

Lime Stabilization of Soils: Reappraisal

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Abstract: Lime generally improves the performance of soils. However, some cases reported an adverse effect. To develop an understanding of the underlying mechanisms, a systematic study covering a wide range of plasticity and mineralogy of soils was carried out. Six different soil samples were reconstituted using two extreme types of soils, in other words, a montmorillonite rich expansive soil and a silica-rich non-expansive soil. The influence of lime stabilization on these soils was evaluated through determination of geotechnical properties such as liquid limit, plastic limit, swell, compressive strength, mineralogy, and microstructure. An optimum lime content beyond which the strength improvement decreased was found. This phenomenon is more prominently observed with silica-rich soils that form silica gel. As the silica gel is highly porous, when formed in large scale the strength gain from cementation is substantially countered by the strength loss from gel pores, giving rise to a visible reduction in overall strength. Additionally, the gel materials hold a large amount of water, leading to increased plasticity and swelling. Therefore, excessive lime treatment should be avoided for silica-rich soils.

Author keywords: Soil stabilization; Lime; Evaluation.

Introduction

Lime, or CaO or Ca OH p , the burned byproduct of lime stone (CaCO_3), is one of the oldest developed construction materials, and humans have been using it for more than 2,000 years, when the Romans used soil-lime mixtures to construct roads. However, its utility in modern geotechnical engineering applications was limited until 1945, mostly because of lack of proper understanding of the subject (Herrin and Mitchell 1961). Today, lime stabilization of soils is widely used in several structures such as highways, rail-ways, airports, embankments, foundation base, slope protection, canal linings, and others. (Anon 1990; Wilkinson et al. 2010). This prevalent use of lime is primarily because of its overall economy and ease of construction, coupled with simplicity of this technology that provides an added attraction for engineers. Several research studies highlighted the beneficial effect of lime in improving soil performance.

An important phenomenon reported by many researchers is the ability of lime to change the plasticity of soils. Both the liquid limit and the plastic limit indices, where the plastic limit indicate the plasticity of soil, are influenced by lime, which affects the thickness of the diffuse hydrous double layer surrounding the clay particles. Whereas the liquid limit of clay soils is found to decrease with increased lime content (Wang et al. 1963; Bell 1988), the plastic limit generally shows an increasing trend (Herrin and Mitchell 1961; Barker et al. 2006). A greater amount of clay results in a higher, lime-induced increase in the plastic limit (Hilt and Davidson 1960).

Correspondingly, the plasticity index, the mathematical difference of the liquid limit and the plastic limit that quantifies the plasticity of soils, is generally found to decrease with lime amendment (Herrin and Mitchell 1961; Bell 1988), making the soil more friable and therefore more workable.

High plastic soils generally contain clay minerals such as montmorillonite, which has large affinity for water. Therefore, such soils undergo large swelling, leading to severe distress and damage to the overlying structures (Petry and Little 2002). Through physico-chemical modifications, lime can effectively control the swelling of soils (Mateos 1964; Bhasin et al. 1978). Correspondingly, the swell pressure and, hence, damage and distortion of the superstructure substantially decreased (Wilkinson et al. 2010).

Apart from modifying the plasticity and swelling characteristics, lime can stabilize the soils through cementation, giving rise to visible increases in strength and stiffness (Bell 1996; Rajasekaran and Rao 2000; Consoli et al. 2011). The cementation is primarily attributable to pozzolanic reactions and can significantly improve the long-term performance of the stabilized soils (Rogers et al. 2006; Khattab et al. 2007). Several case studies highlighted the application of lime stabilization in improving the performance of problematic soils (Joshi et al. 1981; Petry and Little 2002; Wilkinson et al. 2010).

However, in some cases, lime is reported to produce adverse effects on the performance of soils. Increases in the liquid limit and plasticity index (Clare and Cruchley 1957; Prakash et al. 1989; Bell 1996) indicate that lime increased the plasticity of the soils that it treats. This result is suggested from the action of hydroxyl ions modifying the water affinity of the soil particles. Moreover, increase in lime content beyond a certain limit was found to decrease the strength gain (Hilt and Davidson 1960; Herrin and Mitchell 1961; Bell 1996; Kumar et al. 2007). Because lime itself has neither appreciable friction nor cohesion, excess of lime is postulated to reduce its strength. However, soil-lime stabilization is dependent on several factors such as soil type, its mineralogy, lime content, and curing period, and is a complex problem that needs careful reevaluation.

Materials Used

Primarily, an expansive soil (ES) and a non expansive residual soil (RS), which represent the extreme soil type, are used in this study. The expansive soil is a commercially available bentonite. Its liquid limit and plastic limit are found to be 459.9% and 53.7%. As per ASTM D2487 (2006b), the soil is classified as clay with high plasticity (CH). Given its high expansiveness, particle size analysis using a sedimentation process is extremely difficult. However, given the very high plasticity characteristic, the soil can be assumed to have 100% clay-size particles. The BET specific surface area and cation exchange capacity of this soil are found to be 86:45 sq:m/g and 69:12 meq/100 g, respectively. The X-ray diffraction analysis shows the presence of montmorillonite, quartz, and aluminum oxide as the dominant minerals in this soil (Fig. 1).

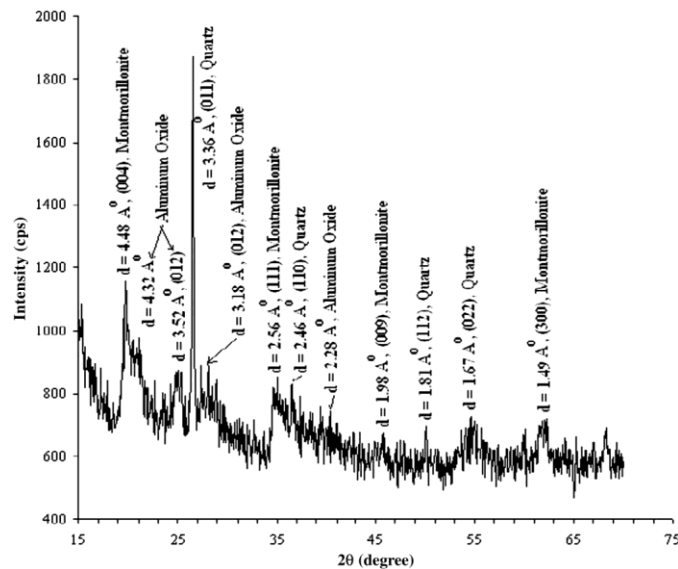


Fig. 1. X-ray diffraction pattern of expansive soil (100%ES)

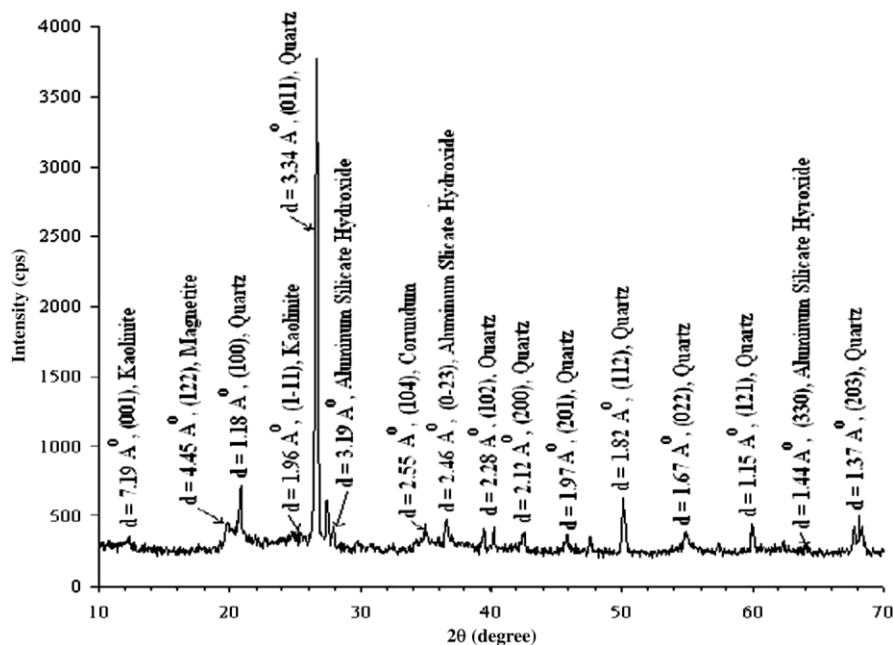


Fig. 2. X-ray diffraction pattern of residual soil (100% RS)

The used residual soil is classified as clay with low compressibility (CL). It has a particle size finer than 425 μm , out of which 71.7% are silt. Its liquid limit and plastic limit are found to be 45.3% and 25.9% respectively. It has a specific surface area of 38:76 sq:m/g and cation exchange capacity of 12:43 meq/100 g. The X-ray diffraction pattern (Fig. 2) indicates the presence of kaolinite, quartz, and magnetite as the principal minerals in this soil. Moreover, the quartz (SiO_2) peak in this soil is almost double that of the expansive soil, 3,750 cps versus 1,900 cps (Fig. 2 versus Fig. 1). This result indicates that, compared with the expansive soil, silica content is much higher in the residual soil.

A laboratory reagent grade quick lime (CaO) was used as the stabilizing agent. Distilled water was used in preparing the test specimens and for curing.

Experimental Program and Test Details

To cover a wide range of plasticity, six different soil samples were constituted by mixing the expansive soil and residual soils in different proportions, the details of which are given in Table 1. All of these soils were amended with lime (i.e., 1, 3, 5, 9, and 13% by weight of dry soil) and cured for varying periods (i.e., immediate, 3, 7, 21, and 28 days), following which different tests were conducted. Tests under series 1 were carried out to study the influence of lime on the plasticity characteristics of soils. The swelling behavior was studied in test series 2 using oedometer swell tests. Strength improvement attributable to lime amendment was evaluated through unconfined compressive strength (UCS) tests in series 3. The microstructural characteristics were examined through scanning electron micrograph (SEM) and X-ray diffraction (XRD) under test series 4.

For liquid limit and plastic limit tests, soils and lime, in requisite quantities, were added with adequate amounts of water and mixed thoroughly to form slurry of uniform consistency. The specimen was sealed in a container and kept in a desiccator for curing until the desired period when the tests were conducted. Liquid limit tests were done using the percussion method, whereas the plastic limit

Table 1. Index Properties of Soils

Soil	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
100%ES	459.9	53.7	406.2
80%ES þ 20%RS	351.9	49.4	302.5
60%ES þ 40%RS	248.2	38.1	210.1
40%ES þ 60%RS	178.8	30.7	148.1
20%ES þ 80%RS	99.2	28.7	70.5
100%RS	45.3	25.9	19.4

was obtained by the thread rolling method, as per ASTM D4318 (2005).

The strength improvement of soils attributable to cementation was evaluated using the unconfined compression tests. The specimens were prepared at the optimum moisture content, as determined from compaction tests. An additional amount of water, i.e., 32% by weight of lime, was added to compensate for the need for hydration of lime (Greaves 1996). The moist soil-lime mix was static compacted in a cylindrical brass mold to size of 38 mm in diameter and 76 mm in length. The specimens thus prepared were sealed in plastic bags and kept in a desiccator under 100% relative humidity for curing. After the desired period of curing, unconfined compressive strength was evaluated. The tests were conducted as per ASTM D2166 (2006a) under a constant strain rate of 1:25 mm/ min.

The swell behavior was studied using the conventional odometer. The soil-lime-water mix was prepared in the same way as that in case of the UCS test, and was static compacted in the oedometer ring to the maximum dry density condition. Subsequently, it was loaded to a surcharge of 5 kPa, inundated with distilled water, and left to swell while the readings were recorded. Curing took place as the test progressed. Since most of the lime-induced pozzolanic reaction is expected to be completed by 28 days, all the swell tests were carried out until 30 days.

Changes in the pH of the soil-water system attributable to lime were determined as per ASTM D4972 (2007) using a pH meter, which has an accuracy of 0:05 units. The instrument was standardized with two standard buffer solutions (pH of 4.0 and 9.2). Ten grams of soil-lime mix was equilibrated with distilled water at a solid-liquid proportion of 1:2:5 (Jackson 1958). The suspension was stirred well and allowed to come to room temperature, and then the pH was measured.

A scanning electron microscope with energy dispersive X-ray analysis was employed to study the microstructural characteristics in the matrix of the lime stabilized soils. Pieces of soil samples

collected from posttest UCS specimens were dried, mounted on the specimen holder, and coated with a thin layer of gold palladium to provide surface conductivity. The coated specimen was placed in the scanning electron microscope operating at 15 kV, and the photomicrographs were recorded. X-ray diffraction tests were carried out to identify the minerals present. Representative soil samples collected from the posttest UCS specimens were air dried, powdered, and sieved through the 75 µm IS sieve. A soil specimen finer than 75 µm was placed onto the X-ray diffractometer equipped with bragg-brentano parafofocusing geometry, a graphite monochromator, and a copper target X-ray tube set to 30 mA and 40 kV. The data obtained were analyzed with Jade 3.1, an X-ray powder diffraction analytical software developed by Materials Data, Inc. (Jade 1999).

Results and Discussions

Plasticity

Plasticity of a soil is closely correlated with the liquid limit, the plastic limit, and their derivative, the plasticity index. Therefore, a detailed study of the variation of these parameters attributable to lime amendment will assist in understanding the plasticity behavior of the lime-stabilized soils.

Influence of lime and curing on liquid limit of the soils, 100%ES and 100%RS, are depicted in Fig. 3, and that of a typical soil mix (40%ES þ 60%RS) is shown in Fig. 4. The responses of the other three soil mixes (i.e., 80%ES þ 20%RS, 60%ES þ 40%RS, and 20%ES þ 80%RS) are intermediate to these trends. Initially, all of the specimens showed a decrease in the liquid limit with an increase in lime content. This reduction is maximum for the expansive soil (100%ES) and gradually declines with increased content of residual soil. With the addition of lime, Ca^b ions are released into the pore fluid. As a result, the electrolyte concentration of the pore water increases and decreases the thickness of the diffuse double layer held on to the soil and leading to a lower liquid limit. For expansive soil, the liquid limit continues to decline until approximately 3% of lime, beyond which it does not change much. However, with very high lime content (i.e., 13%), when cured long (i.e., 21 days, 28 days), the liquid limit showed an increasing trend. This behavior is more prominently observed for specimens having high percentage of the silica-rich residual soil. Because this phenomenon takes place only after prolonged curing, certain physicochemical reaction between soil and lime are expected to be responsible. In fact, the pH of the soil-water system is found to increase with lime and with approximately 3% of lime, increases to 12.3. In an alkaline environment with pH value above 12,

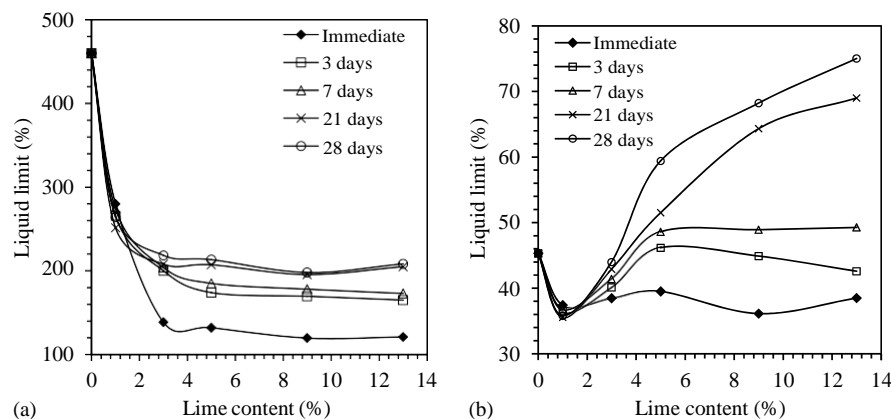


Fig. 3. Variation in liquid limit with lime content for expansive soil and residual soil

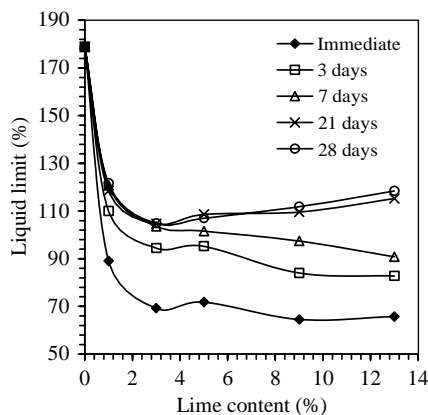


Fig. 4. Variation in liquid limit with lime content for soil mix (40%ES b 60%RS)

formation of calcium silicate hydrate (CSH) gel takes place, which consists of solid products of hydration and water, held physically or adsorbed on the surface of the hydrates. This water, called gel water, is located between the solid products of hydration in the gel pores of very small size (i.e., approximately 2 μm). The volume of gel water was established to be as high as 28% of the volume of gel (Neville and Brooks 2004). Additionally, a large amount of water exists, which is combined chemically or physically with the hydrates, marginalizes the influence of the double layer reduction-induced decrease in water content and thereby enhances the liquid limit. Indeed, the increase in the liquid limit with an increase in lime content is more prominent for the silica rich residual soil that forms a large quantity of CSH gel. Hence, under lime treatment, soils with high silica content are prone to increase in the liquid limit. Moreover, increased duration of curing leads to prolonged pozzolanic reaction, producing increased quantity of water holding gelatinous products and resulting in a further increase in the liquid limit. The other factor responsible for an increase in the liquid limit could be attributed to a possible change in soil fabric. The increase in pH attributable to lime induces an additional negative charge on the clay particle edges (Taylor 1959), leading to edge-to-face attraction that results in a flocculated structure. The relatively open structure of the flocculent fabric holds more water, leading to an increased liquid limit. Sivapullaiah et al. (2000) also reported similar behavior.

Hence, the liquid limit behavior of lime treated soil can be described as having three different phases. The first phase is the reduction in thickness of the diffuse double layer, which takes place

quickly and leads to a lower liquid limit. The second phase is the increase in the liquid limit attributable to fabric changes giving rise to flocculated structures. The last phase is the pozzolanic reactions, producing water holding gelatinous materials, which enhances the liquid limit. This phenomenon is dominant for silica rich soils.

Fig. 5 depicts the influence of the quantity of lime added and the curing period on the plastic limit of soils i.e., 100%ES and 100% RS. The responses of all other soils (i.e., the soil mixes) are found to be intermediate to these two extreme cases. The plastic limit of all the soils was observed to increase with an increase in lime content. The increase is relatively faster until the lime content reaching approximately 3%. From 3 to 5% of lime content, the rate of increase in the plastic limit is comparatively slow. Beyond 5% lime, a visible increase in the plastic limit is noticed only for the residual soil-dominant specimens (i.e., RS > 80%) and longer curing period (i.e., ≥1 days).

The plastic limit is a measure of cohesion of the soil particles against cracking when the soil is worked with (Yong and Workentin 1975). The cohesion and, hence, the shear strength between the soil particles should be low enough that they can slide partly over one another at ease. However, at the same time, the interparticle shear strength should be high enough to hold the soil mass in the re-molded position. Hence, the plastic limit is a measure of the water content of soil when it approaches a certain shear resistance. With the addition of lime, the thickness of the diffuse double layer decreases, which increases the charge concentration and thereby the viscosity of the pore fluid. As a result, the interparticle shear resistance increases, leading to a sharp increase in the plastic limit. Moreover, the lime-induced flocculation enhances the interparticle resistance against movement, leading to an increased plastic limit. Similar to the liquid limit, the plastic limit also does not change much when the lime content is increased beyond 5%. Hence, practically, 5% lime content can be considered as the lime fixation point, at which a substantial increase in soil workability can be obtained. However, for silica-rich soils, during a relatively long curing period, the plastic limit continues to increase with an increase in the lime content. This phenomenon is attributed to the formation of the water holding CSH gel, a viscous material that allows the soil particles to maintain the molded positions over a wider range of water content.

For all of the soils studied in this paper, an immediate decrease in the plasticity index was observed on addition of lime because, as previously noted, immediately on addition of lime the liquid limit decreases and the plastic limit increases. Note that with lime treatment, the plasticity index of the expansive soil decreased from approximately 400 to just 50%. This substantial reduction in the

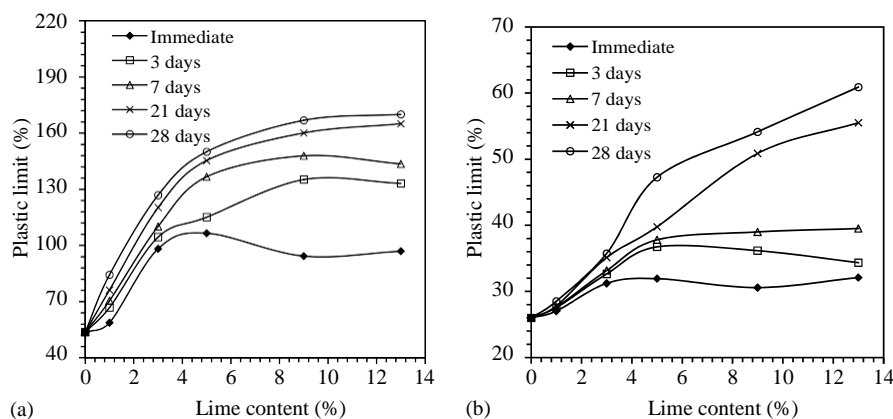


Fig. 5. Variation in plastic limit with lime content for expansive soil and residual soil

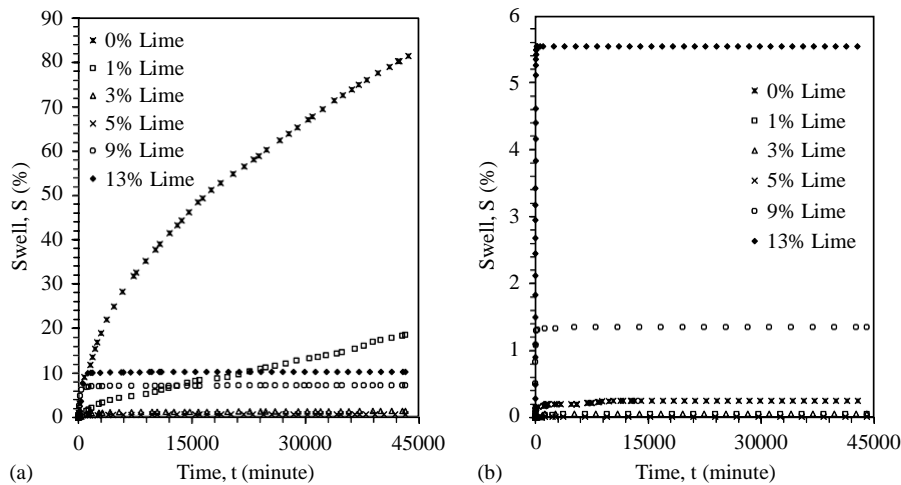


Fig. 6. Time-swell responses of lime-treated expansive soil and residual soil

plasticity index suggests that the soil itself changed. Indeed, in most of the cases, the lime-treated soils crossed the A-line in the plasticity chart to the silt (*M*) region, indicating that the clay soil on lime treatment was transformed to silt. However, with an increase in the curing period, the plasticity index showed an increasing trend, which is more prominent with a higher percentage of residual soil. This pattern is attributed to the excessive formation of silica gel that enhances the overall water holding capacity of the soil.

Swell

Time-swell responses for the two extreme soils (i.e., 100%ES and 100%RS) with varied lime content is presented in Fig. 6, and that of a typical intermediate soil (i.e., 40%ES p 60%RS) is depicted in Fig. 7. In the present tests, the untreated expansive soils did not reach the maximum swell state. Therefore, the maximum possible swell in these cases is obtained through the rectangular hyperbolic relation, proposed by Sridharan and Gurtug (2004). However, the lime amended soils reached the near equilibrium state within the test range. The swell potential values (i.e., maximum swell, S_{max}) for different soils and lime content are presented in Table 2. The swell, *S*, is defined as $\Delta h/h_i \times 100$, where, h_i = initial thickness of the specimen and Δh = increase in thickness at a given time. Even with 1% lime, the swell was observed to have substantially

been lowered. With a further increase in lime, swelling continues to decrease to reach a practically negligible value. This result is attributed to the increased electrolytic concentration attributable to lime, leading to decreased thickness of the diffuse double layer and, hence, the swelling. However, after this initial reduction, the swelling of soils once again picked up, with an increased percentage of lime. This phenomenon manifested in greater prominence in the specimens with a higher percentage of the silica-rich residual soil and, therefore, is primarily attributed to the formation of silica gel. Excessive lime treatment can even alter the very nature of the soil; for example, with 13% lime, the practically nonswelling residual soil changed into a moderately swelling soil [S_{max} 5:5%, Fig. 6(b)].

The data presented in Table 2 shows that the threshold lime content beyond which the soil tends to develop significant swelling is approximately 5% for 100%ES and 80%ES p 20%RS, and approximately 9% for higher percentages of residual soil (i.e., 60%ES p 40%RS, 40%ES p 60%RS, 20%ES p 80%RS, 100%RS). In the expansive soil-rich specimens the intergranular voids are less in volume because of large fines content. However, with increased content of the coarse-grained residual soil, a stage occurs at which the coarser particles come in to contact with one another, forming interclod voids that contain the gel formed. Swelling tends to manifest externally only when the gel volume surpasses the volume of the voids. Hence, for such soils only at higher lime content (i.e., > 9%), the specimen exhibited visible swelling. These observations indicate that grain size also influences the swelling of lime-treated soils.

Strength

Typical strength (UCS at failure) variation of lime-amended soils is depicted in Fig. 8. When lime is small in quantity, at approximately

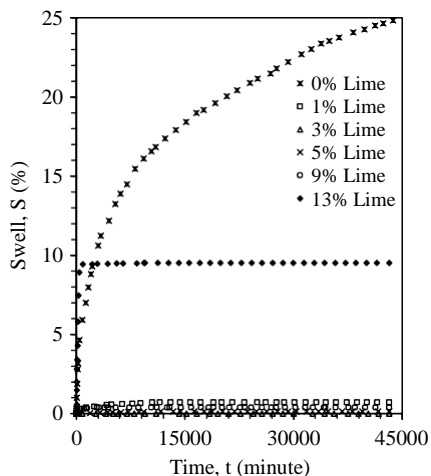


Fig. 7. Time-swell responses of lime-treated soil mix (40%ES p 60%RS)

Table 2. Summary of Soil Swell Potential

Soil	Swell potential, S_{max} (%)						
	Lime content	0%	1%	3%	5%	9%	13%
100%ES		97.1	18.6	1.46	0.72	7.25	10.3
80%ES p 20%RS		48.1	11.9	0.87	1.04	5.96	6.80
60%ES p 40%RS		34.2	5.15	0.63	0.85	0.98	5.68
40%ES p 60%RS		26.3	0.71	0.00	0.13	0.38	9.52
20%ES p 80%R		3.89	0.22	0.00	0.10	0.17	8.95
100%RS		0.25	0.05	0.06	0.01	1.35	5.54

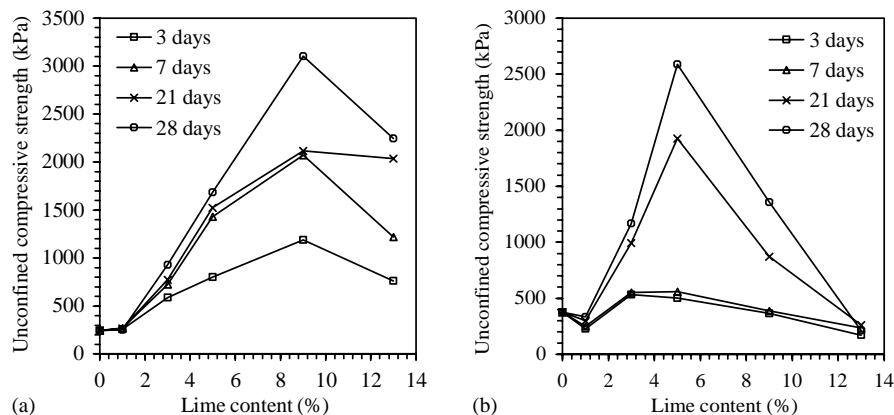


Fig. 8. Variation in unconfined compressive strength with lime content

1%, the strength improvement is practically negligible, even if cured over a long period. At this stage, lime is mostly used in meeting the initial requirement of soil, such as altering its diffuse double layer indicated through a decrease in the liquid limit (Fig. 3). Therefore, cementation is too weak, giving rise to marginal strength gain. With increased lime content, the pozzolanic reaction peaks, producing adequate amounts of cementitious compounds that result in visible strength increases. With 9% lime and 28 days curing, strength increases to 3,000 kPa compared with 250 kPa for the untreated soil, or a 12-fold increase. However, with further increases in lime, a reduction in strength takes place that is more pronounced at prolonged curing. Bell (1996) recommended that because lime has neither appreciable friction nor cohesion, an excess amount serves as a lubricant to the soil particles and thereby decreases the strength. Kumar et al. (2007) attributed such strength reduction to the platy shape of the unreacted lime particles. However, as has been explained previously, lime produces cementitious gel that has substantial volume of pores upon reacting with soil. Therefore, with increased lime content, the soil structure tends to be increasingly porous to counteract the strength gain attributable to cementation. At very high lime content, an overall decrease in strength occurs from excessive formation of this gel material. This effect is more prominent for residual soils, so much so that at 13% lime, the amended soil underperforms the untreated soil [Fig. 8(b)].

The optimum lime content, giving maximum strength for different soils and curing period, is summarized in Table 3. For expansive soil dominant samples (i.e., 100%ES, 80%ES & 20%RS, 60%ES & 40%RS), the optimum lime content was observed to be 9%, whereas for residual soil-rich specimens (i.e., 20%ES & 80%RS, 100%RS) it was reduced to 5%. The expansive soils attributable to large clay fractions need a higher percentage of lime to alter its physicochemical characteristics. Therefore, such soils are in need of more lime for strength gain. In contrast, the residual

soil-rich specimens with low clay contents require less lime to amend their plasticity characteristics. As a result, a relatively large proportion of the lime added is available for pozzolanic reactions, leading to a visible increase in strength. Moreover, the coarse particle structure of these soils is an added advantage for cementation bonding, resulting in early strength gain.

Microstructure

Changes in the engineering properties of soils resulting from lime treatment can be attributed to the microstructural developments studied through XRD and SEM. Typical X-ray diffractograms of stabilized soils, 100%ES and 100%RS, with 13% lime and 28 days curing are depicted in Figs. 9 and 10, respectively. Compared with the untreated soil (Figs. 1 and 2), several new peaks of low to moderate intensity appeared with lime, indicating formation of new compounds. Among these, the major cementitious compounds are gyrolite [2Ca:3SiO₂:H₂O], calcium silicate hydrate (CSH) [5Ca₂SiO₄:6H₂O], and calcium aluminum silicate hydroxide hydrate (CASHH) [Ca₃Si₂Al₂(OH)BO₁₇:5H₂O]. The other compounds present are quartz and montmorillonite, which were originally present in the untreated soil. However, the peaks of these elements

Table 3. Summary of Optimum Lime Contents Giving Maximum Strength

Soil	Optimum lime content (%)			
	3 days	7 days	21 days	28 days
100%ES	9	9	9	9
80%ES & 20%RS	9	9	9	9
60%ES & 40%RS	9	9	9	9
40%ES & 60%RS	5	5	9	9
20%ES+80%RS	5	5	5	5
100%RS	3	3	5	5

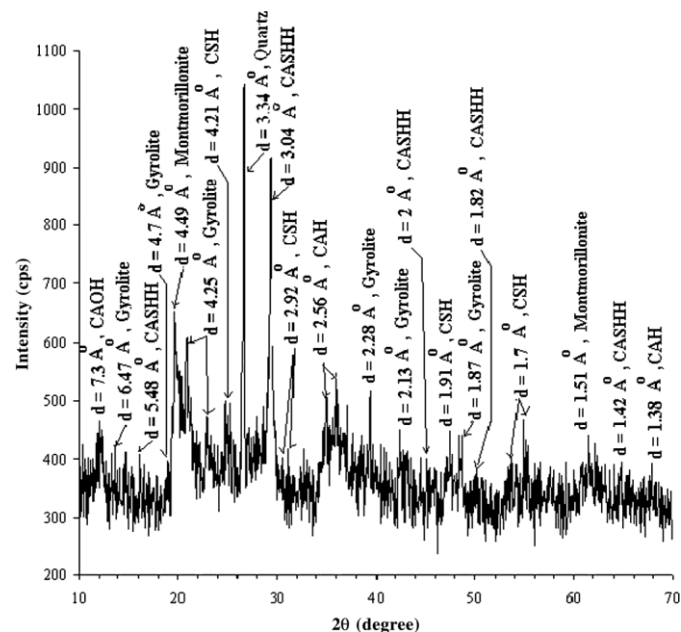


Fig. 9. X-ray diffraction pattern of lime treated expansive soil (100%ES & 13%Lime), 28 days curing

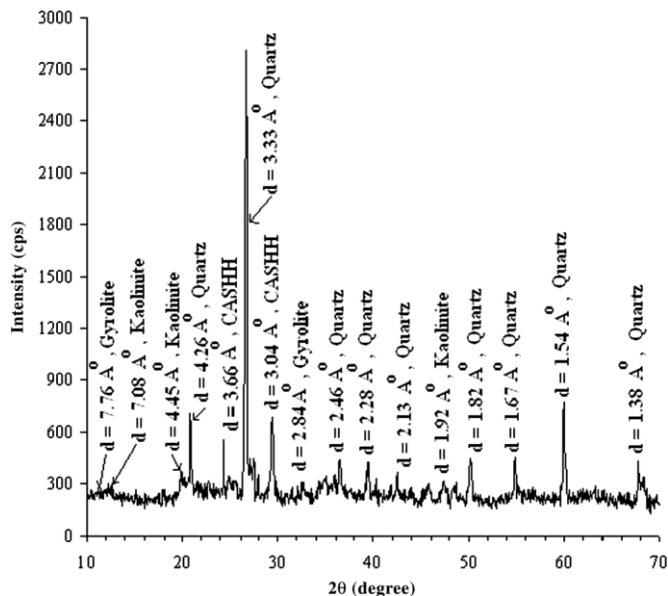


Fig. 10. X-ray diffraction pattern of lime treated residual soil (100%RS þ 13%Lime), 28 days curing

showed a clear reduction. For example, the quartz peak originally approximately 3,700 cps in the untreated residual soil (Fig. 2) decreased reduced to approximately 2,800 cps with lime treatment (Fig. 10). This decrease indicates that quartz was substantially attacked by lime to form silica gels. Moreover, the d -spacing of the cementitious compounds also changed. For example, the d -spacing of gyrolite in the residual soil, with 1, 3, 5, 9, and 13% lime was 4.19, 4.18, 4.19, 4.26, and 4.26 $^{\circ}$, respectively, and that of the compound CASHH was 2.89, 2.99, 2.98, 3.04, and 3.04 $^{\circ}$, respectively. With lime content more than 5%, the d -spacing was observed to increase prominently, indicating that at higher lime content, expansion of the cementitious compounds occurs. An expanded structure is relatively weak because of large open spaces that formed within; therefore, the strength declined (Fig. 8) and swelling increased (Fig. 6). Moreover, the visible reduction of XRD peaks at higher lime content indicates decay of the crystalline structure and formation of relatively amorphous compounds. This aspect is further analyzed through the SEM micrographs. At 5% lime, the micrograph [Fig. 11(a)] shows well developed cemented crystalline structures in reticulated and flocculated form that enable the soil to sustain higher load. With an increase in lime content

to 9%, the micrograph shows the formation of patches of reaction products (i.e., silica gel) and the crystalline structure diminished [Fig. 11(b)]. This phenomenon is more prominently observed, lime content further increased (i.e., 13%).

Conclusions

Lime generally improves the engineering performance of soils. However, in some cases, lime has been reported to have an adverse effect. To develop an understanding of the possible mechanisms involved, a series of experiments through careful variation of different parameters were carried out, based on which the following conclusions are drawn.

The liquid limit of soils initially decreases with an increase in lime content. This result is attributed to a reduction in the thickness of the double layer attributable to increased electrolyte concentration in the pore fluid. In the process, the charge concentration of the pore water increases. As a result, the viscosity of the pore water increases and it offers higher resistance against interparticle movement, leading to an increased plastic limit. However, beyond approximately 5% of lime content, the consistency limits no longer change, indicating that the workability of the soils cannot be improved further. However, for silica-rich soils at relatively higher content of lime and prolonged curing period, both the liquid limit and plastic limit have exhibited phenomenal increases and the soil turned to be increasingly plastic. This phenomenon occurred because lime produces calcium silicate gel upon reacting with silica, and the gel is a viscous material that holds a large amount of water onto itself and therefore enhances soil plasticity.

Correspondingly, the swell potential of soils initially decreases with increased percentage of lime to a practically negligible value, beyond which it once again increases as lime content increases. The lime content at which swelling begins to increase is approximately 5% for fine-grained soils and approximately 9% for coarse-grained soils. With coarse particles, the intergranular voids are larger. Therefore, the cementitious gel formed is initially contained within the void space and does not contribute to swelling. Only with a higher percentage of lime is the gel formed sufficiently large in quantity to fill the intergranular voids, then the external swelling begins. Hence, apart from plasticity characteristics, the grain size distribution also plays a significant role in the swelling behavior of the lime-treated soils.

The major cementitious compounds formed are gyrolite, calcium silicate hydrate, and calcium aluminum silicate hydroxide hydrate, which significantly improve the strength and stiffness of the soil. However, beyond certain limits, further addition of lime

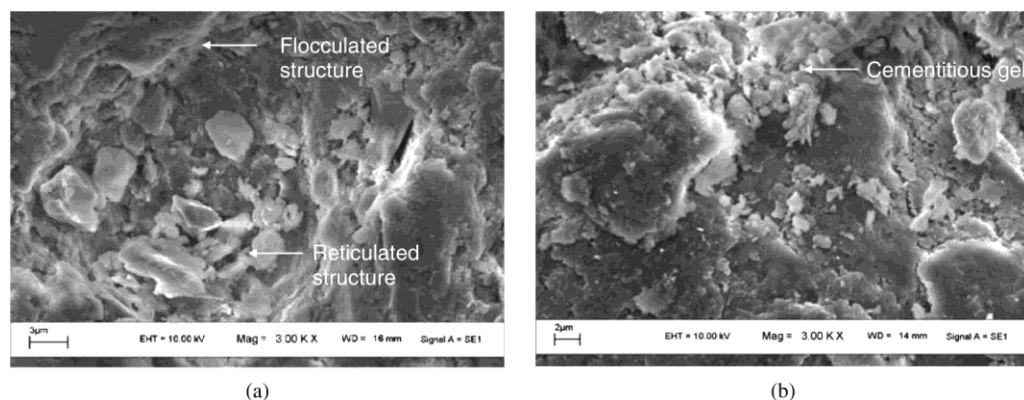


Fig. 11. SEM micrograph of lime treated residual soil, 28 days curing ($M \frac{1}{4} 3KX$)

reduced improvement in strength, more prominently in case of silica-rich soils. This reduction in strength is attributed to the excess formation of silica gel, a highly porous material. The increased *d*-spacing of the compounds establishes the formation of such porous structure. As a result, the strength gain from cementation is substantially undermined. Therefore, in such soils, excessive lime treatment should be avoided.

Acknowledgments

The authors are thankful to Professor A. Sridharan, Professor P. V. Sivapullaiah, Dr. Bulu Pradhan, and Dr. Manoranjan Kar for their valuable comments and suggestions.

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