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ARTICLE TITLE:

Experimental study of clay soil stabilization with lime and sea water for road subgrade use. After 1080 days of curing period.

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Abstract

Extensive areas around the world are covered by clay soils of high swelling potential. These clays are now well known as active clays due to their behavior with volume changes according to their moisture content. In arid and seem-arid regions such as Greece or other Mediterranean countries, the clay material exists in an unsaturated condition due to deep water table. With seasonal climatic changes, the clay tends to change moisture content. The purpose of this laboratory investigation firstly was to examine the engineering properties. For this, grain size analyses, Atterberg limits, x-ray analyses, , shrinkage limits tests, swell pressure in the oedometer, cation exchange capacity and pH in disturbed soil samples have been investigated. Also, an attempt has made to stabilize and increase strength of an active clay soil with different percentage of lime and long curing period of time, in order to use the clay mixture with lime for subbase construction for roads, railway embankments, air-port running- ways. The results were very promising.

Keywords: swelling clay, lime, stabilization.

1. Engineering properties of soil samples

The clay soil samples come from the area of Thebes, between km 70+000 and km 91+000 of the Athens-Lamia National Road. This area was chosen firstly because it was within a reasonable distance and secondly because previous laboratory research (Christodoulias and Gassios 1987) had established the following regarding the physical and mechanical properties of the soils in the area: Liquidity limit 38-85%, plasticity limit 15-26%, plasticity index 18-62%, colloid content 6-70%, fine grains (< 2 μm) 20-74%. In general, the soil is classified by AUSCS as CL and CH. Also, linear shrinkage ranges from 10.7 to 23.0%, shrinkage limit from 13.4 to 10%, and free swelling from 55 to 105%. The maximum dry density according to Proctor ranges from 14.5 KN/M³ to 17.3 KN/M³, the C.B.R. from 4.4% to 15%, for compaction at 95% of the M.E.P. according to modified Proctor.

Table 1. Engineering Properties of initial soil from Thevas Area.

Engineering Test		PERCENTAGE
Liquid Limit	(LL, %)	38 - 85
Plastic limit	(PL, %)	15 - 26
Plasticity Index	(PI, %)	18 - 62
Colloids (<0.002)	%	20 - 74
Κατάταξη κατά AUSCS	-	CL - CH
Linear Shrinkage	%	10,7 - 23.0
Shrinkage Limit	%	13,4 - 10.0
Specific Gravity	kN/m³	26,5 - 27.0
Carbon Organics	%	0,80 - 1,05
Free Swell	%	55 - 105
Dry Density	kN/m³	14,5 - 17,3
C.B.R.	%	4,4 - 15.0
Swelling Pressure	kPa	50 - 600
Swelling Percent	%	1,2 - 13.1

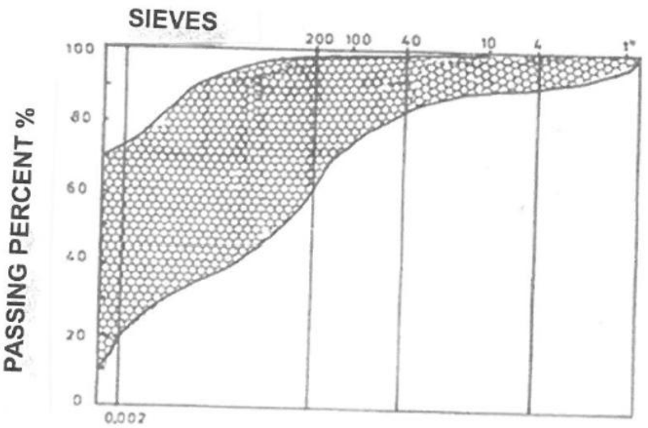

Figure 1. Envelope of sieve analysis for 30 tested soil samples

The soil swelling tendency, as calculated on undisturbed samples in the consolidation apparatus, ranges from 50 KPa to 600 KPa, while the swelling percentage of the same samples ranges from 1.2% to 13.1%. Finally, with the help of X-rays, it was determined that the soil of the samples from the wider area contained the clay minerals illite, montmorillonite, and ferrous allusite in percentages of 20%, 25%, and 10%, respectively.

Within the framework of this thesis, representative soil samples were collected from various points in the Thiva area, between KP 70+000 and KP 91+000 of the Athens-Lamia National Road. - Lamia National Road, were collected, mixed and formed a mixture with a total weight of 200 kg, in which the particle size distribution, Atterberg limits, linear shrinkage, shrinkage limit, specific weight, organic content, dry density according to Proctor, and C.B.R. were determined (Table .2).

Three remolded cylindrical specimens measuring 50 x 100 mm were also prepared from this soil mixture, in which the unconfined compressive strength of the natural soil was measured and their average value was determined to be 70 KPa. These specimens were prepared in the same metal mold used for the other specimens with hydrated lime. To calculate the weight of each specimen, the maximum density and optimum moisture content were taken into account, which were calculated in the laboratory using the Proctor device (Figure .3).

2. Experimental Procedure

It consists of three stages:

- preparation,
- maintenance,
- breaking of the specimens.

Table 2. Engineering Properties for Tested Soil Samples.

Engineering Test		PERCENTAGE
Liquid Limit	(LL, %)	51
Plastic limit	(PL, %)	33
Plasticity Index	(PI, %)	18
Colloids (<0.002)	%	74
Κατάταξη κατά AUSCS	-	CH
Linear Shrinkage	%	16.0
Shrinkage Limit	%	11.0
Specific Gravity	kN/m³	26,7
Carbon Organics	%	0,80
Free Swell	%	105
Dry Density	kN/m³	15,1
C.B.R.	%	5,1
Compressive Strength	kPa	70,0

During the experimental procedure, three types of samples were prepared.

- The first with hydrated lime and distilled water, in order to achieve optimal moisture content.
- The second with hydrated lime and a solution of 1% NaCl in distilled water.
- The third series with hydrated lime and seawater (3.4% NaCl) to also achieve optimum moisture content.

These samples were prepared in three series with hydrated lime percentages of 3%, 5%, and 7%. The hydrated lime was obtained from the company Krinos and is pure calcium hydroxide. It should be noted that three specimens were prepared from each type of mixture, so that the strength value for each mixture was the average strength value of the three specimens. A total of 162 specimens were prepared, i.e., 54 specimens for each percentage series.

Table 3. Chemical analysis of lime. (after KYKNOS.S.A.)

LIME TYPE	**HIGH CALCIUM**
Constituent	Percent %
Silicon dioxide SiO_2	0,3
Iron oxide Fe_2O_3	0,0
Aluminium oxide Al_2O_3	0,2
Calcium oxide CaO	72,4
Magnesium oxide MgO	1,2
Total sulfur S	0,3
Sulfur trioxide SO_3	0,6
Carbon dioxide CO_2	0,5
Water at 120C	1,0
Total combined water	24,2%
Insoluble mater	0,4%
Loss on ignition	24,8%

3. Test preparation and laboratory equipment

- Metal mold specially constructed at KEDE and divided for compressing test specimens in soil stabilization experiments (Photo 11.1)
- Mold specifications
- Length 17.7 cm
- Useful length 10.0 cm
- Wall thickness 0.6 cm
- Inner diameter 5.1 cm
- Outer diameter 6.3 cm
- Hydraulic pressure device with controlled load application speed.
- Extractor for removing the test piece from the die with the aid of a hydraulic jack.
- Precision scale accurate to 0.001 grams and capable of weighing up to 3 kg.
- Mixing tools such as a mixing bowl, trowel, ladle, spatula, scoop, and spray bottle.
- 500 ml volumetric tube

Photo 1. Iron mold for preparing test specimens

Photograph 1. Split divided mould for soil-lime sample preparation + compression

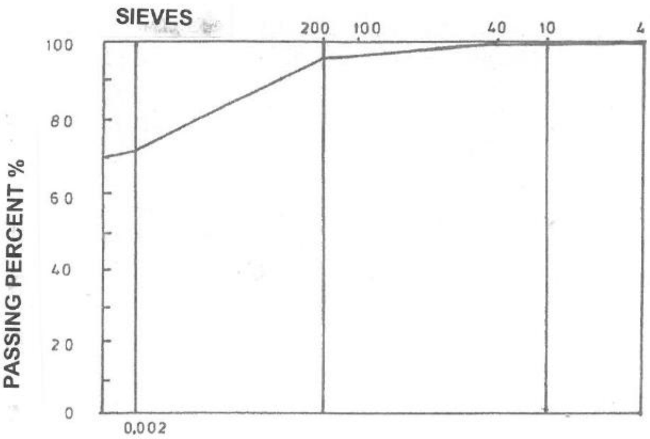

Figure 2. Particle size distribution curve for soil mixtures.

4. Determination of Apparent Specific Gravity (ASG)

In order to determine the apparent wet weight of the mixtures, so that the weight of the mixture required to be compacted in the mold and prepare each test specimen could be calculated, the maximum laboratory density of the mixtures according to Proctor had to be determined beforehand.

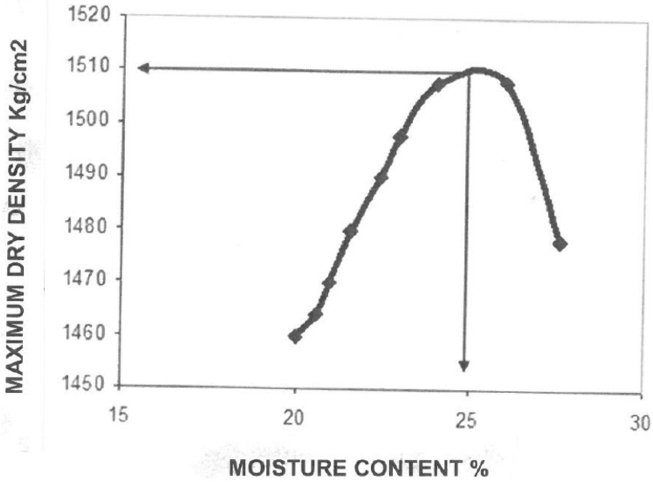

Figure 3. Maximum Laboratory density of soil mixture for samples.

For this purpose, a Proctor test was initially performed on the soil material. This was followed by three more Proctor tests on soil mixtures with hydrated lime:

- oil and 3% hydrated lime
- oil and 5% hydrated lime
- oil and 7% hydrated lime

The curves of dry density and optimum moisture content separately for each mixture are shown in Figure .4.

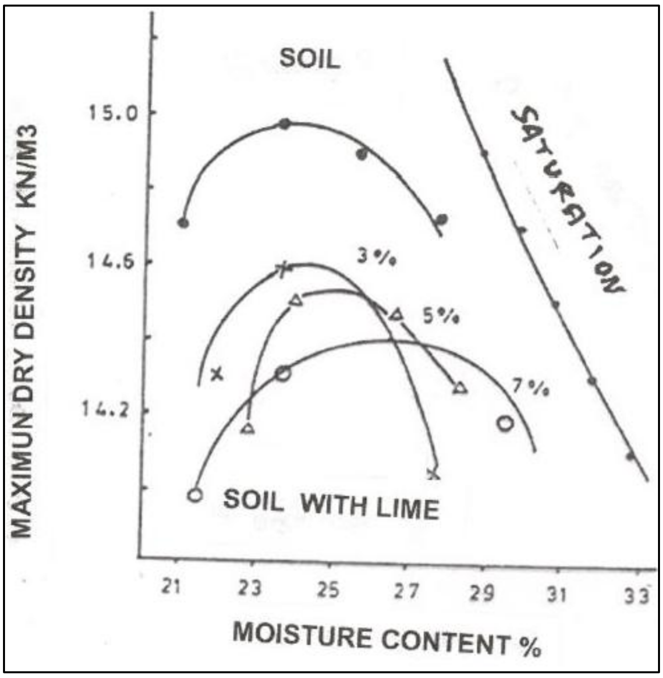

Figure 4. Optimum Laboratory density for soil-lime mixtures.

5. Method of work

To prepare each series of mixtures, the predetermined quantities of soil sample (passed through a U.S. No. 4 sieve) and the corresponding percentage of hydrated lime were mixed. Then, to achieve the optimum moisture content, distilled water was added for the first type of test, distilled water and 1% NaCl for the second type of test, and seawater (3.4% NaCl) for the third type of test. After thoroughly mixing the mixtures, without allowing time for maturation, the mold is filled with the exact predetermined weight of mixture, which is calculated from the volume formula of the mold:

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$$V = \frac{\Pi d2}{4} H$$

It is placed in the pressure device and loaded statically at a low speed in accordance with BS 1924/1975, No. 10, for 60 seconds with a load of 2 tons to form a cylindrical specimen measuring 50 x 100 mm. It is then removed from the mould using an extractor and weighed.

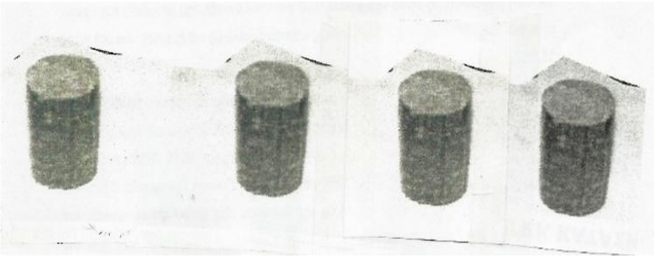


Figure 5. Soil-lime samples after static compression in a mould.

6. Test specimen maintenance

Immediately after compaction, each test specimen was placed in a polyethylene bag which was sealed with adhesive tape to prevent moisture fluctuations. The characteristic percentage of hydrated lime, NaCl, date of manufacture, and breakage were noted on the packaging of each specimen.

For preservation, they were placed in a concrete specimen preservation chamber at a constant temperature of 21 + 2°C and relative humidity of 95%. During the experimental procedure, three series of specimens (162 specimens, i.e., 54 specimens for each stabilizer series) were prepared and stored before breaking for 7, 28, 90, 360, 720, and 1080 days.

7. Breaking of specimens

After the necessary maintenance period for each series of specimens had elapsed, the breaking procedure was followed. Each specimen to be broken was weighed without its polyethylene bag to confirm that there was no significant change in moisture content.

Each specimen was then placed in the breaking device and loaded until breaking, while simultaneously recording the ring reading. The breaking of the specimen took approximately ten seconds.

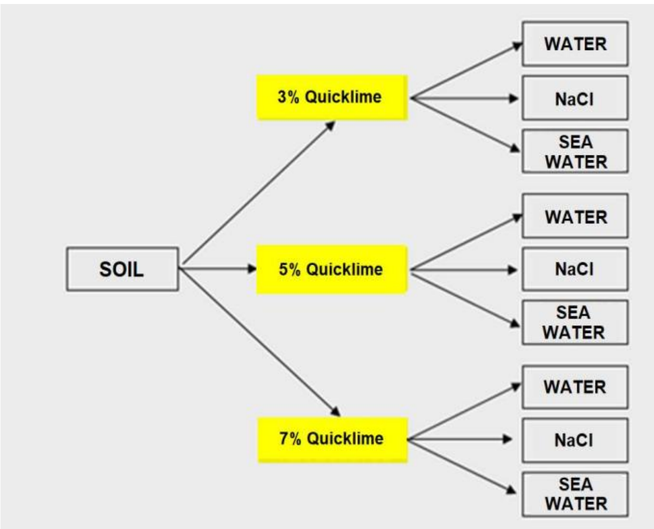


Figure 6. Layout of soil + lime percent mixtures.

8. Compressive strength of specimens and commentary on results

To determine the compressive strength, three groups of specimens were prepared, with lime content of 3%, 5%, and 7% by weight of the natural soil. In order to achieve optimum humidity, the following were used separately for each test group:

- Distilled water
- Water with 1% NaCl
- Seawater (with 3.4% NaCl).

The specimens were condensed statically, in accordance with BS 1924/1975, No. 10, and formed into cylinders measuring 50 x 100 mm.

The samples of each group were broken on predetermined dates and the strength of the mixtures was determined. The final strength of each test represents the average strength of three soil sample tests.

To determine the compressive strength, three groups of specimens were prepared, with lime content of 3%, 5%, and 7% by weight of the natural soil.

Figures 7, 8, and 9 graphically present the average compressive strength values of all tests. Each point corresponds to the average strength of three specimens and is displayed in groups according to the stabilizer, i.e., specimens with:

- Soil and 3%, 5%, 7% hydrated lime and distilled water (Figure 7)
- Soil and 3%, 5%, 7% hydrated lime and 1% NaCl (Figure 8).
- Soil and 3%, 5%, 7% hydrated lime and seawater (Figure 9).

Comparing these diagrams (Figure 7 to Figure 8), we observe that the strength curves develop harmoniously in relation to the curing time and that this increase is proportional to the percentages of hydrated lime and salt. We also observe that:

- The group of tests with hydrated lime and plain water increases the strength of the soil from 70 Kpa (initial value) to 1450 Kpa (final value), (Figure 7), i.e., they showed a 20-fold increase in strength after three years of maintenance.
- The group of tests with hydrated lime and 1% NaCl outperformed the previous group and increased the strength of the soil from 70 Kpa
- (initial value) to 2400 Kpa (final value), (Figure 8). This value is 35 times greater than the initial strength of the soil after three years of maintenance.
- The group of specimens with hydrated lime and seawater (3.4% NaCl) exceeds the strength of the two previous groups of specimens and increases the strength of the soil from 70 Kpa (initial value) to 3200 Kpa (final value), (Figure 9), i.e., we have a 45-fold increase in strength after three years of maintenance.

It appears that the increased percentage of hydrated lime and the increased percentage of salt (3.4% NaCl) contained in seawater played a decisive role in increasing strength, as initially expected based on the literature data (Marks and Hallibuston, 1972, Christodoulis and Giannaros, 1992).

Furthermore, the diagrams in Figures 7, 8, and 9 show the following:

In the first group of tests with 3%, 5%, and 7% hydrated lime and distilled water (Figure7):

- In the samples with 3% hydrated lime and after 28 days of maintenance, the strength curve showed a stable trend and did not increase further even though the samples were maintained for 1080 days.
- In samples with 5% hydrated lime and after 90 days of maintenance, the strength curve showed a downward trend, which, however, in samples maintained for 720 days, returned to a normal upward trend. It appears that the presence of hydrated lime bound the available water so that calcium ions could replace sodium or potassium ions and the flocculation of clay molecules could begin, which leads to an increase in soil strength.
- In samples with 7% hydrated lime and after 720 days of maintenance, the strength curve showed a stagnation or even a decline, which is probably due to a lack of water, as the samples were sealed.

In the second group of tests with 3%, 5%, 7% hydrated lime and 1% NaCl (Figure 8)

- The strength of the specimens with 3% hydrated lime and 1% NaCl shows an upward trend proportional to the small percentage of hydrated lime it contains.
- The strength of the specimens with 5% hydrated lime and 1% NaCl shows an upward trend up to 360 days and then remains stable.
- The strength of the specimens with 7% hydrated lime and 1% NaCl shows an upward trend up to 360 days and then a downward trend, which was not restored as expected and affected the final result. It appears that the simultaneous demand for water from the salt prevented the hydrated lime from reacting and forming the necessary carbonate salts, which, due to their hardening, increase the strength of the soil.

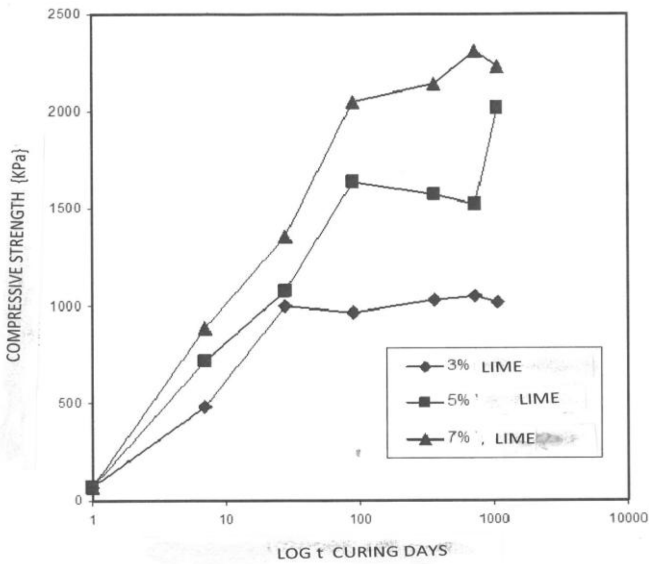


Figure 7. Unconfined compressive strength of soil + lime 3%, 5%, 7% mixtures, and tested after 7, 28, 360, 720, 1080 days curing.

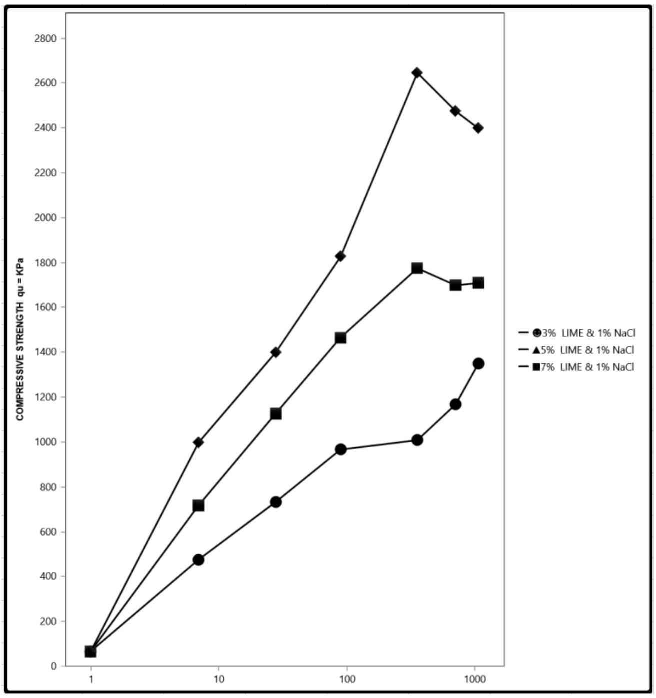


Figure 8. Unconfined compressive strength of soil + lime 3%,5%, 7% and 1% NaCl mixtures, and tested after 7, 28, 360, 720, 1080 days curing.

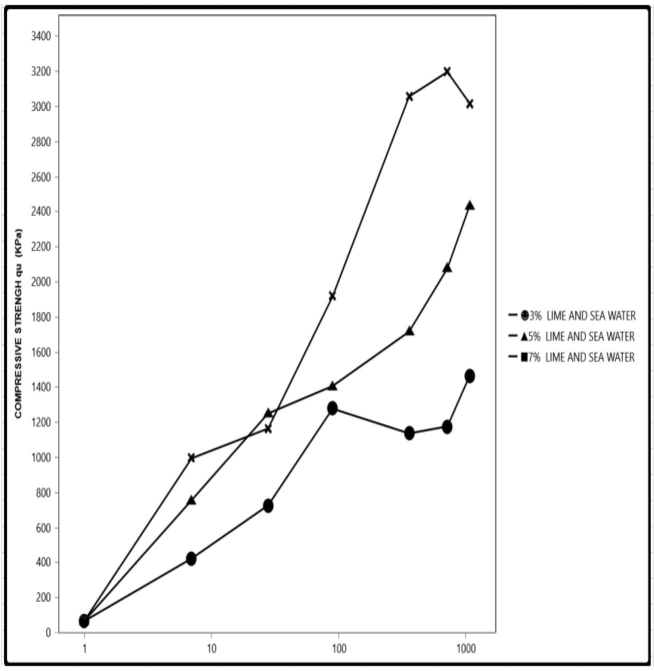


Figure 9. Unconfined compressive strength of soil + lime 3%,5%,7% and sea water mixtures, and tested after 7, 28, 360, 720, 1080 days curing.

In the third group of tests with 3%, 5%, 7% hydrated lime and seawater (Figure 9):

- In the samples with 3% hydrated lime and seawater, after 90 days of maintenance, there was a drop in strength which affected the final result.
- In the specimens with 5% hydrated lime and seawater, the strength increase curve remained on an upward trend until the final strength increase, which reached 2400 Kpa.
- In the samples with 7% hydrated lime and seawater, after 28 days of curing, there was a decrease in strength, lower than the strength of the samples with 5% hydrated lime. Also, after 700 days of maintenance, the final strength

decreased, which affected the final result, because the strength decreased by 200 Kpa.

As mentioned in the international literature (Bell, 1988, T.R.B, 1976, Sherwood, 1995), when hydrated lime is mixed with soil and water, two chemical reactions take place:

1. The first reaction consists of an intense ion exchange, where free calcium ions replace sodium and potassium ions. At the same time, hydrated lime begins to bind carbon from atmospheric carbon dioxide, (carbonation). This forms calcium carbonate, which is the main cementing compound of soil particles (Bell, 1993).
2. The second reaction that takes place between hydrated lime and soil is pozzolanic, where all the free calcium radicals capture silicate and aluminate radicals, and the soil acquires a granular texture. This reaction takes time; it does not happen immediately. Subsequently, these calcium silicate compounds form a gel around the clay crystals. In this way, many crystals are joined together and form aggregates, in which, if cementation extends around the perimeter, soil aggregates are formed, which are responsible for the increase in soil strength (Bell,.1993, Bense, et. al., 2001).

A sufficient amount of water is necessary for all these processes (Bell, 1993, Van der Kerkhof, 2001). As can be seen, the isolation of the samples in plastic bags did not allow for the absorption of excess water, which is why there were fluctuations in the strength curve of the samples. **Figures 7, 8, and 9** show the relationship between compressive strength and curing time, depending on the percentage of hydrated lime and the percentages of NaCl.

9. REMOULTING CURED SOIL SAMPLES.

After crushing each sample of the soil mixture containing hydrated lime, sodium chloride, and seawater, the material from one specimen of each group was collected, crushed, ground, and sieved through a No. 40 American-type sieve to restore it to its original form prior to compaction. The Atterberg limits were then re-determined in accordance with BS 1377. The purpose of this study was to break down the cementation that the clay particles had undergone due to hydrated lime and sodium chloride and to determine whether, due to chemical ion exchange, the material still exhibits non-plastic characteristics.

10. Determination of Atterberg limits in remoulted soil samples with lime, NaCl and sea water.

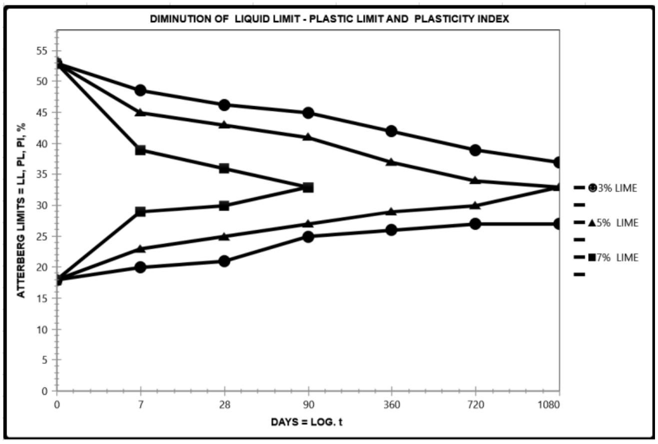


Figure 10. Detailed drawing for change Atterberg limits in remolded soil samples with 3%, 5%, 7% lime, after 1080 days curing.

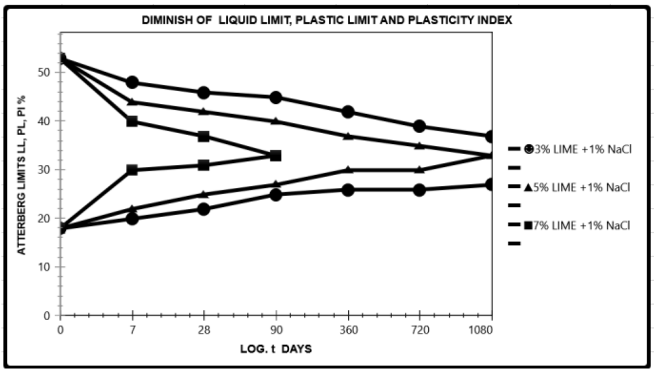


Figure 11. Detailed drawing for change Atterberg limits in remolded soil samples with 3%, 5%, 7% lime and 1% NaCl, after 1080 days curing.

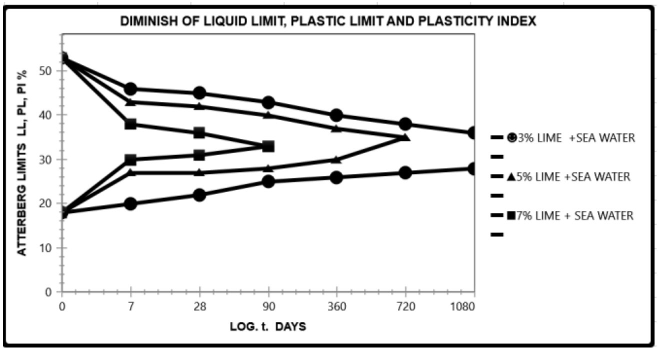
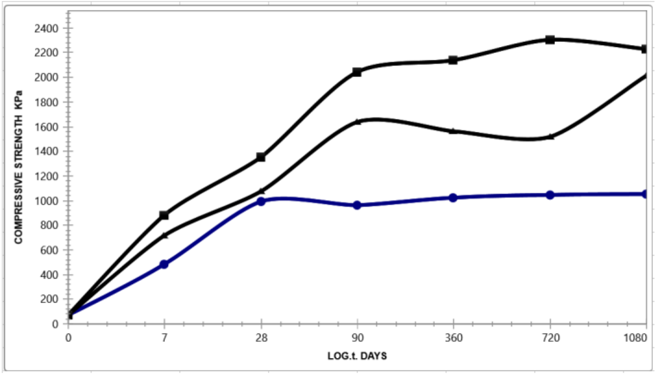


Figure 12. Detailed drawing for change Atterberg limits in remolded soil samples with 3%, 5%, 7% lime and sea water, after 1080 days curing.

11. Determination of linear shrinkage in remolded soil samples with lime, NaCl and sea water.



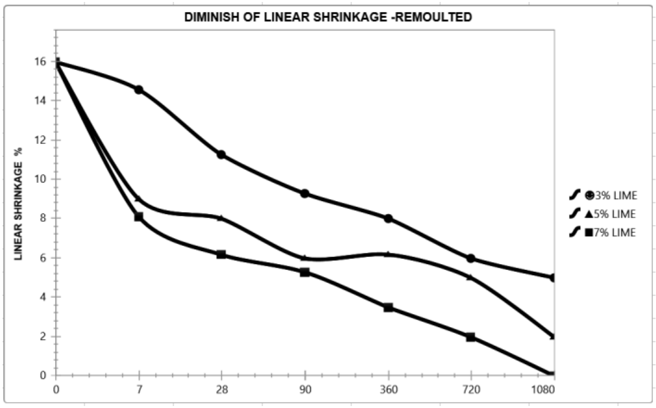
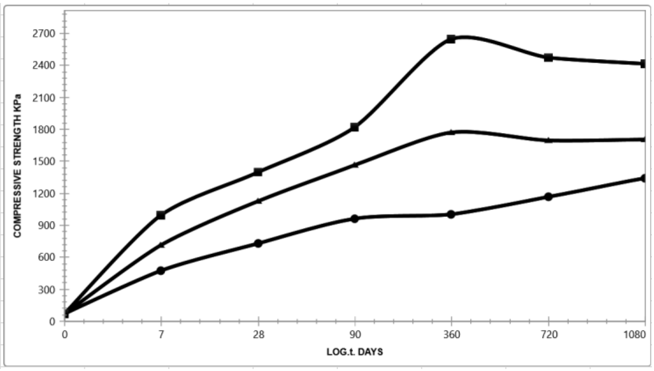


Figure 13. Detailed drawing for change of linear shrinkage in remolded soil samples with 3%, 5%, 7% lime, after 1080 days curing.



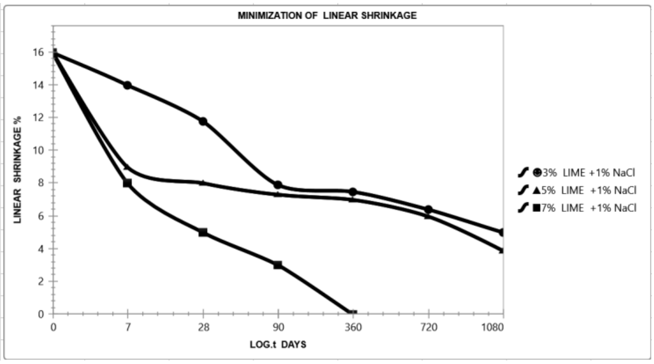
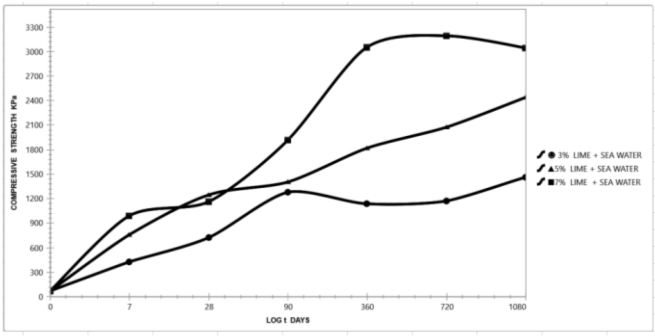


Figure 14. Detailed drawing for change of linear shrinkage in remolded soil samples with 3%, 5%, 7% lime and 1% NaCl, after 1080 days curing.



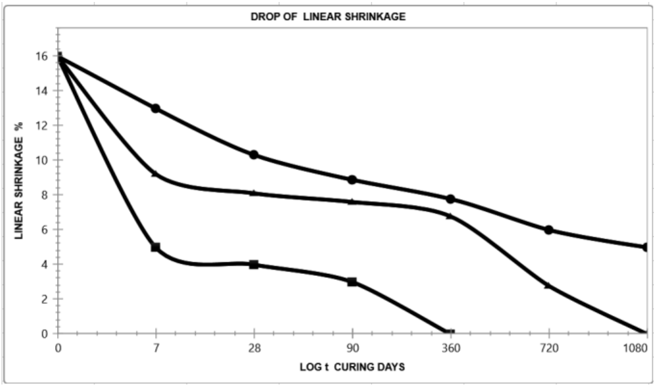


Figure 15. Detailed drawing for change of linear shrinkage in remolded soil samples with 3%, 5%, 7% lime and sea water, after 1080 days curing.

9. CONCLUSIONS

The following conclusions were drawn from the experimental procedure described in Chapter 10.

1. Mixing the soil with stabilizers causes a decrease in the maximum laboratory density (Proctor), accompanied by an increase in the optimum moisture content. This results in improved workability of the clay and requires less energy for soil compaction, allows machinery to move on the job site without getting stuck in the mud, and enables the clay to be compacted at moisture contents higher than the maximum.
2. The liquid limit decreased in soil mixtures with all stabilizer percentages. This decrease was proportional to the increase in the percentage of each stabilizer.

- In the group with 3%, 5%, and 7% hydrated lime and distilled water (Figure 10), the reduction in the water content limit approached 65% in the samples with 3% hydrated lime and 3 years of curing. In the samples with 7% hydrated lime, the water content limit was reduced to zero after 90 days of curing.
- In the group containing 3%, 5%, and 7% hydrated lime and 1% NaCl (Figure 11), the reduction in the water content limit approached 65% in the samples containing 3% hydrated lime and 1% NaCl after 3 years of curing. In the samples containing 5% hydrated lime and 1% NaCl, the water content limit was reduced to zero after 1,080 days of curing. In the samples containing 7% hydrated lime and 1% NaCl, the water content limit was reduced to zero after 90 days of curing.
- In the group with 3%, 5%, and 7% hydrated lime and seawater (Figure 12), the water content limit in the specimens with 3% hydrated lime and seawater decreased by 70% after 3 years of curing. In the specimens with 3% hydrated lime and seawater, the water content limit was reduced to zero after 720 days of curing. In the specimens with 7% hydrated lime and seawater, the water content limit was reduced to zero after 90 days of curing.

3. The plasticity limit increased inversely with the decrease in the water content limit and in proportion to the percentage of stabilizers and the curing time (Figures 10, 11, 12).
4. The plasticity index decreased inversely proportional to the increase in the percentage of stabilizers and the curing time of the specimens.

- In the group with 3%, 5%, and 7% hydrated lime and distilled water, the plasticity index in the specimens with 3% hydrated lime was practically zero (<8) after 1080 days (Figure 10).
- In the specimens containing 5% hydrated lime and distilled water, the plasticity index was practically zero after 720 days, while in the specimens.
- In the specimens containing 7% hydrated lime and distilled water, the plasticity index dropped to zero at 90 days (Figure 10).
- In the group containing 3%, 5%, and 7% hydrated lime and 1% NaCl, while the specimens with 3% hydrated lime and 1% NaCl the plasticity index showed a gradual improvement over the curing period and was practically zero (<8) after 3 years. In the specimens with 5% hydrated lime and 1% NaCl, the plasticity index reached zero at 1,080 days. In the specimens with 7% hydrated lime and 1% NaCl, the plasticity index reached zero at 90 days (Figure 11).

- In the group with 3%, 5%, and 7% hydrated lime and seawater, the specimens containing 3% hydrated lime and seawater, plasticity index practically reached zero (<8) after 1080 days. In the specimens with 5% hydrated lime and seawater, the plasticity index dropped to zero at 720 days. In the specimens with 7% hydrated lime and seawater, the plasticity index dropped to zero at 90 days (Figure 12).

5. Linear shrinkage shows a steady decrease over time for all stabilizer contents.
   - More specifically, in specimens containing plain hydrated lime, it was practically zero (<6) in all mixtures after 3 years of curing (Figure 13). According to Altmeyer (1956), linear shrinkage less than 8 is considered marginal for soil expansion. As observed in Figure 13, in the mixtures with 7% hydrated lime, linear shrinkage decreased to a marginal value (8) immediately after 7 days of curing.
   - In the specimens containing 3%, 5%, and 7% hydrated lime and 1% NaCl, linear shrinkage was practically zero (<6); for the mixtures containing 3% and 5% hydrated lime, but this occurred after 1,080 days, while in the specimens containing 7% hydrated lime and 1% NaCl, linear shrinkage was reduced to zero after 360 days of curing (Figure 14).
   - In the specimens containing 3%, 5%, and 7% hydrated lime and seawater, linear shrinkage progressed more rapidly. In mixtures containing 3% hydrated lime and seawater, linear shrinkage was practically zero (<6) after 1,080 days of curing. In mixtures containing 5% hydrated lime and seawater, linear shrinkage reached zero after 3 years. Finally, in mixtures containing 7% hydrated lime and seawater, linear shrinkage decreased to a marginal level (<8%) after 7 days of curing, while it reached zero after 360 days (Figure 15).

Expansion and shrinkage are two opposing properties that coexist in every expansive clay, and their occurrence depends on the presence or absence of excess water. Since shrinkage was eliminated by the action of hydrated lime, it was not deemed necessary to re-test the expansion of a material that had become brittle or sandy. At the same time, since the soil material became sandy and plasticity was eliminated, the potential for settlement—which causes problems in road embankments—was also indirectly eliminated. For this reason, the tests mentioned above serve as an indirect method for predicting the behavior of swelling clay in the context of a major civil engineering project. Provided that a detailed laboratory investigation is conducted beforehand.

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