# ASSESSMENT OF CLAY MATERIALS STABILIZED WITH LIME, CEMENT AND A POLYMER

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## SUMMARY

Clayey soils are materials that generally do not meet the specifications to be utilized in the construction of highways, thus, when are they are found in the area of the project and it is neccesary to used them then something must be done to improve their properties. One of the solutions often used is the chemical stabilization. This paper shows the degree of improvement of two clay properties when stabilized with lime, cement and a polymer, the properties are compared with those obtained with specimens prepared with soil in natural conditions. The tests that were carried out were unconfined compression, California Bearing Ratio, and resilient modulus. From the results it was observed that there exist properties than increase for the first days of curing and then tend to stay almost constant. On the other hand, there are other properties that seem to show a reduction as the curing age increases; such is the case of the resilient modulus and unconfined compression.

## 1. INTRODUCTION

The construction of means of communication is fundamental for the development of a country. Such means can be highways, airports, ports, railways, and so on. The first can be constructed with a surface of HMA or hydraulic concrete if they will be exposed to high levels of traffic, but in the case of rural roads they are frequently constructed with surrounding material.

In all countries thre are agencies that regulate several aspects of the communication means. In Mexico the Transport and Communications Ministry (SCT) is the agency which provides the specifications of construction materials. On the other hand, a problem that the engineer must face before the construction of a pavement project is to locate the banks to extract the materials that will constitute the layers of the structure. Similarly, there are situations when it is necessary utilize materials such as clays of high plasticity, for example, in the case of rural roads. Due to this, the chemical stabilization is one of the techniques often used to improve the properties of the materials. In the following sections it is presented some aspects about stabilization, followed by the data obtained in this research.

## 2. MATERIAL STABILIZATION

The stabilization technique has been used since ancient times to achieve one or several characteristics. Some of these are: reduction of expansion/contraction of a soil, to increase the strength, to reduce the thickness of the pavement, to utilize local materials, to reduce the susceptibility to moisture, to reduce the dust generated when vehicles ride over the surface, to provide a work platform, and so on.

To utilize a stabilizer it is necessary to know how it works and the impact on the properties that need to be improved. For example, when the soil is mixed with a stabilizer some phenomena can happen: capsulation of the particles, binding and formation of new components. The degree and rate to which these phenomena will happen depend on the composition of the stabilizer. For example, the asphalt capsulate and bind, thus, increases the strength and reduce the susceptibility to moisture. The fly ash requires an activator like lime or cement and after adding water some reactions will occur so that the binding of the particles will occur. This material also increases the strength and reduces the susceptibility to water. Similarly, the cement combined with water produces hydration and new components are formed. Depending on the cement composition the reaction of the silicates and aluminates of the clay can occur.

## 2.1. Lime stabilization

This kind of stabilization has been used since ancient times. An example of its application is in the Roman roads. The evidence is the structure of the roads which were formed with four layers. At the bottom a layer of rock called *statumen* was placed, and then it followed a layer of sand and gravel which name was “rudus”. After these layers it was placed another which was formed with rock mixed with lime and called “nucleus”. Finally, the surface was a slab of rock as shown in Figure 1.

(a) Structure of the Roman roads (b) Via Apia

Figure 1 – (a) Structure of the roman roads; (b) Surface of the via Apia [1]

Needless to say that up to now lime is one of the products which are often utilized to improve the characteristics of materials.

The literature shows that a system soil-water when mixed with lime produces an exotermic reaction. Initially it is the result of the cationic interchange of the $Ca^{2+}$. The effect is the production of a dry and brittle material [2]. On the other hand, in the long run it can take place the solidification of the mixture as a result of the puzzolanic reactions [2]. All these reactions produce compound with cementitious materials that improve the strength. Lime is used to stabilize several soil types; however, it works better in clayey materials. It is recommended to use it when the soil contains at least 25 % of clay or when the PI is larger than 10.

Some benefits of the lime are: reduction of the plasticity, reduction of water absorption, reduction of the expansion and to improve the stability, etc.

## 2.2. Stabilizing with cement

The cement is formed of silicates and aluminates of calcium that combined with water form new components. In addition, during the reaction it is formed lime that makes possible the puzzolanic reaction with the alumina and the siliceous material that are present in the clayey materials [4]. The reactions are responsible of the changes in the soil properties.

An example of a study of cement stabilization is the work of Geiman (2005)[5]. The materials of the research work were clay of the northern of Virginia (CL), clay Staunton (CH) and sand from Lynchburg (SM). One of the stabilizers utilized in the study was the cement which was applied in 3 and 5 %. Figure 2 shows the results of the unconfined compresión obtained for the three soils. It is observed that the rate of increase of the strength is larger for curing times of less than 15 days. For curing times larger than 15 days the increase in strength is sligth, but it is important to mention that the study only contemplated up to 28 days of curing. Other aspect that can be observed of these results is the difference when the material was stabilized with 3 or 5 % of cement relative to the data obtained with natural soil. As a matter of fact, the strength of the materials in natural state is almost constant when the time of curing increases. On the other hand, the effect of the cement is different for the three soil types. It is noted that the stregth of the CH (Staunton clay) is the lowest, as a matter of fact; the larger strength is achieved by the silty sand.

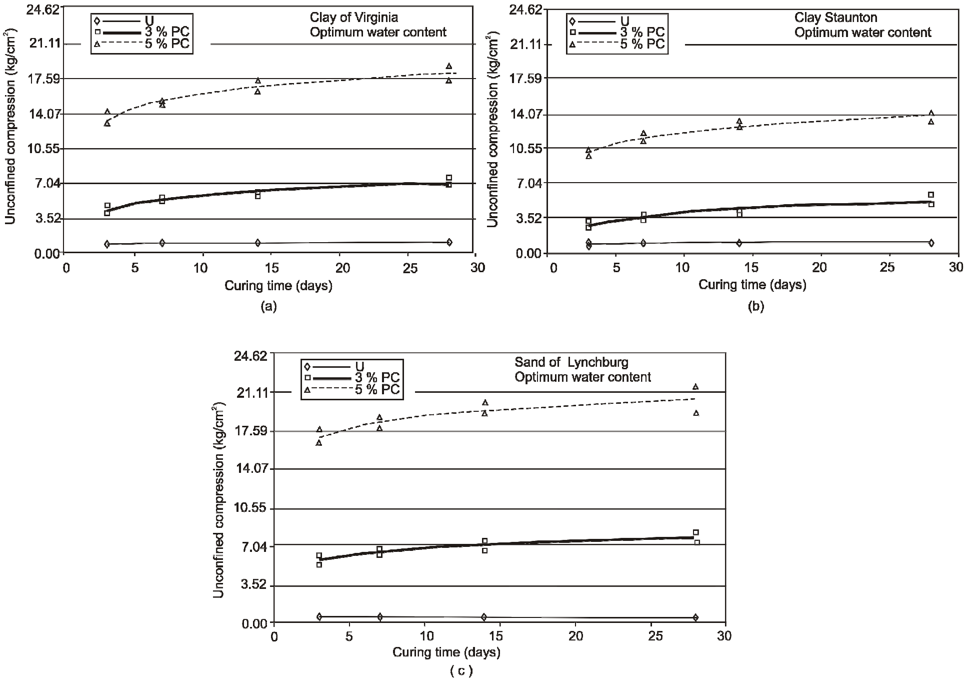


Figure 2 – (a) Curing time versus strength for the soil of northern Virginia; (b) Curing time versus strength for the Staunton clay; (c) Curing time versus strength for the silty sand [5]

From the aforementioned it is concluded that the effect of a product can be different and depends on the soil type. For example, in this case the sand increases its resistance from 1 kg/cm$^2$ when the specimens are prepared with natural soil up to the range of 17 to 21 kg/cm$^2$ when the stabilization process utilized 5 % of cement.

Oher aspect which is important in this type of stabilization is that the hydration of the cement is relatively fast and produces a rapid increase of the strength, thus it is a common practice to compact the mix as son as posible. It is recommended to compact it in an elapsed time of two hours after the mixing.

### 2.3. Other stabilizers

There are some other stabilizers that are offered in the market. In this research a polymer was also evaluated. According to the manufacturer, this polymer binds and consolidates the particles and as a consequence the material properties are improved.

## 3. TEST PROCEDURES

The tests followed to characterize the soils and to determine the mechanical properties adhered to ASTM standards except in the case of the resilient modulust test which is carried out with the NCHRP 1-28A. The next paragraphs briefly describe the most relevant testing.

### 3.1. Unconfined compression

This test consists in placing a sample on a load machine and then a load is apply at a rate in the range of 0.5 to 2.0 %/min. In this research work the rate was 1.2 %/min. The test is finalized when the strength achieves a maximum value.

### 3.2. CBR test (ASTM D 1883)

This test consists in the compaction of a specimen in a mold with the required water content and maximum dry unit weight. Once compacted, the specimen is saturated for 96 hours and then it is penetrated to a rate of 1.27 mm/min. The CBR of the material is computed as:

$$\mathrm{CBR}(\%) = \frac{P_{2.54\mathrm{mm}}}{1360} \times 100 \qquad (1)$$

Where:
$P_{2.54mm}$ = The load for a penetration of 2.54 mm
CBR = California Bearing Ratio

### 3.3. Resilient modulus test (Protocolo NCHRP 1-28A)

The resilient modulus test has the objective of determining the modulus by simulating the application of the load in a cyclic way. In laboratory this test is carried out by applying a series of deviator stresses and confining pressures such that a series of resilient modulus can be obtained for different stress states. The test consists of 16 sequences. In the first sequence 1000 of cycles are applied with a deviator stress of 48.3 kPa and a confining of 27.6 kPa. The remainig sequences 100 cycles are applied with the stress states shown in Table 1. The load is applied during 0.1 s followed by a 0.9 s of delay.

Table 1 – Sequences of the resilient modulus test

| Sequence | $\sigma_d$ (kPa | $\sigma_3$ (kPa | Number | Sequence | $\sigma_d$ (kPa | $\sigma_3$ (kPa | Number |
|---|---|---|---|---|---|---|---|

| No. | | | of cycles | No. | | | of cycles |
|---|---|---|---|---|---|---|---|
| 0 | 48.3 | 27.6 | 1000 | 9 | 69.0 | 55.2 | 100 |
| 1 | 27.6 | 55.2 | 100 | 10 | 69.0 | 41.4 | 100 |
| 2 | 27.6 | 41.4 | 100 | 11 | 69.0 | 27.6 | 100 |
| 3 | 27.6 | 27.6 | 100 | 12 | 69.0 | 13.8 | 100 |
| 4 | 27.6 | 13.8 | 100 | 13 | 96.6 | 55.2 | 100 |
| 5 | 48.3 | 55.2 | 100 | 14 | 96.6 | 41.4 | 100 |
| 6 | 48.3 | 41.4 | 100 | 15 | 96.6 | 27.6 | 100 |
| 7 | 48.3 | 27.6 | 100 | 16 | 96.6 | 13.8 | 100 |
| 8 | 48.3 | 13.8 | 100 | | | | |

## 4. SPECIMENS PREPARATION

To prepare the specimens an important step was to define the percent of the product to be used. For the case of lime it was added 4 % respect to dry weight; for cement it was added 8 % and regarding the polymer, the amount added to the compaction water was about 6 ml, amount that was calculated taking into account the recommendations of the manufacturer. Figure 3 shows the color of the water after the product was added.

Figure 3 – Water mixed with the polymer

### 4.1. Compaction of the specimens for resilient modulus and unconfined compression

The procedure in the following:

- Preparation of the mixture soil-lime, soil-cement or soil-polymer.
- Compaction of the specimens in eight layers in a split mold of 7.1 cm diameter and 14.4 cm height. Specimens of soil-lime and soil-cement were compacted inmediately after the mix was prepared. For specimens of natural soil and polymer, the water was added to the soil and then allowed to equilibrate during 24 hours. The next day the specimens were compacted at maximum dry unit weigth respect to

ASTM D 698 for soil 1 and for soil 2, the specimens were compacted at the same dry unit weight as the soil-cement samples.

- After compaction, the dimensions and mass were registered.
- The specimens were tested at the specified curing times. The curing times for soil 1 were 0, 7, 14, 28 and 90 and for soil 2 were 0, 7, 14, 28, 60, 90 and 180.
- The samples with curing time larger than 1 day were placed in a humid room.
- After the curing time was achieved the samples were tested.

The samples that were used in the analysis were those which met the requirements: $w_{opt} \pm 0.5$ % and $\gamma_{dmax} \pm 1$ %.

## 5. TEST MATERIALS

### 5.1. Index properties

The soil that was stabilized with lime and polymer was a clay classified as CH according to the USCS. The soil has a limit of contraction of 9.8 % (Figure 4); similarly in the stabilization with cement it was utilized a clay with the same classification, however, the Atterberg limits are lower than soil 1. Table 2 is a summary of the properties of both soils.

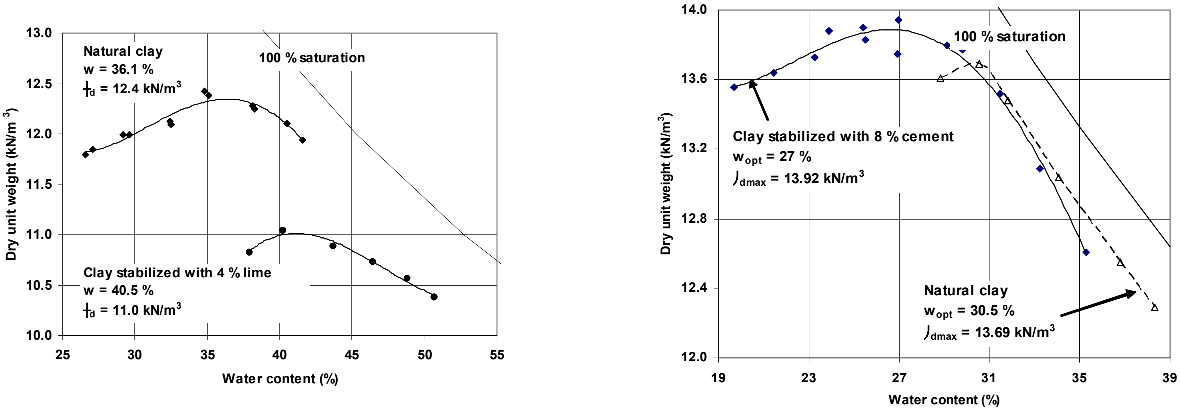
Table 2 – Properties of the two soils

| Soil number | Class | Atterberg limits | | | % Passing No. 200 | $G_s$ |
|---|---|---|---|---|---|---|
| | | LL (%) | PL (%) | PI (%) | | |
| 1 | CH | 94 | 62 | 32 | 95.6 | 2.74 |
| 2 | CH | 55 | 30 | 25 | 81.4 | 2.59 |

Figure 4 – Contraction of soil 1

### 5.2. Compaction characteristics

The determination of the compaction characteristics is one of the other important properties when studying the behaviour of the stabilizers. From this test it is determined the optimum water content and the maximum dry unit weight, values that can be used as reference to prepare the specimens. For soil 1, the compaction curve was determined with the ASTM D 698 (standar Proctor) and for soil 2, it was used the ASTM D 1557 (modified Proctor). Figure 5 shows the compaction curves of the natural soils.



(a) (b)

Figure 5 – (a) Compaction curve of soil 1;
(b) Compaction curve of soil 2

## 6. RESULTS

### 6.1. Results of soil 1

The unconfined compression tests are often used when evaluating properties of stabilized materials. As a matter of fact, many Transportation Departments of United States specify a value of strength to control the quality of the compacted material. This section presents the results of the unconfined compression tests carried out with soil 1.

Regarding the unconfined compression three conditions were studied: natural soil, soil stabilized with lime and stabilized with polymer. For each curing time three tests were performed, for example, Figure 6 shows the plots of the strength versus deformation for three specimens of natural soil and a curing time of 7 days. As can be noted there is good repeteability of the results obtained with the three specimens.

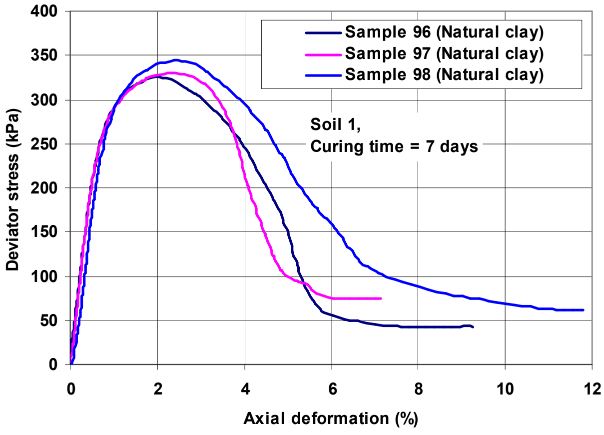


Figure 6 – Stress-strain curves for three soil specimens of natural soil at seven days of curing

Figure 7 shows the behavior of the unconfined compression for different curing times. The plot indicates that the specimens prepared with natural soil and the ones stabilized with polymer present a slight increase in their strength with the curing time, however, the specimens stabilized with lime showed a rapid increase during the first days of curing and after that the rate is reduced. The strength at 28 days of curing is approximately 3.5 times relative to that obtained for samples without curing time (that is to say, samples tested inmediately after compaction).

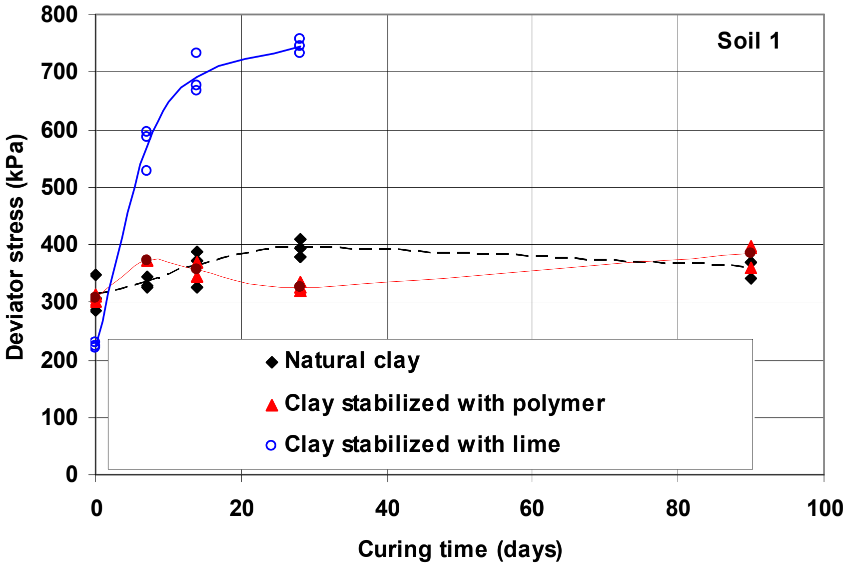


Figure 7 – Stress-strain curves for specimens of natural clay, stabilized with polymer and stabilized with lime

The CBR data demonstrated that the specimens prepared with natural clay and a curing time of cero days have a CBR of 0.6 % and an expansion of 13.1 %; for 90 days of curing the CBR was 0.8 % and the expansion was 12.9 %. So, the CBR and the expansion are independent of the curing time for this condition.

For specimens stabilized with polymer, the values of CBR and expansion were similar to those obtained in natural soils (Tabla 3). Thus, the CBR was not improved once the stabilizer was added. On the other hand, the data of the soil stabilized with 4 % lime show that the CBR values increase up to 48 % while in natural state the soil has a CBR of 1 % (Figure 8). On the other hand, the expansion in natural state was between 12 and 13 % and when stabilized with lime the expansion was reduced up to values of 1 % (Figure 9). The results are summarized in Table 4.

Table 3 – Values of CBR and expansion of the specimens stabilized with polymer

| Sample number | w (%) | $\gamma_d$ (kN/m$^3$) | Average CBR (%) | Average expansion (%) |
|---|---|---|---|---|
| 23 | 35.5 | 12.51 | 0.6 | 12.5 |
| 24 | 35.6 | 12.38 | | |
| 25 | 36.3 | 12.36 | | |
| 17 | 36.4 | 12.38 | 0.6 | 13.9 |
| 18 | 36.1 | 12.46 | | |
| 19 | 37.5 | 12.31 | | |
| 20 | 36.2 | 12.37 | 0.9 | 13.7 |
| 21 | 36.5 | 12.35 | | |
| 22 | 36.1 | 12.42 | | |
| 11 | 36.7 | 12.40 | 0.8 | 12.4 |
| 12 | 36.5 | 12.48 | | |
| 13 | 36.2 | 12.45 | | |
| 14 | 36.1 | 12.41 | 0.9 | 11.3 |
| 15 | 36.6 | 12.41 | | |
| 16 | 36.0 | 12.46 | | |

Table 4 – CBR and expansion of the specimens stabilized with lime

| Sample number | w (%) | $\gamma_d$ (kN/m$^3$) | Average CBR (%) | Average expansion (%) |
|---|---|---|---|---|
| 47 | 40.3 | 11.20 | 27.1 | 0.4 |
| 48 | 40.8 | 11.27 | | |
| 49 | 40.2 | 11.21 | | |
| 44 | 40.1 | 11.00 | 45.5 | 0.02 |
| 45 | 41.0 | 11.02 | | |
| 46 | 40.4 | 11.04 | | |
| 41 | 40.6 | 11.10 | 48.9 | 0.04 |
| 42 | 40.4 | 11.10 | | |
| 43 | 39.6 | 11.21 | | |
| 38 | 40.3 | 10.91 | 48.1 | 0.12 |
| 39 | 39.9 | 10.96 | | |
| 40 | 40.6 | 10.93 | | |
| 35 | 40.5 | 10.93 | 48.8 | 0.15 |
| 36 | 40.5 | 10.95 | | |
| 37 | 40.7 | 11.02 | | |

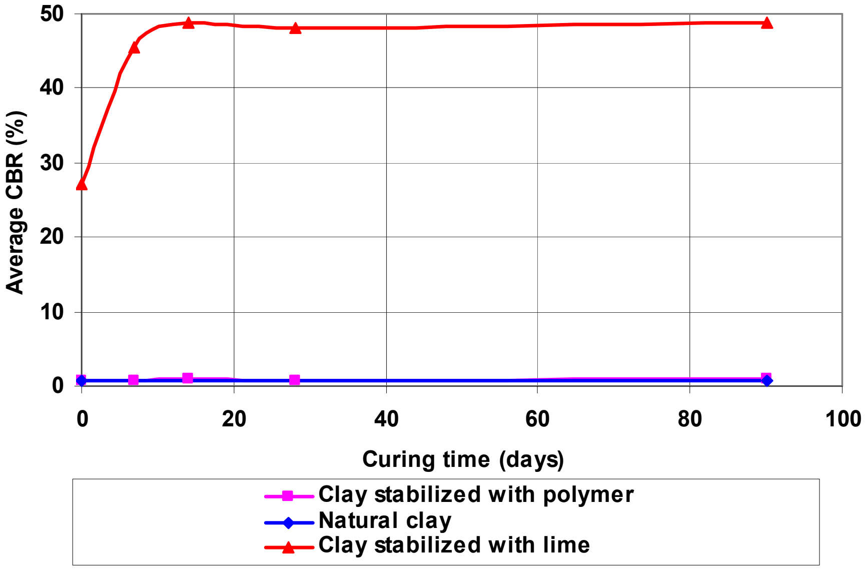


Figure 8 – Behaviour of the CBR of soil 1

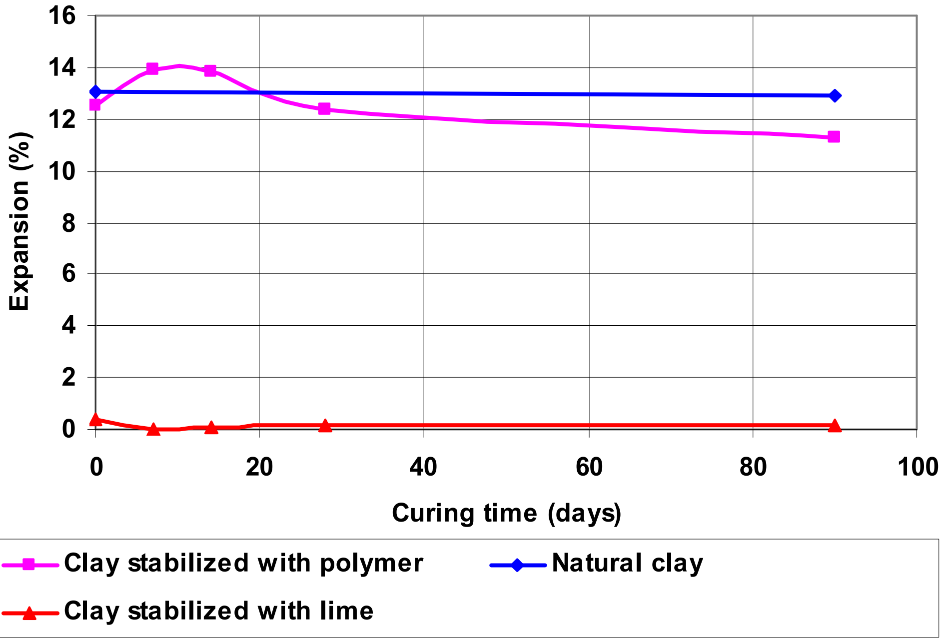


Figure 9 – Behaviour of the expansion of soil 1

The resilient modulus is another parameter presented herein. In this study two or three specimens were tested for each condition. The results of this test are 16 values as indicated in Figure 10, however, for analysis only some values were taken as a reference. As observed in this figure, the results have good repeteability for two samples with the same initial conditions. There is only a difference for the first deviator stress probably because of the sensibility of the LVDTs.

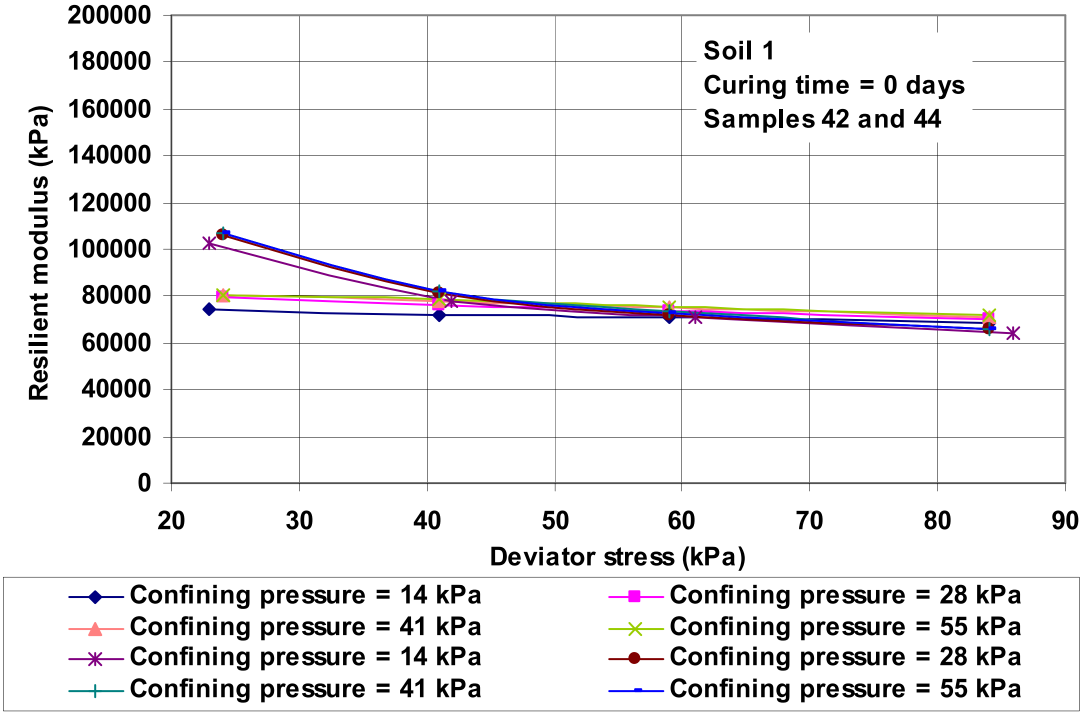


Figure 10 – Resilient modulus for soil 1

Table 5 shows a summary of the characteristics of the specimens tested in natural state, those stabilized with polymer and stabilized with lime.

Table 5 – Characteristics of the specimens tested in resilient modulus

| Natural clay | | | | Clay stabilized with polymer | | | | Clay stabilized with lime | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample No. | Curing days | w (%) | $\gamma_d$ (kN/m$^3$) | Sample No. | Curing days | w (%) | $\gamma_d$ (kN/m$^3$) | Sample No. | Curing days | w (%) | $\gamma_d$ kN/m$^3$ |
| 42 | 0 | 36.2 | 12.54 | 55 | 0 | 36.4 | 12.43 | 112 | 0 | 41.3 | 11.08 |
| 44 | 0 | 35.9 | 12.38 | 56 | 0 | 36.0 | 12.40 | 113 | 0 | 41.3 | 11.02 |
| 99 | 7 | 35.8 | 12.41 | 64 | 7 | 35.7 | 12.56 | 106 | 7 | 39.9 | 11.16 |
| 101 | 7 | 35.8 | 12.49 | 65 | 7 | 35.1 | 12.63 | 107 | 7 | 40.0 | 11.16 |
| 88 | 14 | 35.1 | 12.57 | 26 | 14 | 35.5 | 12.37 | 93 | 14 | 40.2 | 11.12 |
| 89 | 14 | 35.9 | 12.55 | 27 | 14 | 35.7 | 12.44 | 94 | 14 | 40.1 | 11.11 |
| 69 | 28 | 36.3 | 12.39 | 18 | 28 | 36.4 | 12.30 | 84 | 28 | 40.7 | 11.08 |
| 71 | 28 | 35.9 | 12.43 | 19 | 28 | 36.5 | 12.40 | 85 | 28 | 40.7 | 11.10 |
| 51 | 90 | 36.6 | 12.23 | 4 | 90 | 36.4 | 12.41 | | | | |
| 53 | 90 | 35.7 | 12.41 | 5 | 90 | 36.8 | 12.29 | | | | |

If the resilient modulus values of natural soil are compared with the ones obtained with specimens stabilized with lime or polymer, the values of natural soil and with polymer are between 100 and 150 MPa, however, the values of the samples stabilized with lime are in the range of 190 and 270 MPa. On the other hand, it can be observed that the confining pressure has more effect on soil stabilized with lime, this means, the curves of different confining pressures are separated which is not the case for samples of natural soil or stabilized with polymer (Figure 11).

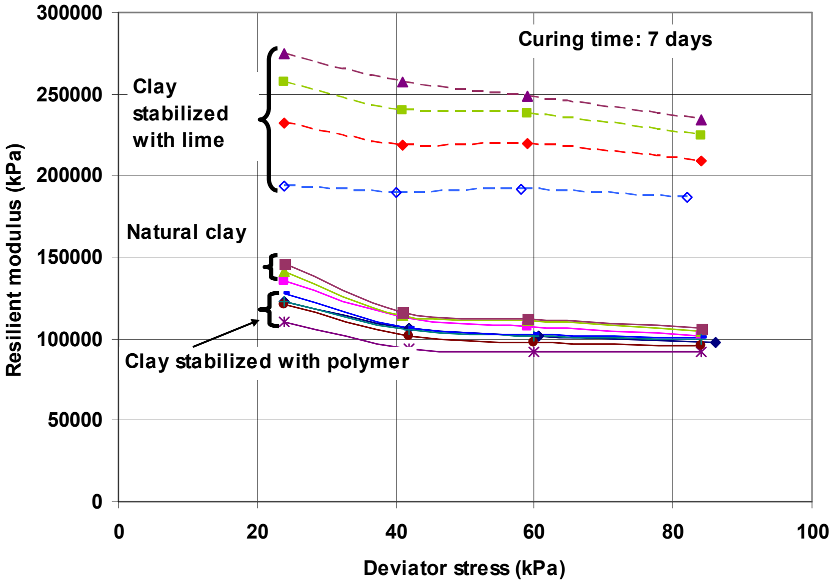


Figure 11 – Resilient modulus of samples stabilized with lime, polymer and natural samples

Similarly, comparing the values of resilient modulus for the condition of $\sigma_d$ = 84 kPa and $\sigma_3$ = 14 kPa for all curing times and the three conditions (natural soil, soil stabilized with polymer and stabilized with lime), it is found that the response is the same as the CBR, that is to say, the natural soil and the stabilized with polymer have similar values and in the case of the soil stabilized with lime the values increase greatly for all curing times except for 28 days where the values are reduced almost to those obtained at cero curing days (Figure 12).

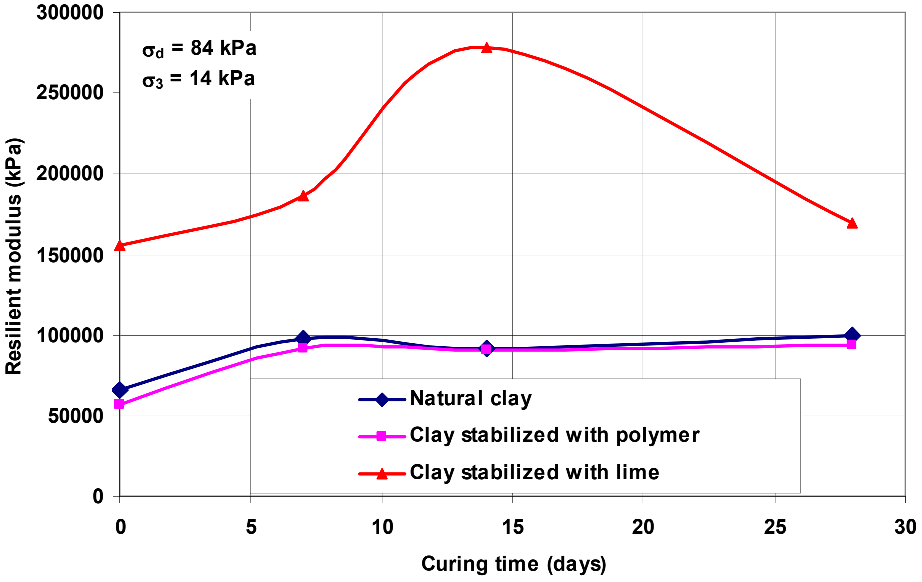
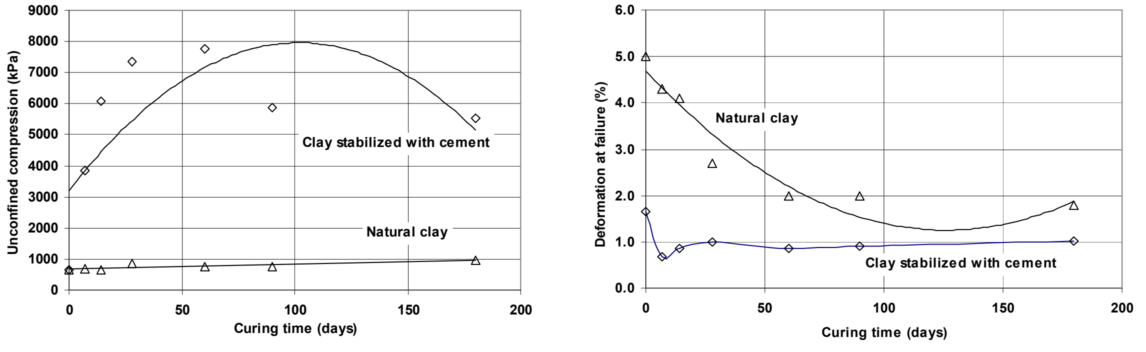


Figure 12 – Variation of the resilient modulus with curing time

## 6.2. Results of soil 2

Finally, Figure 13 shows the comparison of the unconfined compression strength of the clay stabilized with 8 % cement and with soil samples of natural clay. This figure shows that the rate at which strength increases is greater in the first days of curing and tends to be reduced for larger curing times (90 and 180 days).

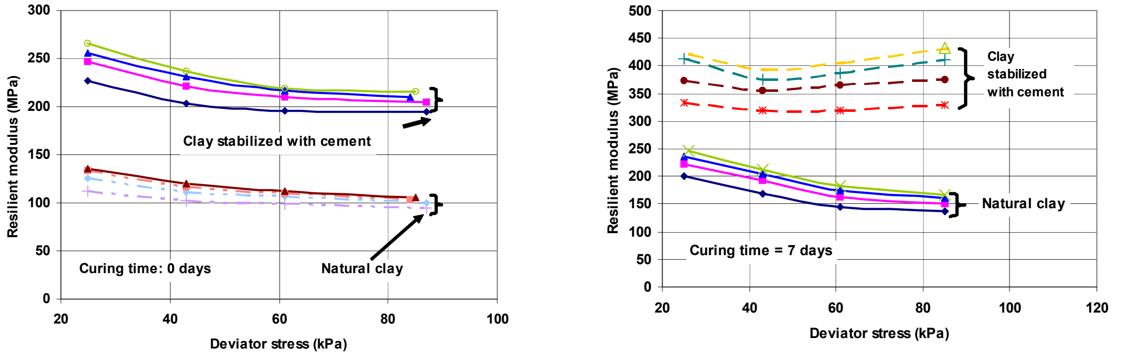
As seen in figure, the strength of the natural soil is almost independent of curing time and the values are very low respect to those obtained when stabilized with cement. On the other hand, the axial strain at failure of natural clay specimens decreases as the curing time increases and the axial deformation of specimens stabilized with cement begins with 1.8 % and then has a steady value of approximately 1.0 %, this characteristic demonstrates that the reaction of the cement-soil-water is very fast (Figure 13b).



(a) (b)

Figure 13 – (a) Plots of unconfined compression; (b) Axial deformation at the failure

Figure 14a and b shows the results of resilient modulus for all sequences for cero and seven days of curing. In this figure it is observed the great difference in the values of resilient modulus stabilized with cement. The values of the natural soil tend to be between 100 and 140 MPa, while for stabilized material the values varied from 200 and 260 MPa (for cero curing days). On the other hand, comparing the plot for seven days of curing (Figure 14b) it is noted that the resilient modulus of the natural soil is increased compared to the values obtained at cero days of curing, similarly for the cement stabilized soil.



(a) (b)

Figure 14 – (a) Resilient modulus test results for 0 days of curing; (b) Resilient modulus values for 7 days of curing

## 7. CONCLUSIONS

The results of this research demonstrate the importance of evaluating the stabilizers offered in the market. For example, in this case, a series of tests were carried out to evaluate the degree at which a polymer improved the properties of a clay, however, the results indicated that there is no benefit because the stabilized soil showed similar properties to samples compacted with natural soil.

At the same time, this work stresses the effects of typical stabilizers such as lime and cement with conventional tests such as California Bearing Ratio and unconfined compression. In addition, resilient modulus testing was also run because it is one of the parameters that are utilized in pavement design.

Also, it is illustrated that in a soil stabilized with lime, the resilient modulus and unconfined compression increase with time, but this increment is not permanent.

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