect of barium chloride in mitigating the effect of sulphates in lime stabilised clay 1 (with varying sulphate contents)

The reaction of lime with clays produces C-S-H (Diamond et al., 1964) or C-A-S-H (Wild et al., 1989) gels together with, in some cases, crystalline calcium aluminate hydrate (Diamond et al., 1964) or calcium silicate aluminate hydrate (Croft, 1964) phases.

In cement terminology, the following abbreviations are used:

C: CaO; A: $Al_2 0_3$; S: SiO_2; S: SO_3; H: H_2O

Long term pozzolanic reactions between the calcium ions of lime and the silica and alumina of the clay minerals results in the formation of cementitious products such as calcium-silicate-hydrates (C-S-H), calcium-aluminate-hydrates (C-A-H), and calcium- aluminum-silicate-hydrates (C-A-S-H). The reaction may be written as:

$Ca(OH)_2$ (ionization of lime) → $Ca^{2+} + 2(OH)^-$

$Ca^{2+} + OH^- + SiO_2$ (soluble clay silica) → calcium-silicate-hydrate

$Ca^{2+} + OH^- + Al_2O_3$ (soluble clay alumina) → calcium-aluminate-hydrate

The hyphens indicate that the composition is indefinite. The specific composition is defined by pH level, solubility of silica and alumina, clay mineralogy, and curing conditions among other reasons (Solanki et al. 2012).

If sulphates which are quite common in clayey soils are present, then both the reaction mechanism and the reaction products are modified (Mitchell & Dermatos, 1990). Normally the calcium sulpho-aluminate phase ettringite ($C_3A.3CS.H_{32}$) is formed and at low sulphate concentrations the metastable phase ($C_3A.CS.H_{12}$) may also be observed.

Presence of Na_2SO_4modifies the initial dissociation of lime as follows:

$Ca(OH)_2 \rightarrow Ca^{2+} + 2\,(OH)^-$ 6.2

$Na_2SO_4 \rightarrow Na^+ + SO^{4-}$ 6.3

$Ca^{2+} + SO^{4-} \rightarrow Ca\,SO_4$ 6.4

$Na^+ + OH^- \rightarrow NaOH$... 6.5

Formation of NaOH increases the pH of the system. pH of saturated NaOH solution gives higher pH than saturated lime solution. The increased pH enhances the dissolution of silica from the clay minerals.

The increased liberation of silica leads to the enhancement of formation of calcium silicate hydrate. Thus the lime reactivity of soils is enhanced in the presence of sulphate.

However the enhanced lime reactivity is counteracted by the formation of $CaSO_4$ which is less beneficial than lime.

This can explain the initial increase in unconfined compressive strength values of samples containing sulphates, up to 30 days and the decrease there after as presented in Table 6.2.

Sridhran et al. (1995) has also reported that the presence of sodium sulphate in the soil system converts lime into insoluble gypsum and sodium hydroxide, and thus reducing the lime available for the reactions with soil. However, the presence of sodium hydroxide increases the pH, and thus the dissolution of silica from the soil.

6.4 Comparative study of the effect of barium chloride and barium hydroxide

The studies on use of barium chloride to mitigate the effect of sulphates were extended to clay containing lesser amount of natural sulphate, viz., clay 2. The role of barium hydroxide in counteracting the effect of sulphate was also studied.

The effect on unconfined compressive strength due to introduction of $BaCl_2$ and $Ba(OH)_2$ to lime treated clay2 in the presence of 3.9% Na_2SO_4 is presented in Table 6.3.

Table 6.3 Unconfined compressive strength of treated clay 2

Sl. No.	Sample description	Curing Period						
		0 day	1 week	1 month	3 months	6 months	9 months	24 months
		Unconfined compressive strength (k Pa)						
1	Clay 2+6%lime	16	43	62	74	79	86	111
2	Clay 2+6%lime +3.9%sulphate	12	87	92	108	76	66	61
3	Clay 2+6%lime +3..9%sulphate +$BaCl_2$	12	79	96	111	120	130	141
4	Clay 2 +6%lime +3.9%sulphate+ $Ba(OH)_2$	9	75	148	153	173	250	321

Fig. 6.6 shows the variation of q_u with curing period for clay 2 containing natural sulphate content of 0.1%. No decrease in strength was observed in this case, as in the case of clay 1 with 0.5% sulphate content indicating no effect at this percentage.

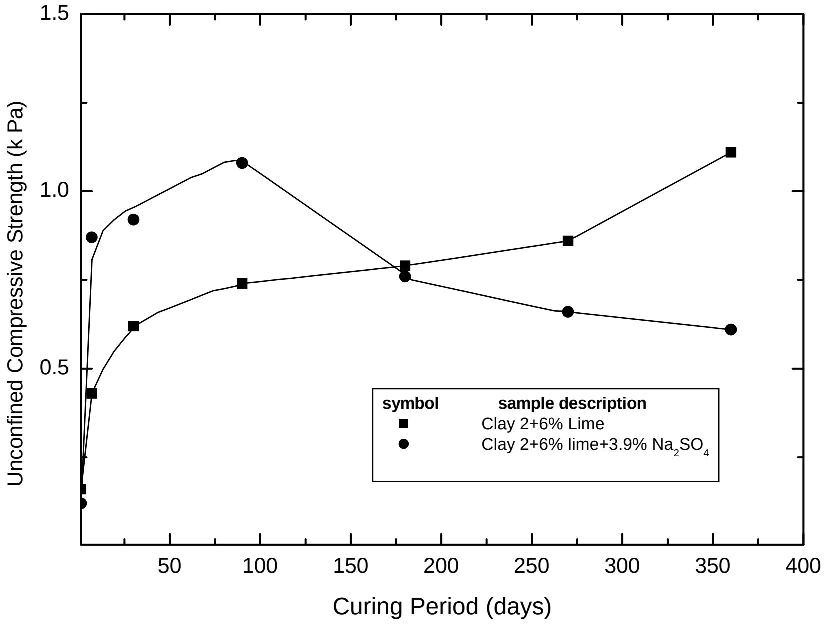

Fig. 6.6 Effect of sulphate in lime treated clay 2 (4% sulphate)

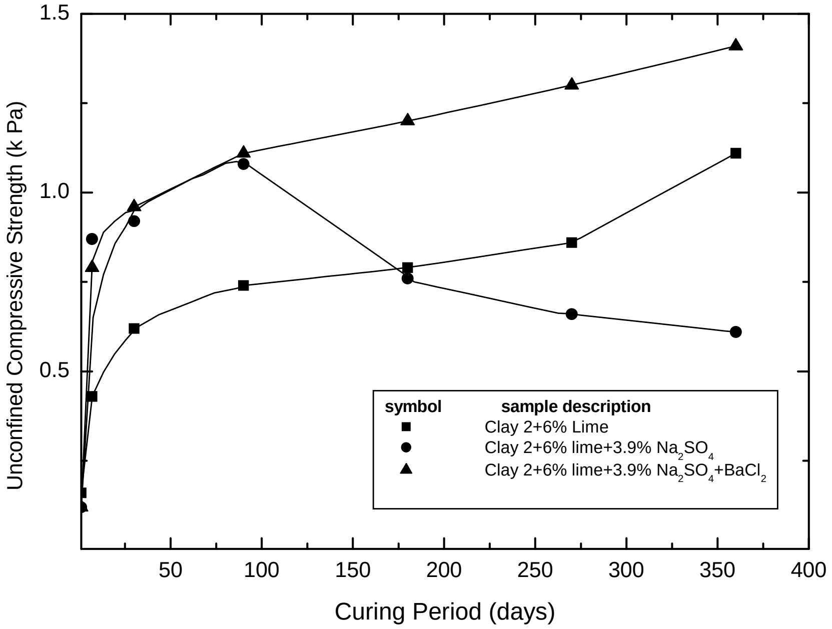

Fig. 6.7 Effect of barium chloride in lime treated clay 2 (4% sulphate)

As explained earlier, the presence of sodium sulphate enhances lime reactivity due to enhanced pH with the formation of NaOH. Presence of $BaCl_2$ slightly constrains the effect of sodium salt by conversion of NaOH to $Ba(OH)_2$ as given by equation 6.6.

$$NaOH + BaCl_2 \rightarrow 2NaCl + Ba(OH)_2 \quad\text{..}\quad 6.6$$

Saturated solution of $Ba(OH)_2$ gives lower pH compared with saturated solution of NaOH (Ramesh, 1993). Still as seen in the case of clay 1 the strength in the presence of barium chloride is higher than with lime alone Fig. 6.7.Fig. 6.8 shows the effect of barium hydroxide in counteracting the effect of sulphate

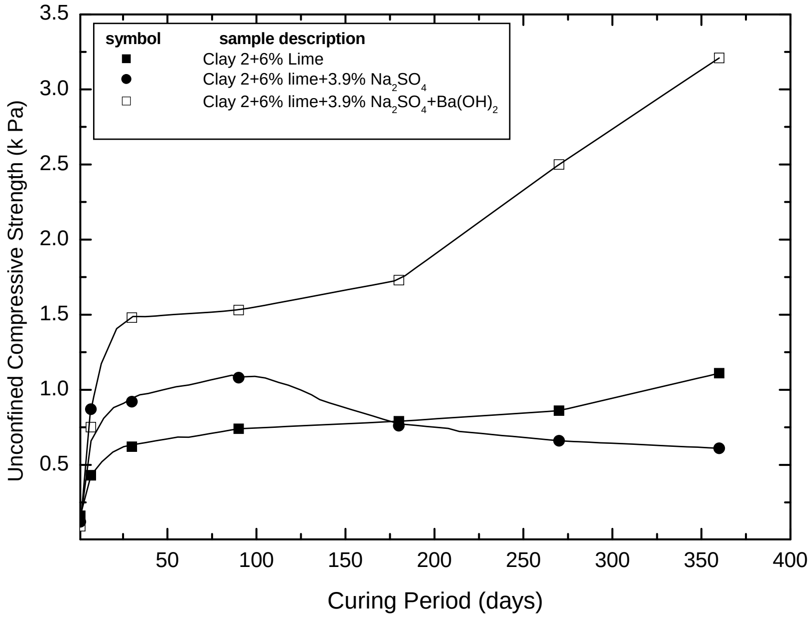

Fig. 6.8 Effect of barium hydroxide in lime treated clay 2 (4% sulphate)

When $Ba(OH)_2$ is used as the additive, the rate of gain of strength during the initial few days is slow when compared with that of $BaCl_2$ as shown in

Fig. 6.9 but a steady increase in strength is observed as curing period increases. The reaction between sodium sulphate and barium hydroxide leaves insoluble barium sulphate as given in equation 6.7.

$$Na_2SO_4 + Ba(OH)_2 \rightarrow 2NaOH + BaSO_4 \quad \text{...} \; 6.7$$

In addition, calcium ion (Ca^{2+}) formed as shown in the ionic equation 6.4 will be attracted to the negative hydroxide ions (OH^-) and Barium ions (Ba^{2+}) will be attracted to the sulphate ions, to form solid barium sulphate.

$$Ba(OH)_2 + CaSO_4 \rightarrow BaSO_4 + Ca(OH)_2$$

This explains the increased strength when $Ba(OH)_2$ is used to inhibit the effect of sulphate in lime treated soil.

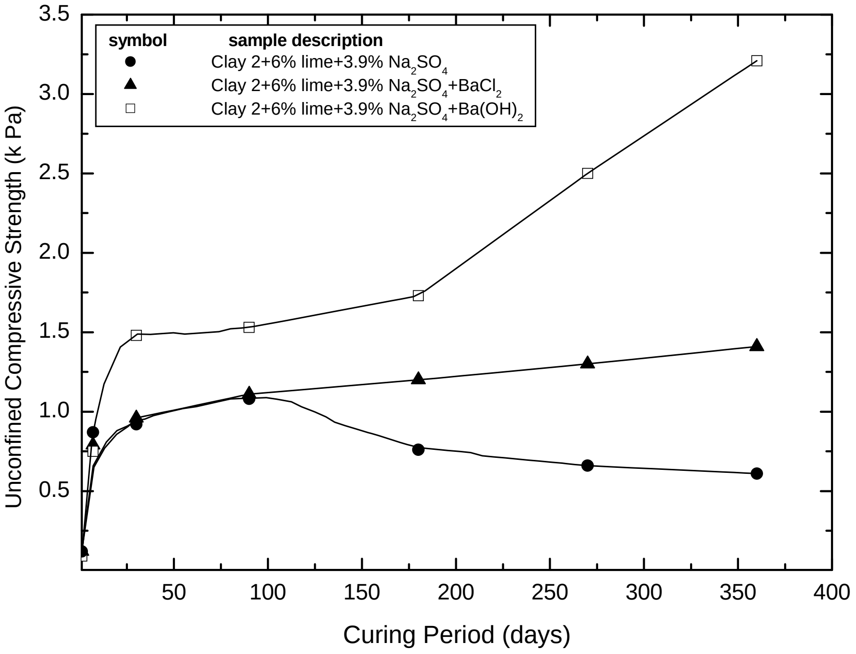

Fig. 6.9 Effect of barium compounds in lime treated clay 2 (4% sulphate)

Thus barium hydroxide in comparison to barium chloride is far more superior in significantly improving the strength on curing of lime treated sulphatic clays. This is in line with the already explained behaviour of reduction in compressibility and increase in bond strength brought about by barium hydroxide as detailed in chapter 5.

Fig. 6.10 presents the variation in unconfined strength of clay 2 treated with 6% barium compounds. It can be seen that barium compounds by itself will not contribute to the gain in strength.

The stress - strain behaviour of clay 2 in the presence of various additives is shown from Fig 6.11 through Fig. 6.14. As expected with increase in curing period unconfined compressive strength value increases in samples containing barium compounds. The shape of stress - strain curves for uncured lime treated soil is similar to that of normally consolidated soils than cemented soils.

Failure strain vs. curing period plot is given in Fig. 6.15. The failure strain for clay 2 treated with 4% sulphate initially exhibits a decreasing trend up to about three months and thereafter increases. This supports the fact that during the initial days strength increases in presence of sulphate. The increasing failure strain after a certain curing period clearly indicates the detrimental behaviour of sulphate in lime treated soil.

As one would expect strain decreases drastically with curing period for clay 2 containing 4% sulphate and treated with barium compounds and 6% lime, decrease being more where barium hydroxide has been used as an additive.

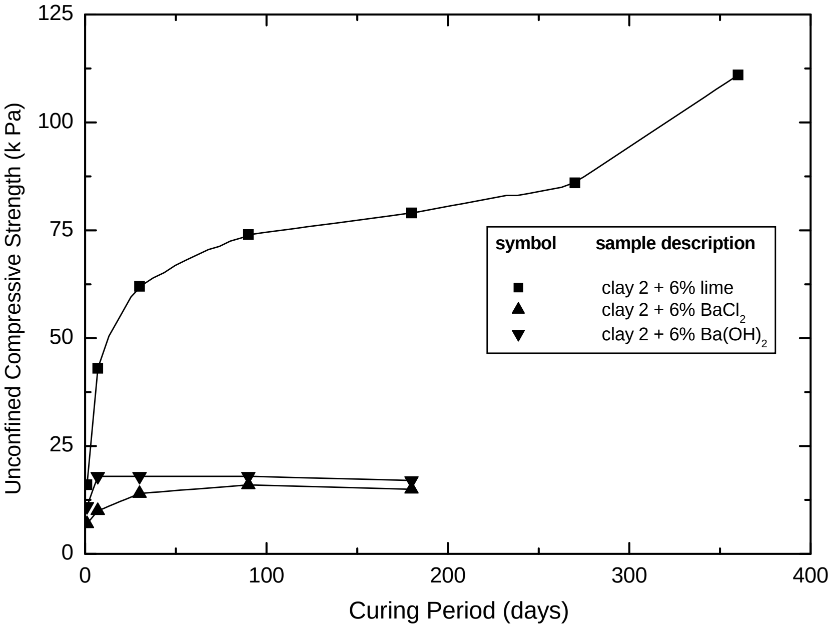

Fig. 6.10 Effect of various additives on clay 2

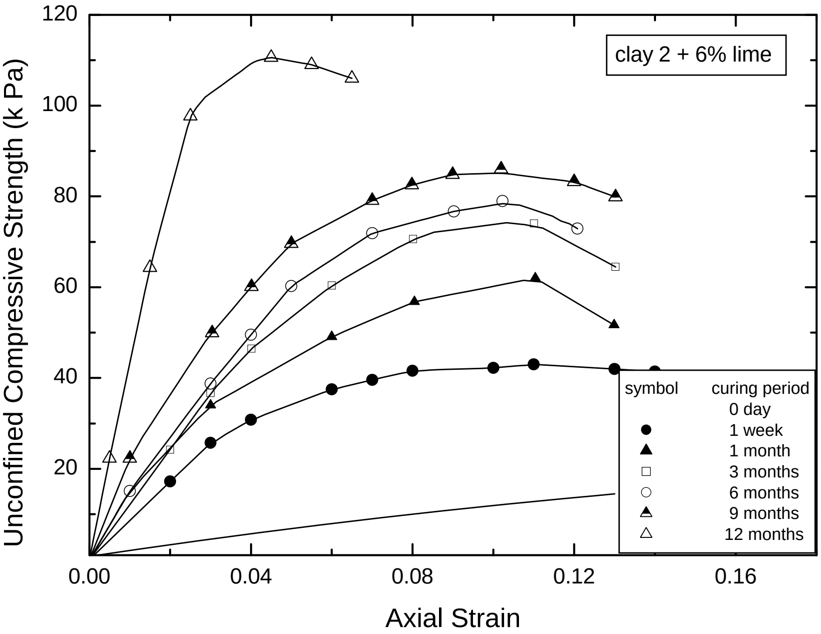

Fig. 6.11 Stress – strain plots for lime treated clay 2

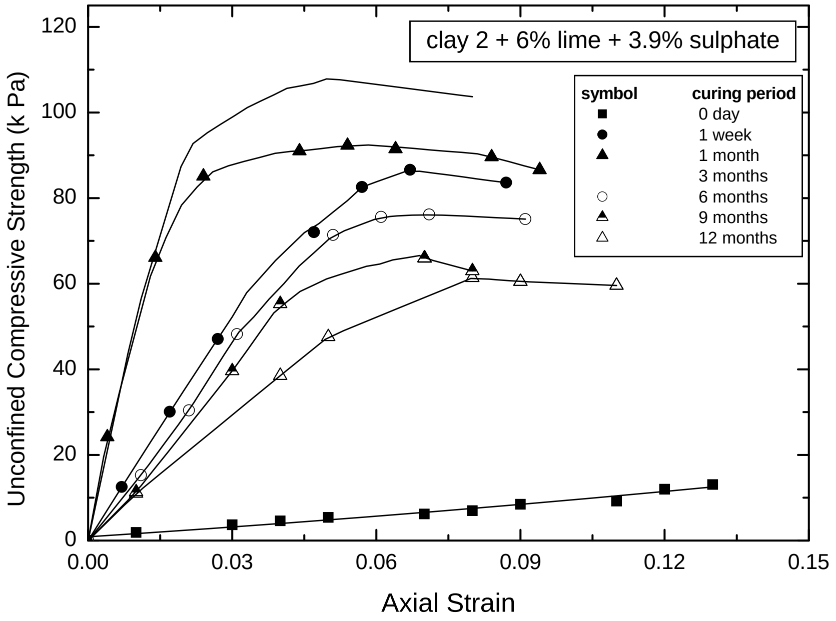

Fig. 6.12 Stress – strain plots for lime treated clay 2 (4% sulphate)

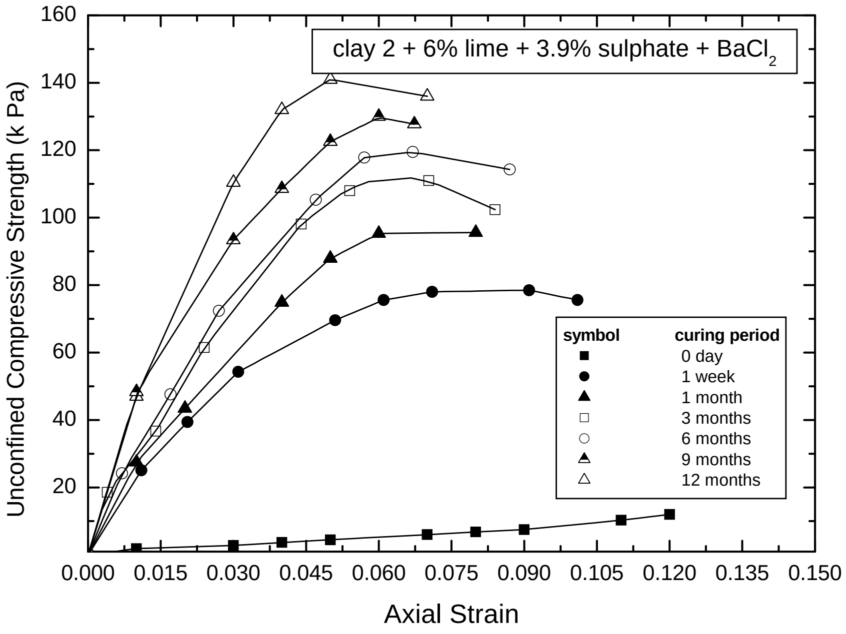

Fig. 6.13 Stress – strain plots for lime treated clay 2 (4% sulphate & barium chloride)

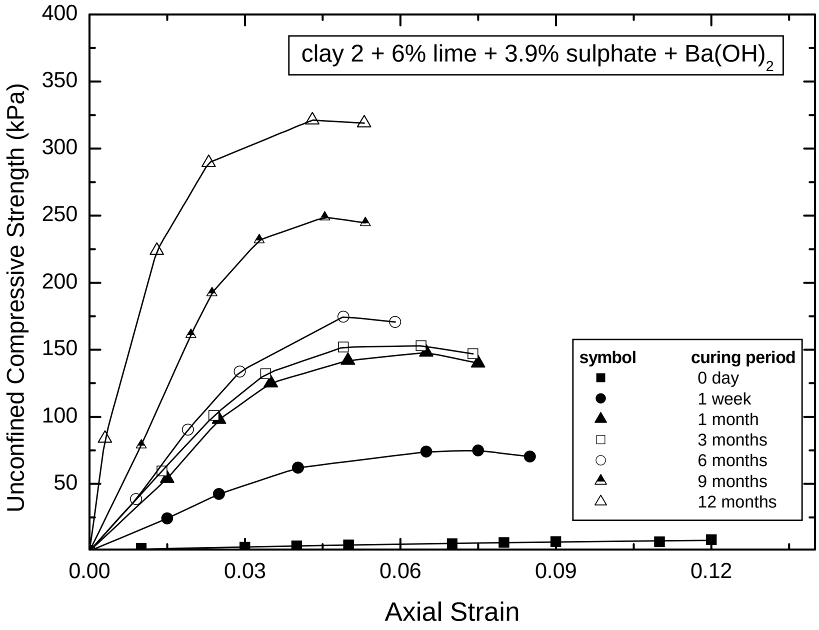

Fig. 6.14 Stress – strain plots for lime treated clay 2 (4% sulphate & barium hydroxide)

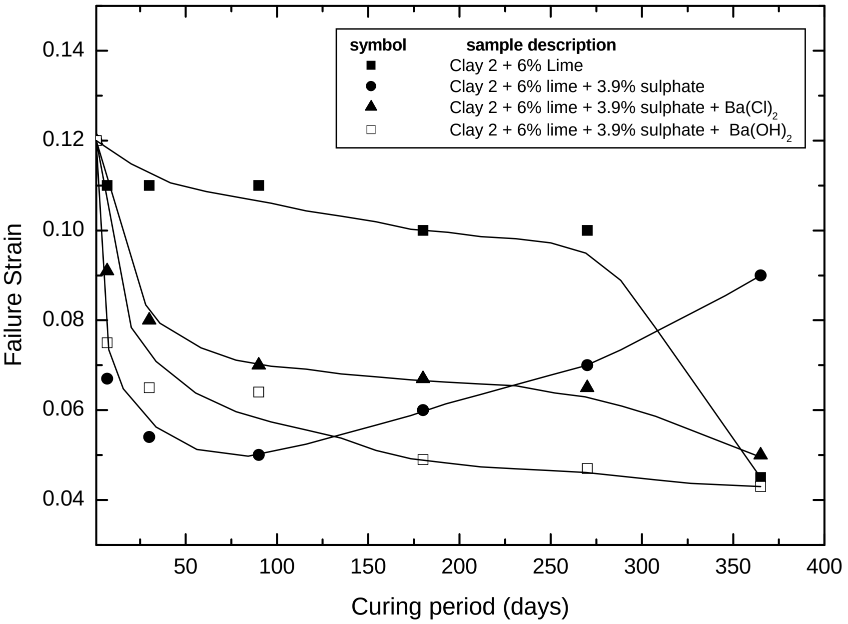

Fig. 6.15 Failure strain vs. curing period

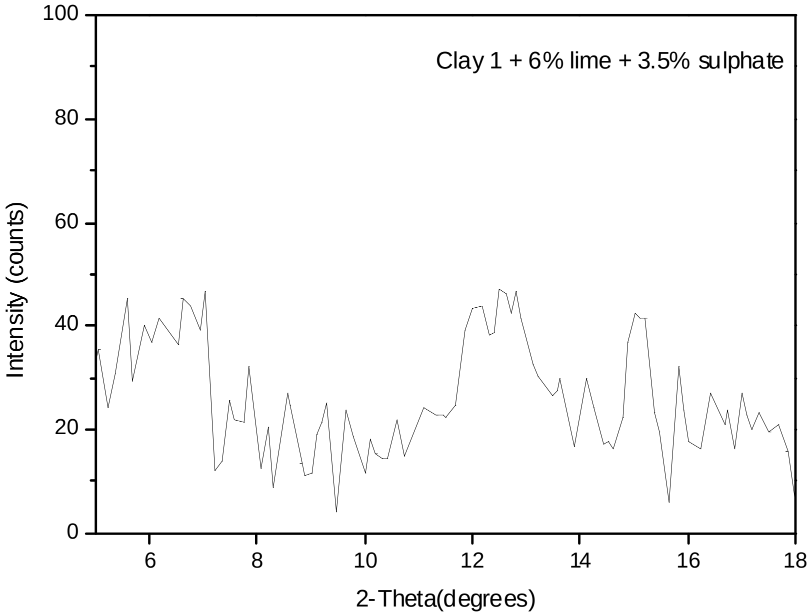

Fig. 6.16 X -ray diffraction pattern of lime treated clay 1 cured for 12 months (4 % sulphate)

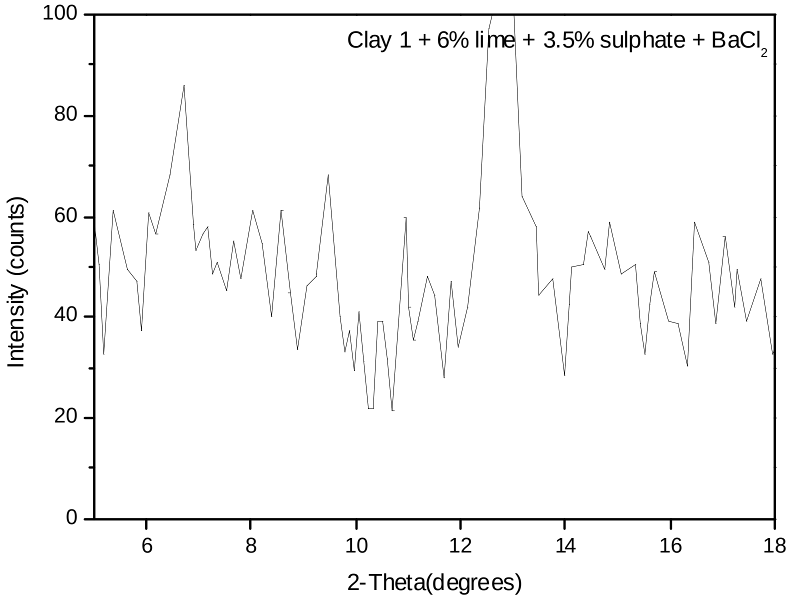

Fig. 6.17 X - ray diffraction pattern of lime treated clay 1 cured for 12 months (4 % sulphate and barium chloride)

Formation of ettringite can be detected by X–ray diffractograms by its peaks at 9. 6 A^0 (2θ at 9.14^0) and $5.6A^0$ (2θ at 15.86^0) (Reis, 1981).

No distinct peaks could be observed in the treated samples as shown in Figs. 6.16& 6.17. Wang (2002) has reported that XRD pattern between 8.5 – 9.5^o will show a peak of ettringite with d = 0.9753 nm, if it occurs. But no obvious ettringite peaks can be identified from the XRD pattern between 8.5 – 9.5° as given in Fig. 6.18 for clay 1 treated with 6% lime and with 3.5 % sulphate cured for 12 months. Sample treated with $BaCl_2$ is also devoid of any peaks in this range (Fig. 6.19). On the other hand, small ettringite crystals were revealed in high abundance through SEM observation. Figure 6.20 illustrates the micrograph of 6% lime treated clay 1 with 3.5% sulphate after curing for 365 days. The SEM image shows the existence of the well-known ettringite needle. The particles are ~ 0.6micron wide and are surrounded by shapeless gel particulates and the same is absent in barium chloride treated sample as shown in Fig. 6.21.

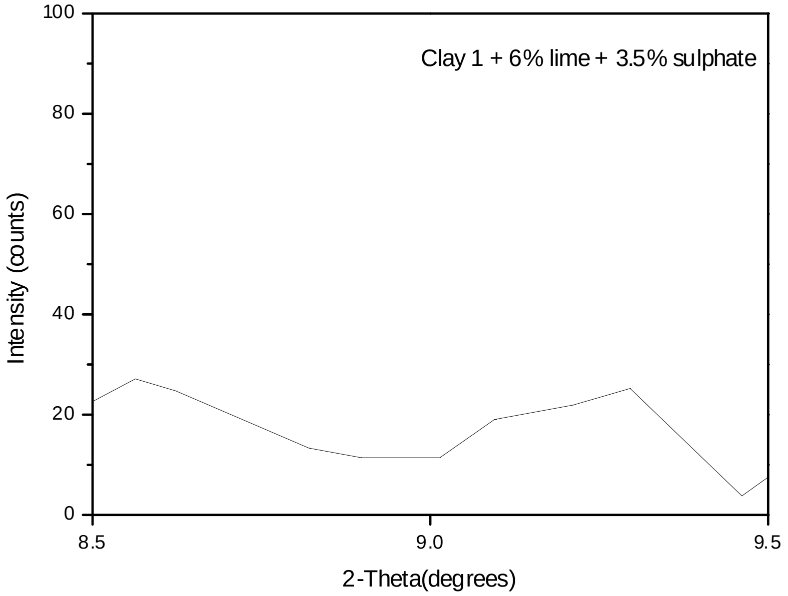

Fig. 6.18 X - ray diffraction pattern of lime treated clay 1 cured for 12 months (4% sulphate)

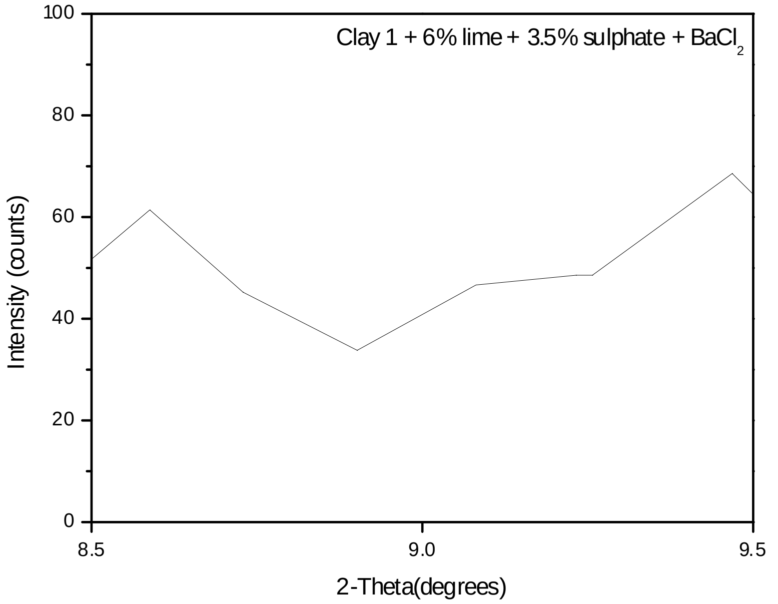

Fig. 6.19 X - ray diffraction pattern of lime treated clay 1cured for 12 months (4 % sulphate and barium chloride)

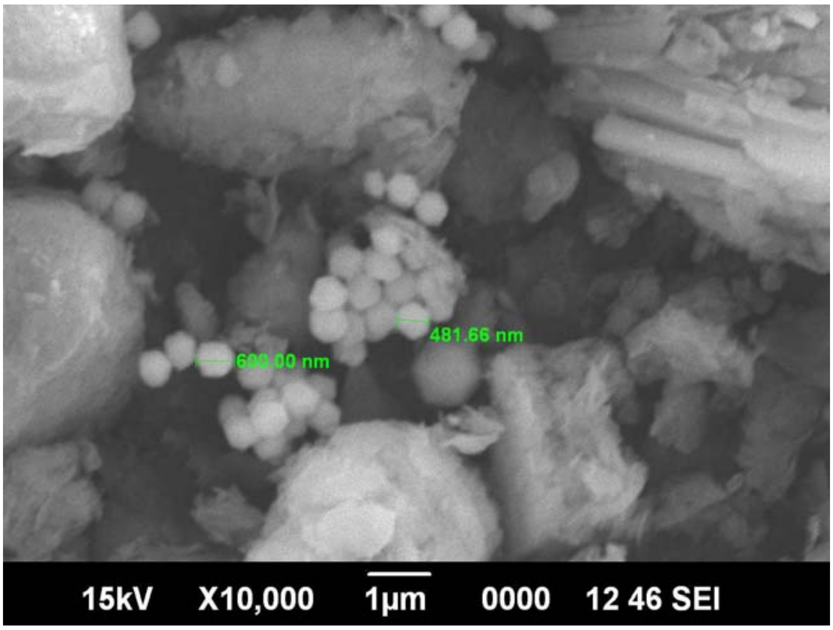

Fig. 6.20 SEM images of ettringite in lime treated clay 1 cured for 12 months (4% sulphate)

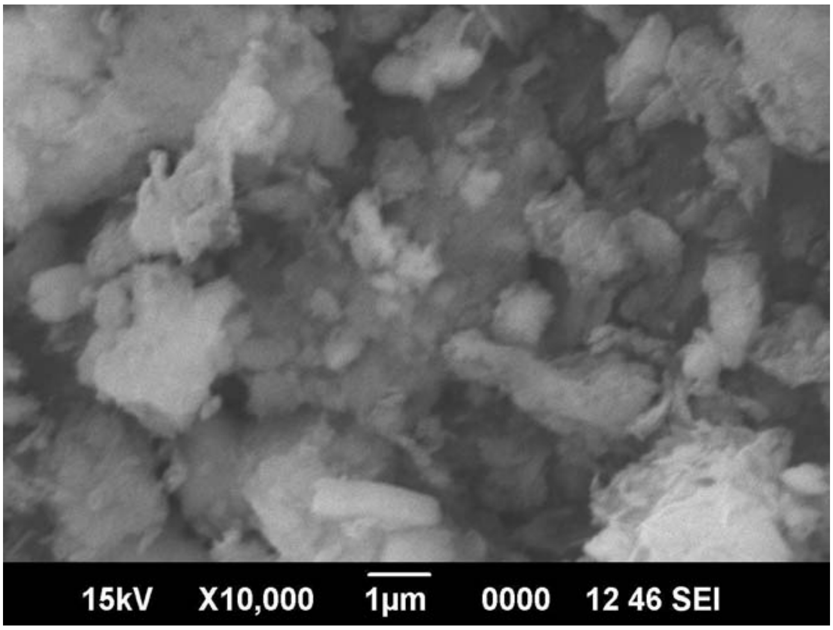

Fig. 6.21 SEM images lime treated clay 1 cured for 12 months (4% sulphate barium chloride)

Kota et al. (1996) noticed the same phenomenon, that is, ettringite in lime-treated soil could not be identified by XRD, but SEM tests demonstrated the visual presence of substantial amounts of needle-shaped crystals. It was speculated that either some of the ettringite minerals were lost in sample preparation or the overall amount of ettringite in the sample used for XRD is less than 10 percent. Anyway, further research work is needed in order to understand this phenomenon.

In addition to the XRD and SEM analyses, The Energy Dispersive X-ray Analysis (EDAX) was conducted on representative specimens. EDAX result for 6% lime treated clay 1 (natural sulphate content 0.5%) cured for 1 month and 6 months is presented in Fig. 6.22 and 6.23. EDAX analyses of the sample treated for one month shows that all the ingredients, including suphur (S), aluminium (Al), and calcium (Ca), which contribute to ettringite formation are present in the treated soils (Sirivitmaitrie, 2008). The EDS pattern was used as a basis to monitor the changes that occurred in the chemical composition of clay 1 after stabilization with 6% lime. The EDS pattern showed presence of Ca and Si with higher Ca/Si ratio than was observed after 1 month curing indicating the development of C-A-S-H. The SEM micrographs reveals evidence of the development of a compact matrix after one month of curing time (Fig. 6.24) and a densified compact network of pozzolanic reaction products with the increase in the curing period to six months (Fig. 6.25).

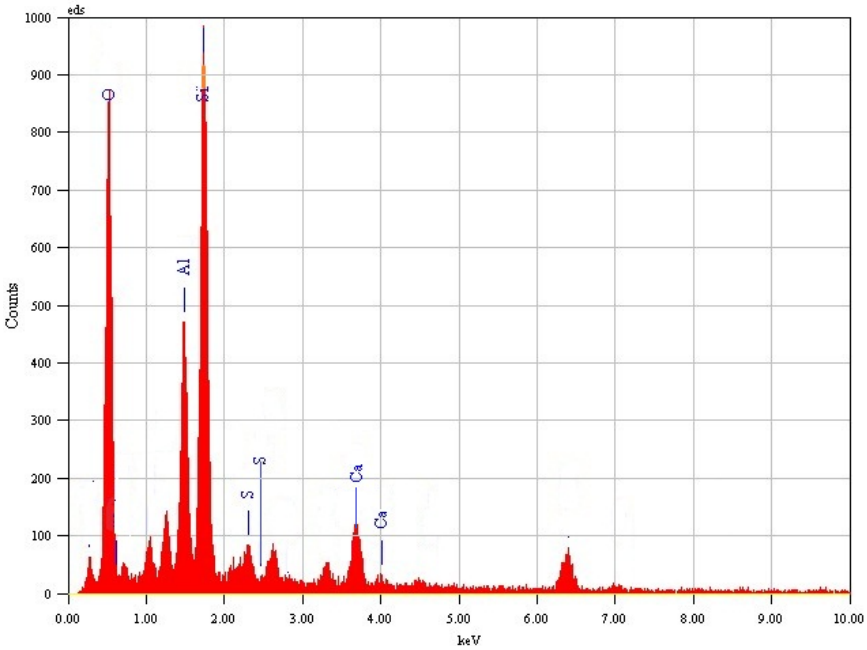

Fig. 6.22 EDAX results for 6 %lime treated clay 1 after one month curing

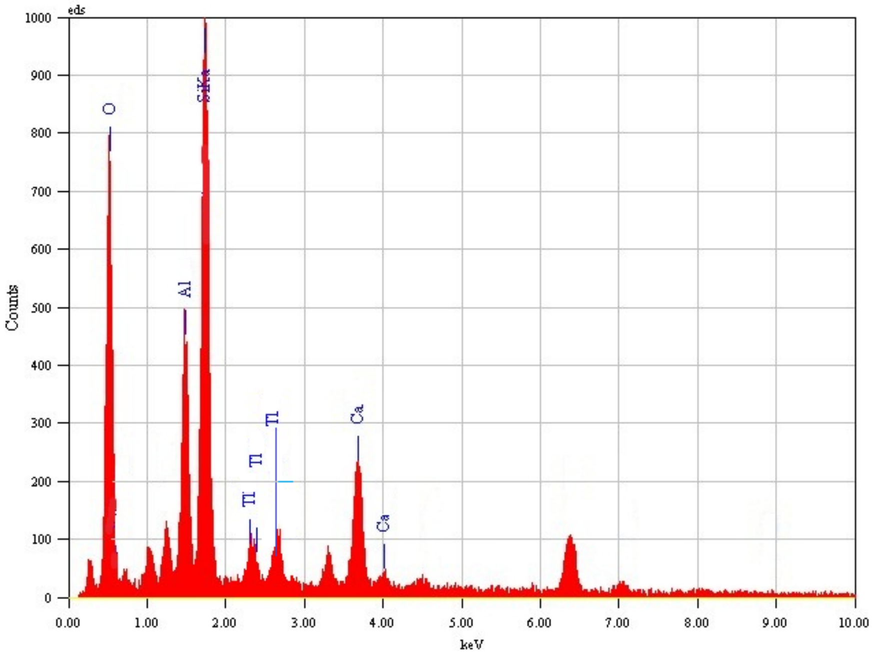

Fig. 6.23 EDAX results for 6 % lime treated clay 1 after six months curing

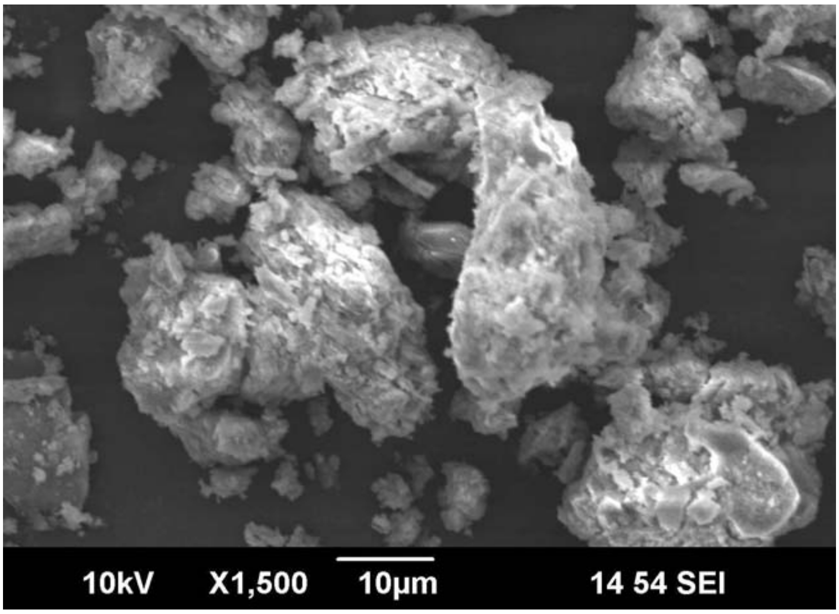

Fig. 6.24 SEM images of 6 % lime treated clay 1 after one month curing

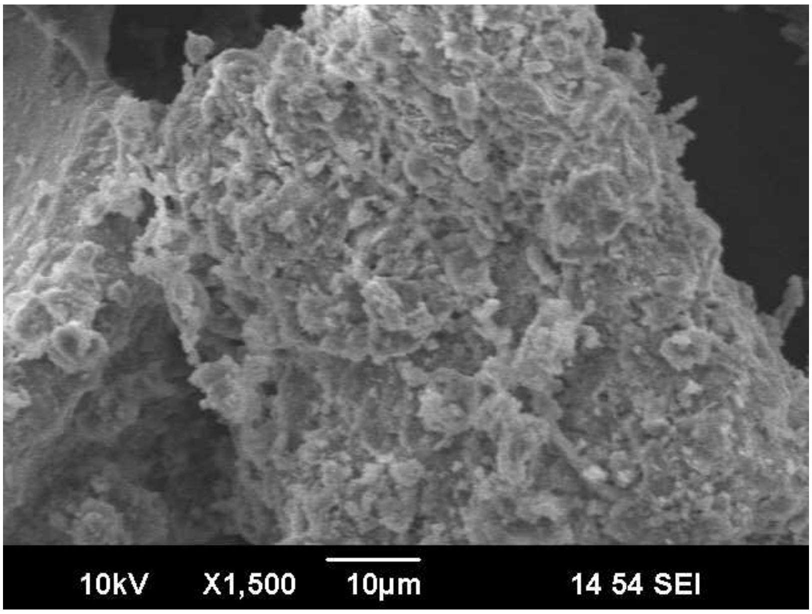

Fig. 6.25 SEM images in 6 %lime treated clay 1 after six months curing

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Chapter 7

SUMMARY AND CONCLUSIONS

Contents

7.1 Introduction

Based on the series of experiments carried out on samples of Cochin marine clays, the following conclusions have been drawn out regarding the influence of sulphates on the physical and engineering properties of lime treated clays. The role of barium compounds in mitigating the deleterious effects of sulphates is brought out and summarised.

7.2 Sulphate quantification

- There is a necessity to determine the sulphate content prior to stabilisation of Cochin marine clays with calcium based stabilisers.
- Sulphate quantification of the two clays selected for the present study was done by all the three IS methods viz., (a) precipitation method or standard method (b) volumetric method or subsidiary method and (c) calorimetric or turbidimetric method. All the three

methods gave similar results and yielded sulphate content of 0.5% and 0.1% for the clays tested.

- As per easiness of conducting the test especially when large number of representative samples need to be tested, the order of preference is as follows, i) calorimetric method by use of nephelometer, ii) volumetric method, and iii) precipitation method.
- At the same time there is a need to evolve and popularise rapid field tests for determination of sulphates.
- Sulphate concentration of 0.1% is not of concern but 0.5% can cause adverse effects when lime stabilization is resorted to.

7.3 Physical properties

- With both 3% and 6% lime and presence of any quantity of sulphate, liquid limit is found to show a decreasing trend with time.
- Significant increase in liquid limit is observed on curing with 6% lime and sulphate. Higher the concentration of sulphate, greater is the increase. However, on curing for larger periods, the liquid limit of lime treated clay in the presence of sulphate decreases.
- No definite trend could be established regarding the variation of plastic limit either with sulphate content or with curing period.
- Presence of any concentration of sulphate decreases plasticity index on curing.

- Addition of barium compounds further decreases liquid limit and plasticity index with curing period when compared to lime treated clays cured in the presence of sulphates.
- Good correlation could be established between plasticity index and liquid limit on chemically treated clays.
- Addition of barium chloride did not cause significant change in shrinkage limit of clay 1 but in clay 2 the shrinkage limit increased with curing period, indicating development of a more open fabric.
- Addition of barium hydroxide also tends to increase shrinkage limit indicating a well developed flocculant fabric.
- Free swell index decreases with curing period for lime treated sulphatic clays. Treatment with barium compounds further decreases the free swell index.

7.4 Compressibility characteristics

A series of consolidation tests were carried out to analyse the compressibility characteristics of lime treated clays under the influence of varying concentrations of sulphate with duration of curing time. Investigations to understand the effectiveness of barium compounds in beneficially modifying the consolidation characteristics by mitigating the adverse effects likely to be induced by these sulphates were also carried out.

- Sulphate concentration of 0.1% is seen to have no adverse effect on the lime treatment. The compressibility steadily decreases with time.

- At short durations of curing, the deleterious effect of sulphate is not brought out in the compressibility behaviour. The compressibility decreases initially in presence of sulphates but increases on curing for longer periods.
- Presence of any concentration of sulphate increases the compressibility of lime treated clays on curing. Higher the sulphate content, greater will be the increase. This trend was observed for sulphate concentrations of 0.5%, 1%, 2% and 4%.
- Addition of barium chloride could reverse this trend and upon curing the compressibility decreased for any concentration of sulphate.
- Barium hydroxide in comparison to barium chloride could bring in far more reduction in compressibility, indicative of the superiority of barium hydroxide in mitigating the effect of sulphates. This might be because barium ions are more available in the mix of barium hydroxide plus lime than barium chloride plus lime.
- Variation of de/d(log p) values with curing period for lime treated samples with sulphates also prove that amount of compression undergone by the samples is much higher and goes on increasing with increasing pressure and curing period. Whereas barium chloride and barium hydroxide have the effect of beneficially decreasing de/d(lop p) values of lime treated sulphatic clays on curing.
- No definite trend could be established for variation of coefficient of consolidation, c_v with additives upon curing.

- Variation of secondary compression coefficient with curing period is seen to be same as that observed for de/d(logp).
- Bond strength is found to pick up instantaneously on curing lime treated clays in the presence of sulphates, especially smaller concentrations of sulphates. This suggests increased lime reactivity in the presence of sulphates. But higher periods of curing cause drastic reduction in bond strength establishing the adverse effects brought about by sulphates.
- Addition of barium chloride or barium hydroxide effectively arrested this reduction in bond strength and there was continuous increase in the value of pre-consolidation pressure, p_c on curing, in comparison to decrease of bond strength on curing in presence of sulphates.
- Thus reduction brought about by barium chloride and barium hydroxide in compression index, C_c values accompanied by corresponding increase of P_c values of lime treated clays with varying sulphate contents clearly suggests their effectiveness in nullifying the reactions that form ettringite.
- Barium compounds, thus used to mitigate the adverse effect of sulphates might have reacted to form less soluble barium sulphates, thereby reducing the availability of calcium sulphates for ettringite formation.

7.5 Strength characteristics

Series of unconfined compression tests were performed to evaluate the effect of sulphates on lime treated marine clays. The effectiveness of barium additives in suitably modifying the reactions by decreasing the amount of sulphates available to react with calcium hydroxide and aluminium thereby reducing/preventing ettringite formation was also analysed. This process in turn helps in making available more free lime thereby increasing the pH of the system allowing for more dissolution of the clay fraction to produce additional cementing materials during lime stabilisation.

- 0.1% sulphate has in no way interfered with gain in strength of lime treated clay.
- At the same time, 0.5% sulphate could induce adverse changes in normal pozzolanic reactions and could cause a reduction in strength on curing, though results prove that once the sulphate is consumed, further reduction in strength does not occur.
- Unconfined compressive strength results prove that sulphate concentrations of 0.5% to 4% are capable to modify/ hinder lime induced aggregation and formation of cementation products. The continuous increase in strength normally observed in lime treated clays is absent here. The extent to which the strength gets affected depends on the sulphate content.
- At all sulphate contents, strength first increased up to a certain curing period and then decreased. The same trend was also observed in the case of development of bond strength.

- Barium chloride and barium hydroxide is seen to have marked influence in mitigating the adverse effect of sulphate in reducing the strength.
- Barium hydroxide is observed to remarkably increase the strength as compared to barium chloride, when used in conjunction with lime to counteract the effect of sulphate.
- Thus clay containing sodium sulphate has increased strength values when either of the barium compounds was used with lime as compared with specimens treated with lime only.

7.6 Microstructural & mineralogical characterization

Investigations on microstructures of lime stabilized marine clay in order to elucidate their changes in relation to consequent adverse effects/ improvement on engineering properties proved to be useful.

- X-Ray diffraction patterns of the clays indicate the presence of montmorillonite, illite, kaolinite, along with non clay minerals quartz and feldspar along with calcium carbonate.
- Though the presence of ettringite could not be identified from XRD, the same could be clearly identified from SEM images.
- SEM micrographs of lime treated soils indicated formation of new cementitious compounds by pozzolanic reactions through the long-term curing, contributing to the strength gain.

- EDS patterns indicated presence of compounds/altered reaction products and could be used effectively for qualitative analysis to support SEM results.

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