Lime columns technique for the improvement of soft clay – A review

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***Abstract*— Lime columns is a stabilization technique that uses either quick or hydrated lime as stabilization agents to improve the ultimate bearing capacity of soft clay soils and reduce settlement of structures. It is one of the soil stabilization techniques that are used to increase strength, decrease the compressibility of soft soils such as soft clays, accelerate a consolidation effect and reduce the settlement. It is believed that this method was used first in 1975 and 1979 by Broms and Bomans who used a special type of auger to form the bores in which lime was mixed with the soil in-situ. In this technique, it was assumed that the improved soil column in the bore was acting as a pile to support the superstructure. Later, it was found that lime can diffuse into the surrounding soil and can stabilize a greater volume of soil. This article sheds the light on the mechanism and chemistry of lime column stabilization in addition to applications and installation methods, of lime columns. Also, some geotechnical applications of such technique on improving soft clay are discussed with details.**

Keywords*— *Soft clay; lime column stabilization; mechanism of lime stabilization, installation of lime columns.

I. Introduction

Applying lime column stabilization is a ground improvement method is used by the geotechnical engineers for reforming the problems of weak soil in construction projects without facing any structural failures or cracks due to low shear strength of soil or excessive settlement values. Stabilization using lime is a well-known practice to improve the characteristics of fine-grained soils. The first field application in the construction of highway and air fields pavements were reported in (1950) as reported by Broms and Bomans, (1979). With the proven success of these attempts, the technique was extended for large scale soil treatment using lime for stabilization of subgrades as well as improvement of bearing capacity of foundations. Lime column technique is one of the considerable techniques used for deep stabilization of soft clay soil. It has been used for improving the behavior of soft clay soil, decreasing settlement and increasing shear strength. Soil improvement by lime column method overcomes the settlement problem and low stability. It is considered one of the most economical techniques to improve the engineering behavior of soft soil. Lime addition causes significant improvement in a short time in clayey soil properties by reducing plasticity and increasing strength of soil. Bell, (1996) indicated that the optimum gain of strength in clay is achieved with the lime addition of 4-6%. The increase in strength is affected by the amount of mixing water, the curing time, and the temperature at which curing takes place. Many researchers carried out different studies to understand the behavior of soft clay improved with lime column techniques (Hasan et al., 2018 [6]; Rostami et al., 2016; Chong et al., 2015 [8]; Larsson, 2000 [13]).

II. Mechanism of lime stabilization

Based on the structure of crystal and mud, it is possible to divide the clay minerals into three basic groups: Kaolinite, Montmorillonite and Mica. Clays are secondary minerals that are built in nature from chemical weathering products and are composed of silica and alumina in a specific vacuum distribution, forming clay crystals that resemble mica sheets. It was possible to identify two basic structural units that are forming the clay minerals, namely the unit of the quadrilateral pyramid and the unit of the eight pyramid as shown in Fig. 1. In the quadrilateral pyramid unit, the silicon ion is surrounded by four ions of oxygen to form a quadrilateral pyramid and the units are linked together to form the silica sheet. As for the unit of the eight pyramid, where the aluminum ion is surrounded by six ions of oxygen or hydroxy to form an octagonal pyramid and the units are linked together to be an alumina sheet.

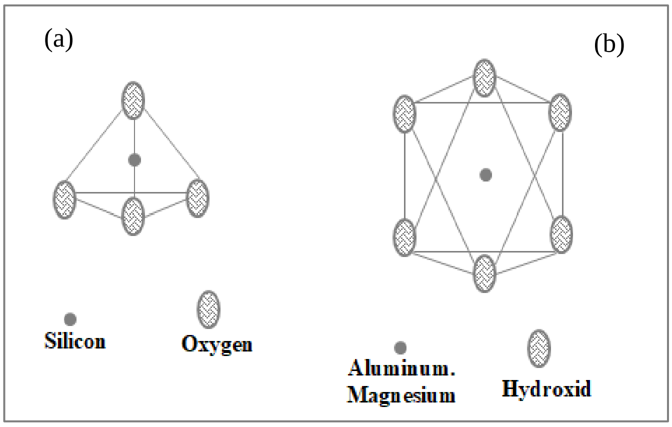

Fig. 1. Structural units that are forming clay minerals, (a) quadrilateral pyramid unit, (b) eight pyramid unit

The addition of lime affects the shear strength, compressibility, and the permeability of soft clay soil. These beneficial changes occur due to the diffusion of lime in addition to soil lime reactions (Cation exchange, Flocculation, Aggregation, and Pozzolanic reaction). Improvement of soft clay soil with lime depends on type of lime were quick or hydrated lime can be used. But using quick lime is preferable for making use of hydration process which results in chemical reaction between lime and clay minerals. This reaction is accompanied by a heat emission of about 300oc and as a result, water is absorbed from the soil reducing its water content and increasing its strength. Basma and Tuncer, (1991) [3] concluded that "quick lime shows more stabilizing effect than the other lime types". They also reported that quick lime is the best type of soil stabilizing agent than other types of lime products. The efficiency and effectiveness of quick lime is due to the fact that the quick lime produces higher curing temperature and hence absorbs more moisture than the hydrated lime, which makes the soil stronger and durable. Fig. 2 shows the conversion cycle of lime from one form to another.

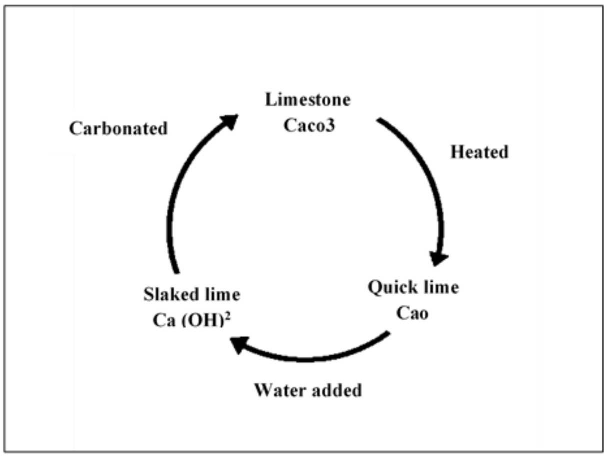

Fig. 2. Conversion cycle of lime from one form to another https://en.wikipedia.org/wiki/Lime (material)

III. CHEMISTRY OF LIME TREATMENT

A. *Drying*

If quick lime is used, it immediately hydrates and releases heat. Soils are dried, because water present in the soil participates in this reaction, and because the heat generated can evaporate additional moisture. The hydrated lime produced by these initial reactions will subsequently react with clay particles. These subsequent reactions will slowly produce additional drying because they reduce the soil's moisture holding capacity. If hydrated lime or hydrated lime slurry is used instead of quick lime, drying occurs only through the chemical changes in the soil that reduce its capacity to hold water and increase its stability.

B. *Modification*

After initial mixing, the calcium ions (Ca++) from hydrated lime migrate to the surface of the clay particles and displace water and other ions. The soil becomes friable and granular, making it easier to work and compact. At this stage, the Plasticity Index of the soil as shown in Fig. 3 decreases dramatically, as does it is tendency to swell and shrink. The process, which is called "flocculation and agglomeration," generally occurs in a matter of hours.

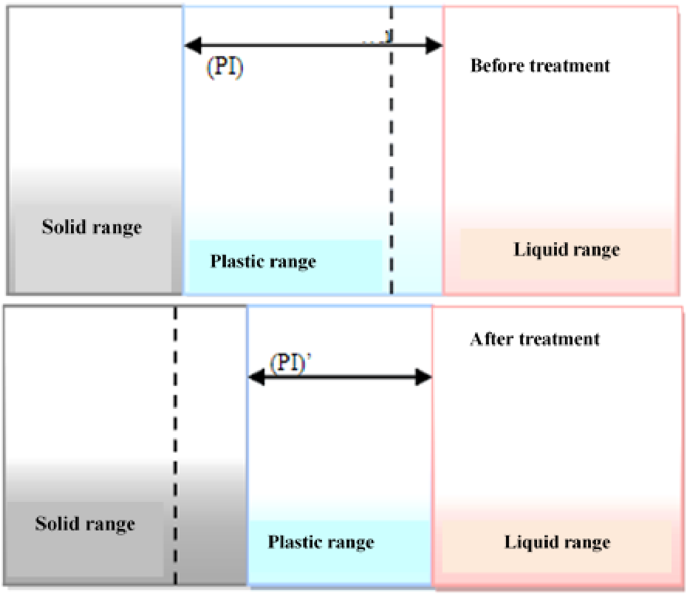

Fig. 3. Effect of lime treatment on the consistency of soil (Babu and Poulose, 2018)

C. *Stabilization*

When adequate quantities of lime and water are added, the pH of the soil quickly increases to above 10.5, which enables the clay particles to break down.

Silica and alumina are released and react with calcium from the lime to form calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH). CSA and CAH are cementations products similar to those formed in Portland cement. They form the matrix that contributes to the strength of lime stabilized soil layers. As this matrix forms, the soil is transformed from a sandy, granular material to a hard, relatively impermeable layer with significant load bearing capacity. The process begins within hours and can continue for years in a properly designed system. The matrix formed is permanent, durable, and significantly impermeable, producing a structural layer that is both strong and flexible.

IV. Use of lime as a deep soil stabilization agent (Lime Columns)

Lime column technique has been applied successfully in recent years to improve the physical and mechanical properties of the soils. Both the dry and wet lime mixing are carried out by injecting a preferable pressure into soil and form a lime-column in-situ. This technique increases soil bearing capacity and reduces soil settlement owing to improving of soil strength and stiffness. It was found that lime can diffuse into the surrounding soil and can stabilize a greater volume of soil. Effect of lime columns on the surrounding soil is represented in four main points. First, Consolidation / dewatering effect in which quick lime, CaO, absorbs water from the surrounding soil, causing the lime to swell and forms slaked lime (Ca(OH)2) as per the following chemical reaction (Jawad et al. 2014) [10]:

$$Cao + H2O \rightarrow Ca(oH)2 \ldots\ldots (1)$$

Second, Ion exchange effect, as the surface of fine particles of clay is negatively charged, the addition of lime to the soil produces (Ca+2) and (OH¯). In cation exchange, calcium ions (Ca+2) are replaced by cations. The Ca+2 ions link the negatively charged soil minerals together, as a result reducing the repulsion forces and the thickness of the diffused water layer. This layer encapsulates the soil particles, increasing the bond between the soil particles. The remaining anions (OH¯) in the solution are responsible for the increased alkalinity (George et al., 1992; Mallela et al., 2004; Geiman, 2005 and Jawad et al., 2014). After the reduction in water layer thickness, the soil particles closing to each other, causing the soil texture to change as shown in Fig. 4. This phenomenon is called flocculation (Jawad et al., 2014 [10] and Babu and Poulose, 2018 [2]).

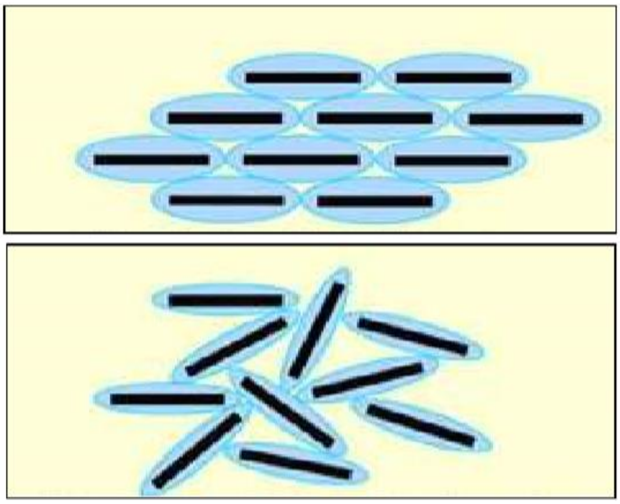

Fig. 4. Explanation of flocculation process (Babu and Poulose, 2018)

Finally, the Pozzolanic effect occurred because the silica and alumina that exist in the soil minerals become dissolvable and free from the soil when pH exceeds 12.4. The reaction between the released dissolvable silica and alumina and the calcium ions from lime hydration process resulted in cementitious materials such as Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A-H) (Eades and Grim, 1960; Eisazadeh et al., 2012 and Jawad et al., 2014). These Pozzolanic reactions can be clarified using the chemical equations illustrated below (Paresh and Sandip, 2012 [17] and Jawad et al., 2014 [10]):

$$Ca\ (OH)2\ +\ SiO2 \rightarrow CaO - SiO2 - H2O \ldots \quad (2)$$

$$Ca\ (OH)2 + Al2O3 \rightarrow CaO - Al2O3 - H2O \ldots (3)$$

Calcium ions continue to react with SiO2 and Al2O3 in the clay for a long-time forming compounds that cause the clay strength to be improved as can be seen in Fig. 5.

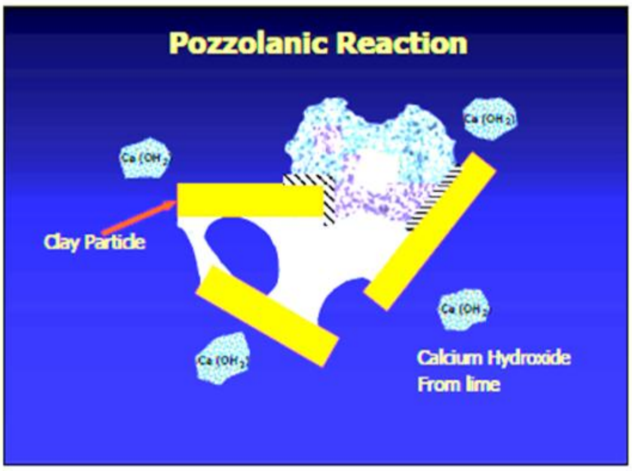

Fig. 5. Pozzolanic reaction process between lime and clay minerals (Babu and Poulose, 2018)

A. Installation methods of lime Columns in the field

Broms and Bomans (1975 [5] and 1979 [4]) showed a method of lime column construction in the field. In this method, powdered unslaked lime is mixed in-situ with soft clay or silt using an auger formed like a giant "egg beater", as illustrated in Fig. 6. The auger is screwed down into the soil to a depth that corresponds to the prescribed column length. Powdered unslaked lime is forced into the soil with compressed air through a hole located just below the horizontal blade of the auger, and the lime is mixed thoroughly with the soil. The withdrawal rate of the tool is about one-fifth of that when the auger was initially drilled down into the soil. The high mast of the drilling unit is mounted on a standard front wheel loader as shown in the same figure. Capacity of the machine is about 1 meter of lime column per minute or about five, 8m long columns per hour so that in an eight hour shift some 30-40 columns can be produced. The costs of lime columns installation are being affected by different factors as the accessibility of the site, the need for predrilling and the number of columns.

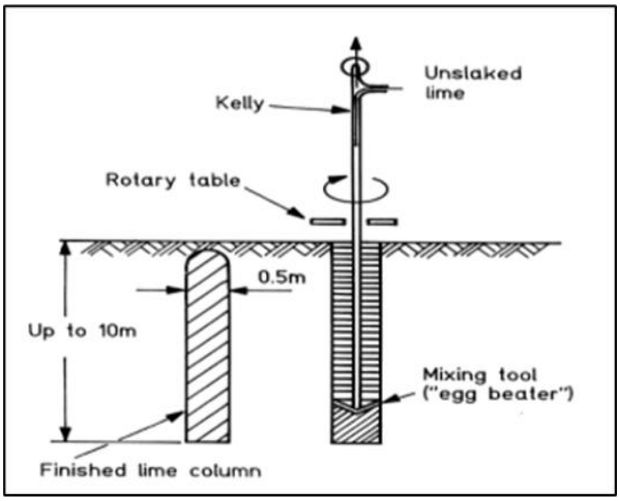

Fig. 6. Installation of lime column in clays (Broms and Boman, 1979)

Deep mixing soil equipment has also been developed in other countries of the world such as Trevimix method in Italy by (Paviani and Pagotto, 1991) and one almost same method in England by Harnan, (1993). Fig. 7 and 8 show such devices which have been used in Europe for installation of lime columns in the field. The Trevimix method was developed in Italy and has many similarities to the Japanese method of lime column installation (Fig. 7), while the Colmix method was developed by Bachy, (1999) which involves mixing the soil with water-based or dry binder by means of a helical tool (Fig. 8). The binder is injected as the tool penetrates the soil while mixing and compaction take place as the tool is withdrawn.

Fig. 7. Installation of lime column in the field using Trevimix method (Paviani and Pagotto, 1991)

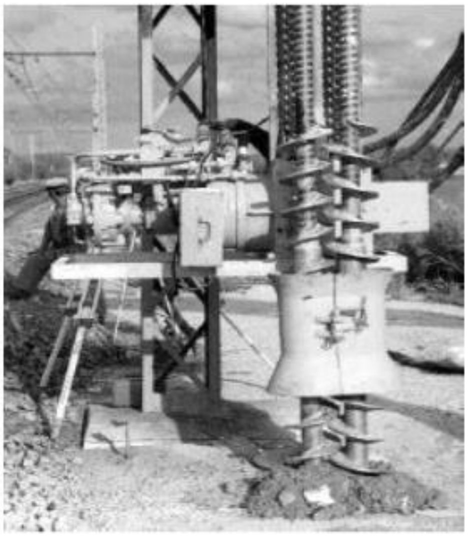

Fig. 8. Installation of lime column in the field using Colmix method (Larsson, 2002)

The soil strength increase near the column to a distance up to 2 to 3 times of the column diameter in radial direction (Ashok and Reddy, 2015 [1]). After lime column installed in soil mass, the lime or calcium ions migrate into soil surrounding the lime column. The soil properties around lime column will change due to consolidation, densification and hardening resulted by the chemical reaction between lime and soil. For an efficient stabilization, calcium and hydroxy ions should migrate through the clay because, hydroxy ions cause highly alkanic conditions give rise to the slow solution of aluminasilicates which are then precipitated as hydrated cementitious reaction products. These reaction products contribute to flocculation by bonding adjacent soil particles together and curing is allowed the clay soil to be strengthened. This mechanism will control the strength of the soil surrounding the lime column.

V. CONCLUSIONS

In this study, the effect of lime columns stabilization on the behavior of soft clay is presented. The previous studies confirmed that the use of lime columns is an effective ground improvement technique. Based on this study, it can be concluded that;

I. Lime columns were developed to improve the bearing capacity and reduce the settlement of soft clay. It is a good soil improvement technique that increases the soft soil bearing capacity and shear strength under lateral loading conditions.

II. This increase in the soil shear strength is due to the reactions between lime and clay minerals. The major short-term stabilization is resulted from a reduction in pore water pressure and dehydration of soft clay soil surrounding the lime column due to the hydration of the quick lime. Increasing the number of lime columns leads to more increase in the shear stress and more reduction in the shear strain of the stabilized soft clay soil.

III. The diffusion of lime into the surrounding clay suggests that the lime penetrates only to a small distance. Therefore, the beneficial effect of Pozzolanic reaction between lime and clay minerals will be restricted to a distance around the lime column ranges between 2D to 4D where D is the column diameter.

IV. Lime acts quickly and improves different properties of soil such as carrying capacity of soil, reduction in plasticity index, and settlement with the increase in curing time. The lime reaction with clay mineral is very quick and the improvement of soil starts within few hours.

V. In conclusion, lime column increased the shear resistance of soft clay soil. The increase of shear resistance was dependent on area ratio, curing duration and column strength. Lime column with higher area ratio and column strength produced higher increase in the shear resistance.

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