LIME STABILIZATION TECHNIQUE FOR THE IMPROVEMENT OF MARINE CLAY

G. RAJASEKARANⁱ⁾ and S. NARASIMHA RAOⁱⁱ⁾

ABSTRACT

Marine clays are present in many parts of the world and these deposits are characterized by poor engineering properties such as low strength and high compressibility. These deposits are sensitive to changes in the stress system and the system chemistry of the pore fluid, and the use of a lime stabilization technique for such problematic clays is not new. In the present investigation an attempt was made to examine the diffusion of lime in the lime treated marine clay from the lime column or lime injection points and the changes which occurred in the engineering behavior of the soil system. The formation of new reaction products due to soil-lime reactions has resulted in particle growth of soil particles and the same has been confirmed using scanning electron microscopy. The test results indicated that the presence of excessive sodium ions in sea water do not retard the effective penetration of lime into the soil and that there is significant improvement in the engineering behavior of the soil system. The lime column and lime injection techniques can therefore be conveniently used to improve the behavior of soft marine clay deposits.

Key words: lime columns, lime diffusion, lime injection, pH, scanning electron microscopy (IGC: F2/K6)

INTRODUCTION

Weak clay deposits of low strength and high compressibility are encountered in coastal and offshore areas, and there are several foundation problems encountered in these soils. There is a need to improve the engineering behavior of the soft clays because of the necessity to design and construct engineered structures in these deposits. The success of the deep lime mixing method depends on the effective penetration of lime into the soil system, and it is necessary to establish a radial lime penetration zone before the application of this technique in the field (Somayazulu, 1987; Broms, 1987). The changes on the engineering behavior of the soil system attributed to the lime depends on the radial distance of lime migration into the soil systems with time. The movement of lime from the lime column or lime injection points to the soil system depends on the characteristics of the subsoil profile such as the natural moisture content, mineralogical content of soil, permeability, clay content and void ratio as reported by earlier investigators (Diamond et al., 1965; Thompson, 1966; Broms and Boman, 1975; Rajasekaran, 1994). Lime is diffused into the soil system due to the difference in lime concentration gradient between the lime column and soil system. Lime can segregate in the water and release Ca^{2+} cations. The diffu-

sion of Ca^{2+} ions through the soil media is due to the force of attraction caused by the negatively charged surface of the soil mass which results in a higher pH (Taylor, 1959). This results in the breakdown of clay minerals and release of silica and alumina, and may give rise to aggregation due to soil-lime reactions. The alteration of texture in the soil system allows the lime to diffuse effectively even to distant points and thereby increases the overall engineering behavior of the soil system.

Several researchers brought out the beneficial effects of lime stabilization on soil properties (Arizumi et al., 1962; Yanese, 1968; Terashi et al., 1977; Kitsugi and Azakami, 1982; Kado et al., 1987; Kamon and Bergado, 1991). A limited application of the lime stabilization technique in a modified form was attempted for stabilization of soft marine clays in a Japan harbor area (Okumura and Terashi, 1975; Kamon, 1992). In these early attempts, the penetration of lime from the columns into the surrounding soil and the induced beneficial effects on the formation of reaction products due to soil-lime reactions were not derived. Although the earlier investigators brought concluded that the lime contributed to beneficial changes which occurred in land based clays, only limited studies were carried out on the lime stabilization of marine clays (Jose et al., 1987). In addition, the microstructural changes which occurred in the soil system due to the effec-

ⁱ⁾ Professional Officer, Dept. of Civil Engineering, National University of Singapore, Singapore 119260. (Formerly, Research Scholar, Ocean Engg. Centre, Indian Institute of Technology, Madras 600036, India.)

ⁱⁱ⁾ Professor, Ocean Engg. Centre and Dept. of Civil Engg., Indian Institute of Technology, Madras 600036, India.
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tive penetration of lime from the lime columns/lime injection points in marine environment were not derived. There is a necessity therefore determine the effectiveness of the lime stabilization technique in a marine environment with excessive monovalent (sodium ions) present in the pore water of the soil system.

In this investigation a testing program was planned and carried out to establish both the penetration of lime into the surrounding soil (using pH measurements) and the microstructural changes which occurred in the soil system due to lime penetration. The associated changes occurred in the strength and compressibility behavior of the lime treated soil systems due to lime diffusion were confirmed.

EXPERIMENTAL INVESTIGATIONS

Soil and Chemicals Used

Marine clay samples were procured from the coast of Madras, India (Lat. 13.04°N and Long. 80.17°E) where soil samples were taken at depths of 1 to 2 m using an open trench excavation method. The physical-chemical properties of the untreated soil are given in Table 1. In the first series of tests, both quicklime and hydrated lime (in powdered form) were used as column filling materials. In a few test setups, lime with calcium sulphate, sodium sulphate and calcium chloride additives were used as a column filler material to bring out the utility aspect of lime along with compounds usually present in the marine environment. A lime slurry injection test was also carried out in a larger test tank and lime slurry was prepared using calcium hydroxide of 40% concentration in water (by weight). In order to establish the migration of lime from the lime columns/injection points into the surrounding soil, a number of samples were collected at different radial locations of the soil bed with time. The variations in

pH values with time for different lime treated soil systems were determined using the procedure suggested by Jackson (1958).

Test Programme

Basically there were two experimental setups used in this investigation. In the first setup, lime columns were installed in the clay bed formed in a test tank. The lime column work was carried out in a circular tank of diameter 600 mm and 550 height (Fig. 1). A homogeneous soil bed with 70% water content was prepared under soft to medium stiff consistency to the required thickness of

Fig. 1. Details of lime column experiment

Table 1. Untreated soil properties

S.No	Physical and chemical properties	Fresh water system	Sea water system
1.	Liquid limit (%)	88	85
2.	Plasticity index	55	53
3.	pH	7.06	7.3
4.	Organic content (%)	1.36	1.41
5.	Sulphates (%)	0.02	0.2
6.	Chlorides (%)	0.05	1.8
7.	Cation exchange capacity (m.eq/100 g of soil)	38	42
8.	Lime content (%)	0.19	0.21
9.	Particle size distribution (%) (0.425 mm-0.075 mm)	6	4
	(0.075 mm-0.002 mm)	39	44
	(<0.002 mm)	55	52
10.	Dry density (g/cm ³)	1.08	1.04

500 mm. A PVC pipe of 50 mm internal diameter was placed at the center of the tank and the lime powder was placed in layers and compacted lightly with a wooden tamper. Lime columns of 50 mm diameter and 500 mm height were thereby installed at the center of the soil bed using quicklime and calcium hydroxide as column filling materials. In the second setup tests were carried out in a tank of size, 1000 mm $\times$ 1000 mm $\times$ 750 mm filled with a soft marine clay (Fig. 2) and a homogeneous soil bed was prepared for a thickness of 700 mm. Lime injection was carried out in three stages. First a steel injection pipe with inner diameter 18 mm and of length 1250 mm was slowly pushed into the soil strata until it reached the bottom of the soil bed. The pipe had 40 perforations over a length of 300 to 400 mm in the bottom portion. Lime slurry with 40% concentration (by weight) was forced through the pipe into the soil bed and injection was effect-

Fig. 2. Details of lime injection test

ed by means of an air compressor under a pressure range of 0.2 to 0.3 N/mm². The pipe was then slowly withdrawn in stages and the slurry was injected into the middle and top layers of 200 mm height in two stages.

In most cases, free water of 50 mm was always maintained on top of the soil bed using sea water. Fresh water was used for mixing and curing the fresh water lime treated soil system. In order to avoid free swelling of the soil, a nominal surcharge pressure of 5 kN/m² was applied for all the test setups before the lime treatment was undertaken. The location of the samples are shown in Figs. 1 and 2 and the various test procedures adopted are discussed in the following sections of this paper. The samples were obtained at a radial distance of 200 mm (at a depth of 250 mm for lime column and 350 mm for lime injection work) after 45 days of treatment in order to study the changes attributed to the lime on the engineering behavior of the soil and microstructural changes which took place in the particle system. Considering all these factors, the test programme was planned and carried out and the details of the experimental setups used are presented in Table 2.

RESULTS AND DISCUSSIONS

Variation of pH

The samples were obtained at a radial distance of 50 mm, 75 mm, 100 mm, 150 mm, 200 mm and 250 mm away from the center of the lime column/injection points. The pH measurements of the samples was carried out according to the procedure suggested by Jackson (1958). A typical set of curves showing variation of pH along the radial distances for the middle layers of different lime treated soil systems are presented in Figs. 3(a) to 3(h) (middle layer, 0.2 to 0.6H; H=thickness of clay layer). Figure 3(a) shows the variation of pH for the top layer of the quicklime column treated soil system in the

Table 2. Details of experiments

S.No	Test programme		Water used for mixing and curing of soil	Test setup used	Total duration used (days)	Schedule of sampling (after treatment-days)
	Lime column work	Lime injection work				
	Column filler material used	Injection material used				
1.	Quicklime	—	Fresh water	Setup 1	45	2, 7, 15, 30 and 45
2.	Quicklime	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
3.	Hydrated lime	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
4.	Quicklime-sand	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
5.	Quicklime-calcium sulphate	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
6.	Quicklime-calcium chloride	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
7.	Quicklime-sodium chloride	—	Sea water	Setup 1	45	2, 7, 15, 30 and 45
8.	—	Hydrated lime slurry	Sea water	Setup 2	120	2, 7, 15, 30, 45, 60, 90 and 120

fresh water setup. The pH value of the soil varied from 7.6 to 8.9, whereas, for untreated soil the pH value was 7.3. It was observed that a significant increase in the pH of the soil system up to a time period of 15 days and later, took place but there was not much variation in pH with time.

The variation of pH in the quicklime column treated soil system for the sea water setup is shown in Fig. 3(b) and it can be seen that there is an increase in pH value from 7.3 to 8.25–9.0 for the middle layer after 45 days of treatment. There was not much variation in pH for both fresh water and sea water treated soil systems. As in the case of previous system, there is a significant increase in pH up to 15 days and after that the variation with time

was not significant. These test results indicate that the presence of sea water was not affecting the migration of lime from the column.

Figure 3(c) indicates the variation in pH for the hydrated lime column treated soil system, and there is an increase in the pH of the soil system which varies from 8.1 to 8.6. The pH changes which occurred in both hydrated and quicklime column systems are similar, and thereby indicates a uniform seepage of lime into the soil. The variations which occurred in the quicklime-sand column indicated an increase in pH of the soil from 7.3 to 8.6–8.8 (Fig. 3(d)). The test results indicate that a quicklime-sand mixture caused similar changes as that of other lime treated systems.

Fig. 3(a). Variation in pH with radial distance and time in quicklime column treated soil system in fresh water

Fig. 3(c). Variation in pH with radial distance and time in hydrated lime column treated soil system in sea water

Fig. 3(b). Variation in pH with radial distance and time in quicklime column treated soil system in sea water

Fig. 3(d). Variation in pH with radial distance and time in quicklime-sand column treated soil system in sea water

The addition of calcium sulphate with lime as column filling material increases the pH of the soil system from 7.3 to 8.7–9.25, and the presence of sulphate in the form of gypsum does not affect the lime diffusion (Fig. 3(e)). In the quicklime-calcium chloride column treated soil system, there is an increase in the pH of soil system from 7.3 to 9.3 (Fig. 3(f)). These test results indicate that the addition of calcium sulphate and calcium chloride supplied excess Ca^{2+} ions and thereby increased the pH of the soil system significantly. Figure 3(g) show the variation of pH in the quicklime-sodium sulphate column treated soil system and the pH values are fluctuating with time. The pH of the treated soil system varies from 8.1 to 8.5 after 45 days treatment and this tendency may be due to the

dominance of sodium (Na^+) cations in the soil system which retards the diffusion of Ca^{2+} ions.

Figure 3(h) indicate the variation of pH for the lime injected soil system (lime slurry injected at a radial distance of 400 mm from the central injection point) and the pH value varies from 8.6 to 9.2. There is an uniform increase in pH of the soil for the initial time period (15 to 30 days of treatment) and later, the changes are not significant. After 120 days treatment, the closest point achieved a pH of 9.4 (up to a diameter of the column), whereas, at the most distant point a pH of 8.5 was achieved (at a radial distance of 5 times the diameter of the column). It was observed that there was not much change in pH for both lime injection and lime column treated soil systems with

Fig. 3(e). Variation in pH with radial distance and time in quicklime-calcium sulphate column treated soil system in sea water

Fig. 3(g). Variation in pH with radial distance and time in quicklime-sodium sulphate column treated soil system in sea water

Fig. 3(f). Variation in pH with radial distance and time in quicklime-calcium chloride column treated soil system in sea water

Fig. 3(h). Variation in pH with radial distance and time in lime injection treated soil system in sea water

respect to time.

From the pH measurements for all setups, it is clear that adequate quantities of lime had seeped into the surrounding soil and this was indicated by the improved values of pH with time. At the face of the column the measured pH values was higher and the pH values varied from 8.3 to 8.95 for both fresh water and sea water treated soil systems. The test results, indicate that there is an effective diffusion of lime up to a radial distance of 4 to 6 times the diameter of the columns and 8 to 10 times that of the diameter of the lime injection pipe. Overall, this improved the alkalinity of the soil system which resulted in several beneficial changes in the soil system including the reduction in water content of the treated soil systems with time. It was observed that after 45 days treatment water content of treated soil system varied from 42 to 48% near the lime column and 46 to 51% at a radial distance of 4 times the diameter of lime column, but in the lime-sodium sulphate column treated soil system the water content varied from 65 to 71%.

Strength and Compressibility Behavior of Soils

The lime attributed changes on the strength behavior of the soils was studied using a laboratory vane shear apparatus according to the procedure given in ASTM D 4648-87 (1989). Several undisturbed samples were also collected after 45 days of treatment to conduct standard consolidation tests using Oedometer as per the procedure suggested in ASTM D 2435-80 (1989). There was a significant reduction in the compression index (Cc) values from 0.85 to 0.36 (Table 3).

It was also observed that there was an improvement in the strength and compressibility values of about 6 to 8 times that of the untreated soil near the lime column at a radial distance of 80 mm (1.5 times the diameter of the column) and 4 to 6 times that of the untreated soil at a radial distance of 200 mm (4 times the diameter of the column). These improvements can be due to the effective penetration of the lime and the formation of new cementation products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) which bind the soil particles together, and improve the engineering behavior of the soil. The results observed in the lime-sodium sulphate treated soil system, however are not encouraging and this may be due to the formation of ettringite which cause, swelling with time as reported in lime treated land clays enriched with sodium sulphate (Rajasekaran, 1994).

Scanning Electron Microscopic Studies

It is known that the arrangement of soil particles influences the engineering behavior of a soil mass (Tchalenko, 1968; Keller, 1985). Qualitative visualization of the reaction products formed in different lime treated systems can be studied using a scanning electron microscopy (SEM). In the present investigation, samples were prepared using Polyethylene glycol 6000 as a resinous compound to replace the pore water and a standard gold coating was given on the vertical plane fractured surface of the samples as per the procedure given by Wilson (1987).

The micrograph of the untreated soil in the sea water

Table 3. Strength and compressibility behavior of lime treated soil systems

Type of lime treatment	Shear strength values (kN/m ²)		Compression index (Cc) values	
	Radial distance of the samples = 80 mm	Radial distance of the samples = 200 mm	Radial distance of the samples = 80 mm	Radial distance of the samples = 200 mm
Quicklime column treated soil system in fresh water setup	135	124	0.51	0.62
Quicklime column treated soil system in sea water setup	120	104	0.58	0.63
Hydrated lime column treated soil system in sea water setup	106	81	0.63	0.65
Quicklime-sand column treated soil system in sea water setup	135	98	0.57	0.68
Quicklime column-calcium sulphate treated soil system in sea water setup	142	121	0.44	0.54
Quicklime-calcium chloride column treated soil system in sea water setup	163	162	0.42	0.53
Quicklime-sodium sulphate column treated soil system in sea water setup	86	57	0.84	0.83
Hydrated lime injection treated soil system in sea water setup	86	81	0.63	0.72

setup shows fairly open fabric elements (Fig. 4(a)). The clay particles are assembled in a flocculated arrangement and this type of open fabric arrangement can be expected

Fig. 4(a). Scanning electron micrograph of untreated soil sample in sea water

Fig. 4(b). Scanning electron micrograph of lime column treated soil sample in sea water

Fig. 4(c). Scanning electron micrograph of lime injection treated soil sample in sea water

in sea water sedimented samples. Most of the clay particles are of montmorillonite and kaolinitic origin as confirmed by the X-ray diffraction (XRD) studies (Rajasekaran, 1994; Narasimha Rao and Rajasekaran, 1994). The micrographs obtained for lime column and injection treated systems in sea water setup after 45 days of treatment are shown in Figs. 4(b) and 4(c) respectively. The diffusion of lime has consolidated the soil particles to form floccules of various sizes and similar observations were reported in land based lime treated clays by the earlier investigators (Diamond et al., 1965; Gillot, 1968; Kawamura and Diamond, 1975). The various cementation compounds formed were identified using X-Ray Diffraction (XRD) to be CSH and CAH and this resulted in the aggregation of particles and increased the particle size (Rajasekaran, 1994; Narasimha Rao and Rajasekaran, 1994). In order to verify this, the procedure given in ASTM D 422-63 (1989) was used for the grain size distribution analysis of soils and the test results indicate that significant changes occurred in the particle size distribution curves of lime injection treated soil system as shown in Fig. 5. There was an increase in the silt and fine sand contents from 52% and 4% (untreated soil system) to 92% and 8% (treated system) respectively with a corresponding decrease in clay content to 0%. The test results indicate that the clay fraction slowly converted to silt/fine sand fractions due to the effect of lime induced aggregation, and the addition of lime did not retard the formation of reaction products in the marine environment.

CONCLUSIONS

Lime has effectively penetrated into soil through lime columns and lime injection points, which was confirmed by an increase in the pH values and these values varies from 8.3% to 8.9%. Most of these changes have taken place in a period of about 15 to 30 days. The tendency of lime penetration noted in both fresh and sea water systems are quite similar. The use of calcium chloride with quicklime is very effective in diffusing the lime into the surrounding soil, and best results are obtained in the engineering behavior of the soil. In the case of the setup with quicklime and sodium sulphate as column filler material, however, there was not much improvement in the strength and deformation behavior of the soils. The results of this investigation have established that the presence of excessive sodium ions in sea water do not retard the effective penetration of lime into the soil. There is an improvement in the size of the particles with time due to the formation of various cementation products, and the same has been confirmed with Scanning Electron Microscope (SEM). Both the lime column and lime injection techniques can therefore be conveniently used to improve the behavior of soft marine clay deposits.

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Fig. 5. Grain size distribution of lime injection treated soil samples in sea water

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