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Improvement of Soft Clay Soil with Different Techniques – State of the Art

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ABSTRACT

Soft clay soil layers are recent alluvial deposits presumably formed through the most recent 10,000 years described by their featureless and flat ground surface. Such clays identified by their low undrained shear strength and high compressibility. These soils are found at high natural moisture content. Soils with such characteristics create serious problems to geotechnical engineering associated with stability and settlements problems. A soft sub grade in construction of roadways is one of the most frequent problems for highway construction in many parts of the world. In addition, existence of soft clay soil which is unsuitable for supporting structures in construction sites, lack of space and economic motivation are considered important reasons for using soil improvement techniques rather than using deep foundation system. Many soil improvement techniques can be applied to increase its shear strength and decrease the consolidation settlement. This paper will shed light on several techniques that are used to improve the soft clay soil, idea about different techniques, how they are applied and work.

Keywords: Soft clay, Improvement, Different techniques.

INTRODUCTION

Soft clays belong to the well-known category of problematic soils. Low shear strength and consequently low bearing capacity, high water content, high compressibility and consolidation settlements are typical properties of soft clays. Several problems as related to soft clays exist from field investigation to their modeling behavior. Coring undisturbed samples in soft clays is a challenge because of disturbance during drilling. Such a task is sometimes unfeasible because of very weak consistency [3]. To minimize disturbance effect on soft clays properties, in-situ tests is a possible solution. As an example the field vane test is usually performed in upper soft clay layers (less than 10 m depth) to determine the profile of undrained cohesion. The recourse to correlation may be another way to estimate mechanical characteristics of soft clays from identification parameters, such as compression index from liquid limit [16]. However; the risk of overestimating or underestimating, the parameters is potential since a correlation is primarily valid for a given type of soil in a given location. Therefore, making recourse at correlations, if necessary, should be handled with care. It is then concluded, as it was pointed out for the field vane test, a methodology might be formulated to avoid overestimated soft clay characteristics [2]. This paper presents some of the current techniques which are used for improvement the soft clay soil. Soft clay soil improvement with sea shells is first addressed, and then improving with egg shells is considered. Reinforcement by columns is presented in detail with focus on soft clay improvement with lime columns and lime-cement columns and a comparison between them. Depending on the improvement techniques, adding to the incorporation of improving elements, Properties of soft clay soil can be greatly improved as a result of the primary consolidation which is resulted from the installation of reinforcing columns.

IMPROVEMENT OF SOFT CLAY SOIL WITH DIFFERENT TECHNIQUES

Improvement with lime columns and lime-cement columns

Deep stabilization techniques such as, lime columns, lime-cement columns and cement columns are widely applied in Sweden, Japan and United States to stabilize soft clay. This technique of soft clay stabilization reduces its settlement and increases its shear strength. Lime and lime-cement columns are frequently used in the construction of roads and railway embankments or lightweight structures on soft soil, especially in Scandinavia, Japan and the United States. Their main effects are to accelerate construction by eliminating the consolidation times, decrease settlements and improve embankment stability. It is often an economical solution compared with other soil improvements methods such as excavation and replacement and embankment piles. These columns are the most common ground improvement method used in Sweden where soft sediments are common.

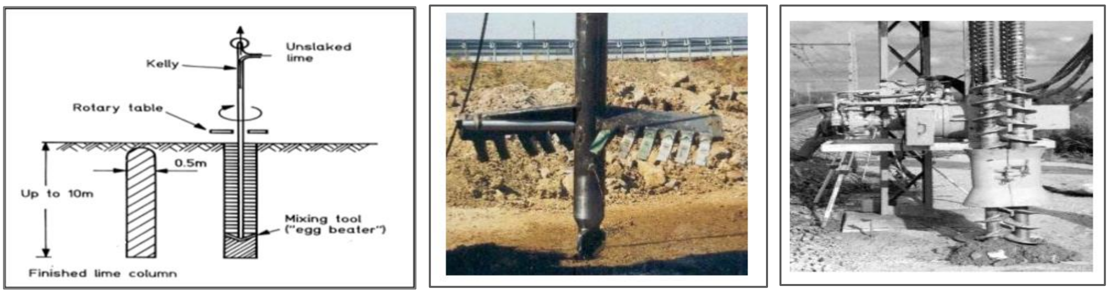
Currently these techniques find several applications as presented: Ground improvement; Improvement of slope stability (structures and embankments); Reduction of settlements (embankments and structures); Support of slopes and excavations; Improvement of bearing capacity; Reduction of vibrations and their effects on structures; Seismic and liquefaction mitigation; Construction of containment structures; Immobilization and/or confinement of waste deposits or polluted soils.

The existing code in Sweden is based on lime column properties, and on the assumption that the columns fully interact with the unstabilised soil between them, that is, the reinforced soil behaves as a composite material. Limit equilibrium slip circle analyses of slope stability are then performed using the composite strength of the improved ground. However, as discussed by [11], this method has shown practical limitations. One of the reasons is that the properties of lime columns are not identical to those of lime-cement columns. The shear strength and the modulus of elasticity are much higher and the failure strain is reduced when cement is added. Another reason is the assumption of full interaction between soil and columns, as pointed out by [11]. Based on Broms [4], it was suggested that a lime-cement column behaves more like a pile when laterally loaded.

Installation process of lime columns in the field

Broms and Bomans [6] show a method of lime column construction in the field. In this method, powdered unslaked lime is mixed insitu with soft clay or slit using an auger formed like a giant "egg beater", as illustrated in the Fig.1a. 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 shown in the same figure. This method produces both a consolidation and strength gain effect on the treated soil, without additional loading, via lateral expansion of the lime columns as they absorb water from the soft soil.

Deep mixing soil equipment has also been developed in other countries of the world such as Trevimix method in Italy [15]. Figure1b shows such devices which have been used 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 while the Colmix method Fig.1c was developed by Bachy [16]. It involves mixing the soil with water based or dry binder by means of a helical tool. The binder is injected as the tool penetrates the soil. Mixing and compaction take place as the tool is withdrawn.



(a) Broms and Bomans [6] (b) Trevimix method [15] (c) Colmix method [16]

Fig. 1: Different methods for installation process of lime columns in clays

Chemistry of lime columns treatment

The addition of lime affects the shear strength, compressibility, and the permeability of soft clays. These beneficial changes occur due to the diffusion of lime causing some chemical reactions with clay minerals which lead to a clear improvement in soft clay soil properties. These chemical reactions can be illustrated as follows:

- **<u>Cation exchange</u>**

Quick lime, CaO, absorbs water from the surrounding ground, causing the lime to swell and forms slaked lime (Ca (OH) ^{2}) as per the following chemical reaction.

$$CaO + H2O \rightarrow Ca\,(OH)2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

This cation exchange increases the electrolytic concentration and pH of the pore water and dissolves the silicates (SiO_2) and aluminates (Al_2O_3) from the clay particles. As can be seen in Fig. 2, Na^+ and other cations adsorbed to the clay mineral surfaces are exchanged with Ca^{++} ions. A cation is a positively charged molecule. Common soil cations include sodium (Na^+), potassium (K^+), magnesium (Mg^{2+})' and calcium (Ca^{2+}). Cations can make clay particles stick together (flocculate).

- **<u>Flocculation</u>**

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 covers the particles, increasing the bond between them. The remaining anions (OH^-) in the solution are responsible for the increased alkalinity. After the reduction in water layer thickness, the soil particles closing to each other, causing the soil texture to change as shown in Fig. 3, this phenomenon is called flocculation.

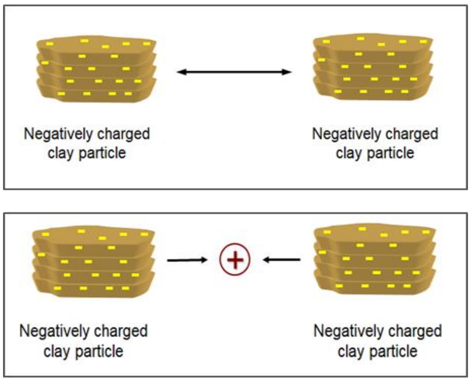


Fig. 2: Cation exchange through clay particles [1]

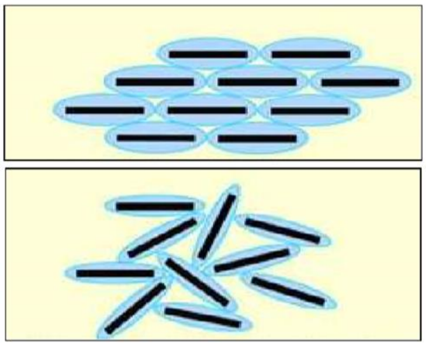


Fig. 3: Explanation of flocculation process [1]

- **<u>Pozzolanic reactions</u>**

The addition of lime to soil alters the properties of soil and this is mainly due to the formation of various compounds such as calcium silicates hydrate (CSH) and calcium aluminate hydrate (CAH) and consequently, micro fabric changes. Calcium ions continue to react with SiO_2 and Al_2O_3 in the clay for a long-time forming compounds that cause the clay strength to be improved as can be seen in Fig. 4. This reaction is termed a Pozzolanic reaction. The lime columns themselves have considerable strength and therefore act to reinforce the soil as well as alter its properties.

$$Ca2 + 2(OH -) + SiO2 \rightarrow CSH \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$Ca2 + 2(OH^{-}) + Al2O3 \rightarrow CAH \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Installation process of lime-cement columns in the field

The Lime-Cement columns method is one of the most used stabilization techniques in Sweden to stabilize the weak soils as soft clay, to avoid the settlements and to increase the stability. It is a dry mix method because no water is required to inject the binder into the soil. The main functionality of the method is to improve the geotechnical properties of the soil, due to the formation of stiff reinforcing columns which can act also as a drain and accelerate the consolidation process. Moreover, the load applied on the surface is carried partly by the columns and partly by the surrounding soil.

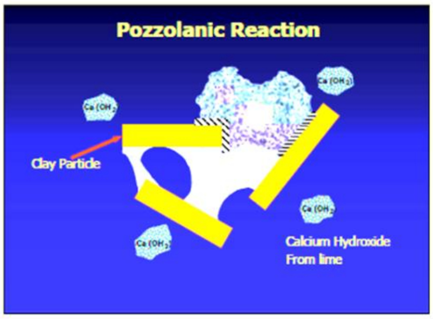


Fig. 4: Pozzolanic reaction process between lime and clay minerals [1]

Since the lime-cement columns method was born, it has been improved and new applications have been found. For example, the method used only lime as binder, then cement was add to accelerate the column formation and to achieve a considerably higher shear strength, and finally the cement has almost completely replaced the lime. The installation of the columns occurs with the instrument illustrated in Fig. 5 which presented the Swedish standard mixing tool specific for the Lime-Cement columns. The mixing tool rotates with a specific velocity, while compressed air is injected, and the binders are mixed with the soil. The mixing tool is progressively pulled upward while the column is forming and the binders are distributed so the chemical reactions can take place and produce uniform columns. The design of the mixing tool is that to distribute uniformly the binders both in the cross section and along the length of each column.

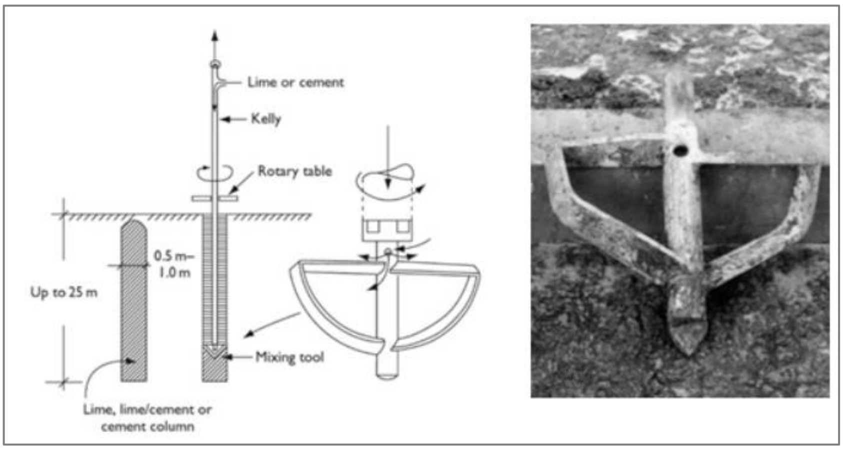


Fig. 5: Swedish standard mixing tool [5-13]

Major applications of lime-cement column

The main growing of the Lime-Cement columns method occurred after the construction of Kansai international airport in Japan, between 1989 and1994. This airport has been built on an artificial island constructed through the excavation of some of the mountains surrounding Osaka Bay, and has been stabilized with Lime-Cement columns because very big settlements (some meters) have occurred [9]. In Sweden one of the biggest and most important application of the lime-cement columns has been the stabilization of the road E4 at Ullanger, 500km north of Stockholm. The road was subjected to landslides, so reinforcement was necessary, and the method used was the Lime-Cement's one. The reason of the use of the lime-cement columns was the continuously working of these and the no needs of maintenance. Some soil samples were extracted from the soil and mixed in the laboratory with lime and cement, to test the new strength parameters. Then the columns were designed with a definite diameter, a specific ratio of lime-cement, a specific pattern and finally were installed to stabilize the soil. The design process procedure adopted in Ullanger continues to be the nowadays procedure in Sweden.

Improvement with seashells

The sea shell powder is the residue powder that is made by powdering of the naturally available hard sea shells which is the exoskeleton of Mollusks. Sea Shell Powder contains 90% of calcium (Ca) which is the major constituent of lime (CaO) that makes it a better and economic stabilizing admixture. Studies reveal that lime stabilization is one of the traditional and economic process and show a better improvement.

Shells are marine single-celled organisms (protozoa) and are like an amoeba in tiny multi-chambered shells. They have short lives, from a few weeks to a few months, and when they die, their shells accumulate on the sea floor and are carried by the Atlantic drift up to the shores as shown in Fig.6. The shells are of calcareous material, and then, not as hard as quartz grains. Their sharp edges act like tiny scalpels grind them down as they are transported and deposited. It makes that the particles in Dog's Bay sand (DBS) are easily crushed and grading need to be conducted with great care [7]. Carbonate sands were generated from shell, horny substance of mollusk and keratose of red algae by weathering process due to waves [10]. Kohirata [12] reported that Crushed shell is composed mainly of calcium carbonate, is covered by hard skin on the inside, and has a soft thin plate layer on the outside; it also has voids which serve as a habitat for sea organisms. It comes in various shapes and sizes ranging from 8 -14 cm in length, 4 - 7 cm in width, 2 - 4 cm in thickness. It has 2 pieces of shell. Right side shell is flat and heavier than the left side, while left shell is rising and lighter than the right. Crushed shell is rather thin, but well graded when crushed.

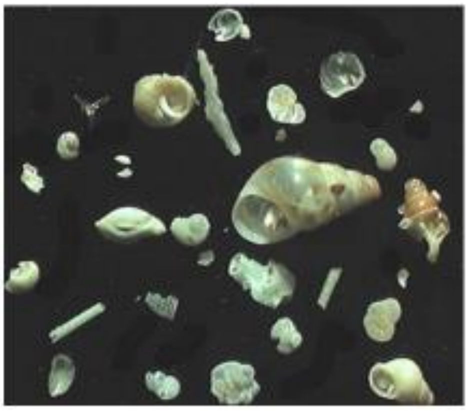


Fig. 6: Shell particles from a sample of DBS [7]

Chemical composition of seashells

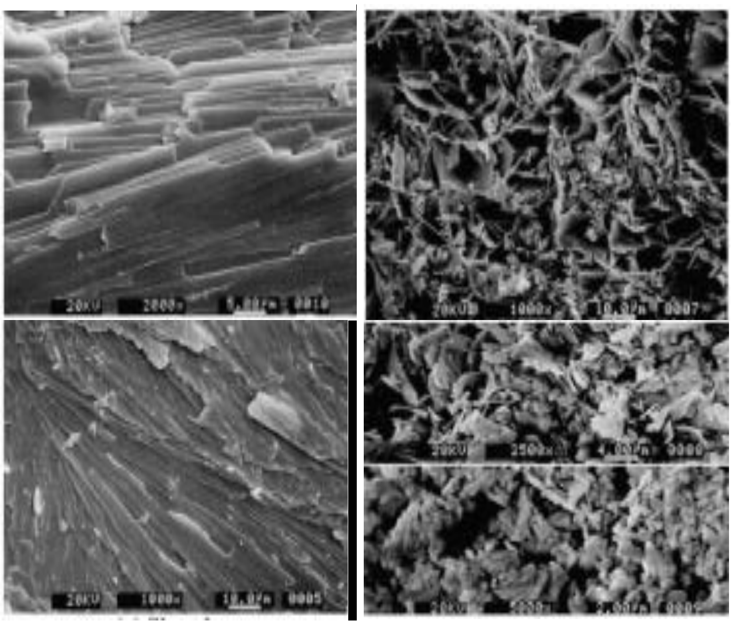
Shells are mixed during the process of marine deposition with different kinds of soils such siliceous sand, calcareous sand and clay. Chemical analysis, X-ray diffraction analysis (XRD), and microstructure analysis by electron microscope (SEM) were carried out to investigate the properties of crushed shell as raw materials [18]. Table (1) shows chemical composition of crushed shell. It is noted that crushed shell is entirely composed of CaCO3 (approximately 96%) and other minerals of trivial amount. Various crushed shells due to sources and individual characteristics are almost similar in the chemical composition. The mineral phase of calcium carbonate turns out to be calcite.

Table (1): Chemical composition of crushed seashell [18]

$CaCo_3$ (%)	SiO_2 (%)	MgO (%)	Al_2O_3 (%)	SrO (%)	P_2O_5 (%)	Na_2O (%)	So_3 (%)	Total (%)
95.994	0.696	0.649	0.419	0.33	0.402	0.984	0.724	100

$CaCo_3$: Calcium Carbonate; SiO_2: Silicon Dioxide; MgO: Magnesium Oxide; Al_2O_3: Aluminum Oxide; SrO: Strontium oxide; P_2O_5: Phosphorus pentoxide; Na_2O: Sodium Oxide; So_3: Sulfur Trioxide

Microstructure of crushed shell can be divided into two parts, sheet phase layer and porous bulky layer as shown in Fig.7.Sheet phase layer is oriented to the growth direction of shell and porous bulky layer is between sheet phase layers. Although two layers have the similar chemical composition (CaCO3), the microstructure of two layers is different The sheet layers are oriented to each sheet direction and the sheets of bulky layers wrap the 5–15 mm pores with non-orientation. Except these two layers, there are two small parts, the growth stem and the parasite. The growth stem is the starting point of crushed shell's growth and the parasite lives on the outside of crushed shell. The main compositions of two parts are calcite made of CaCO3. Therefore, it can be concluded that the crushed shell are composed of $CaCO_3$ [18]



(a) Sheet layer (b) Bulky layer

Fig. 7: SEM micrographs of surfaces and fractured surfaces of the different areas of an oyster shell [18]

Improvement with eggshells

Considering millions of tons of eggshell waste produced annually across the country, which not only poses the problem of disposal but also adds to environmental contamination and health risks, utilization of such refuse and industrial wastes and their subsidiary products as alternatives to construction materials may effectively contribute to environmental preservation and minimization of their adverse effects on the environment.

Eggshell powder (ESP) has not been being in use as a stabilizing material and it could be a good replacement for industrial lime, since its chemical composition is similar to that of lime. Hence it is proposed to utilize ESP for soil improvement which serves two purposes like waste utilization and also soil stabilization.

Eggshell Structure and Composition

An eggshell is the hard outer layer of a chicken egg and can be brown or white coloured. A chicken egg consists of 60% albumen (the liquid white colored substance), 30% yolk (the liquid yellow colored substance) and 10–11% shell (the solid eggshell and organic membrane). The total weight of an average egg was reported to be between 60.0–60.2 g, while the empty shell weight ranges between 6.6–7.3 g. The eggshell structure shown in Fig.8 is composed of three main layers; an outermost layer surrounding the eggshell called the cuticle, the layer beneath is referred to as the testa "the shell" and the innermost layer termed the mammillary layer

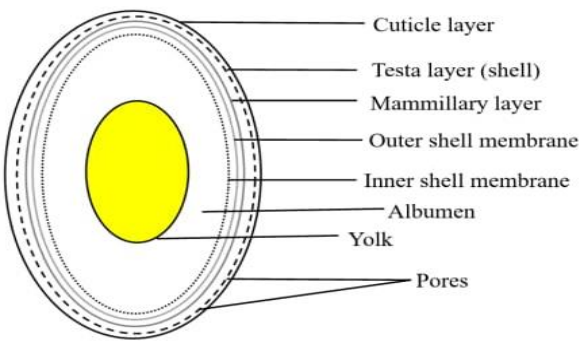


Table (2): Chemical composition of eggshells [14]

$CaCo_3$ (%)	Organic matter (%)	MgO (%)	So_3 (%)	P_2O_5 (%)	Al_2O_3 (%)	K_2o (%)	SiO_2 (%)	Cl_2O_3 (%)	SrO (%)
94-97	3-4.5	0.83	0.66	0.43	0.15	0.08	0.07	0.06	0.04

$CaCo_3$: Calcium Carbonate; MgO: Magnesium Oxide; So_3: Sulfur Trioxide; P_2O_5: Phosphorus pentoxide; Al_2O_3: Aluminum Oxide; K_2o: Potassium oxide; SiO_2: Silicon Dioxide; Cl_2O_3: Dichlorine Trioxide; SrO: Strontium oxide

Sources of Eggshell Waste

Sufficient quantities of waste eggshells would be required for industrializing a recovery process. Households and restaurants would not be a viable route to obtain waste eggshells; rather they would be obtained from egg processors 'breaker plants'. The first known egg breaker plant was invented in 1928 in the United States before World War II. In this process, the liquid egg is mechanically separated from the shells, which lead to eggshells being obtained in large quantities. For instance, a modern breaker plant can process 188,000 eggs per hour. Eggs are classified into sizes and standards where sub-standard eggs not suitable for the general market are sent to breaker plants while quality medium, large and extra-large eggs are sent to market. The top 10 egg-producing countries are presented in Fig.9 and Table 3. Roughly 30% of eggs are sent to breaker plants for processing into liquids. The amount of calcium carbonate (CaCO3) from eggshell waste that could be recuperated is outlined in Table 3.

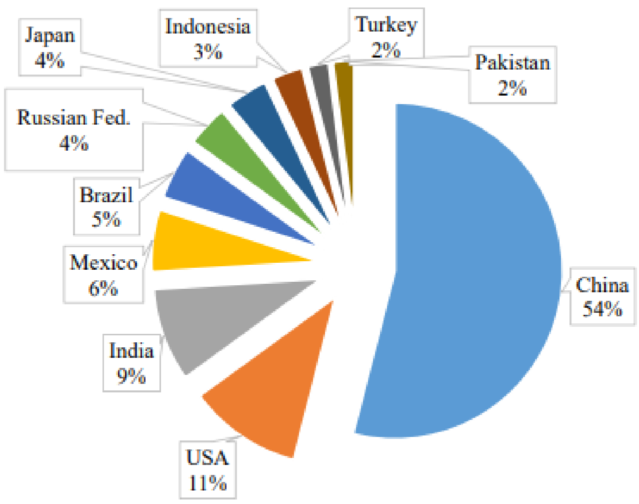


Fig. 9: Global pie chart of eggs produced annually in 2017 [14]

Table (3): Annual egg production by the top 10 countries in 2017 (values multiplied by 1000) [14]

Country	Number of eggs produced annually in (2017)	30% of eggs are sent to breaker plants (Quantity of egg)	Amount of CaCo3 recuperated (kg)
China	536,818,007	161,045,402	1,062,899,654
USA	106,688,700	32,006,610	211,243,626
India	88,137,000	26,441,100	174,511,260
Mexico	55,418,430	16,625,529	109,728,491
Brazil	43,352,883	15,283,022	100,867,918
Russian Fed.	44,351,037	13,305,311	87,815,053
Japan	43,352,883	13,005,865	85,838,708
Indonesia	33,940,000	10,182,000	67,201,200
Turkey	19,281,196	5,784,359	38,176,768
Pakistan	17,083,000	5,124,900	33,824,340

Chemical reaction between both of seashells and eggshells with soft clay soil

Both of seashells and eggshells have the same chemical composition. So, the chemistry of seashells and eggshells treatment is almost the same, where chemical reactions take place in two stages, as shown below in Fig. 10.

- **Calcination process**

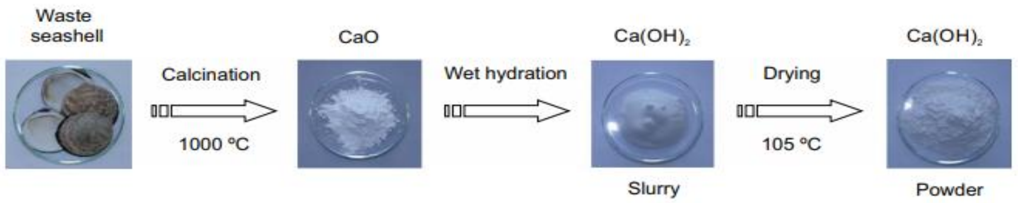


Fig. 10: Calcination process of waste seashell [8]

$$CaCo3(s) \rightarrow (heating) \ \rightarrow CaO(s) + CO2(g) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

- **Pozzolanic reactions**

After heating both of seashells and eggshells we obtain Cao (quicklime) as shown in equation (4). Consequently the Pozzolanic reactions take place in the same manner as explained before in lime column stabilization technique as illustrated in equations (2 and 3).
Finally stabilization of soft clay using seashells powder or eggshells is considered to be very effective as it possess the properties of lime and there are huge amounts of both of them which can be considered as a waste material.

CONCLUSIONS

There are many available treatment techniques that can be used for treatment of soft clay soil. This paper sheds the light on most of these techniques which are used to treat the soft clay soil regarding to increasing the strength and reducing the settlement. Few points can be concluded from this study:

- Soft clay is one of the problematic soils which need to be treated before getting started with constructing the foundations.
- Lime columns technique is one of the best techniques used to treat the soft clay soils, the treatment process mainly depending on the lime type and chemical reactions between lime and soil minerals.

- There is an essential need to study the soft clay soil treatment techniques that depends on chemical treatment in the form of chemical reactions between soil minerals and treatment materials such as lime, cement, seashells and eggshells.
- Seashell and Eggshell Powders contain 90% of calcium (Ca) which is the major constituent of lime (CaO) that makes it a better and economic stabilizing admixture.
- The stabilization of soft clay soil using seashell and eggshell powders mainly depends on two processes which are calcination and pozzolanic reaction.
- Stabilization of soft clay using seashell or eggshell powders is considered to be very effective as it possess the properties of lime and there are huge amounts of both of them which can be considered as a waste material.

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