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## **CONTROL OF VOLUME CHANGES IN EXPANSIVE SUB-GRADE SOIL USING LIME AND DOLOMITIC-LIMESTONE BY-PRODUCT**

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### **ABSTRACT**

Expansive soils undergo uncontrolled volumetric changes due to variations in moisture content. Consequently, the overlying structures, including pavements, are severely damaged. The common practice is to remove the natural expansive soil and replace it with a non-expansive soil. However, other economic solutions should be considered such as using stabilizers. In this paper, the effect of adding two stabilizers on the performance of an expansive soil is investigated. The hydrated lime is used as a chemical stabilizer and dolomitic limestone by-product (DLP) is used as a mechanical stabilizer. The study examines the effect of these stabilizers on the physical and mechanical properties of the soil mixtures. A series of tests are performed on expansive artificial soil-mixtures with lime contents of 3%, 6%, and 9% and DLP contents of 12%, 24%, and 48%. The tests include sieve analysis, Atterberg limits, modified Proctor, free swell, CBR, pH, and chemical analysis. The volume changes upon wetting are evaluated using free swell index (FSI) and swelling potential (SL), whilst, the effect of stabilizers on soil strength is assessed based on CBR value.

**Keywords:** Expansive soil, stabilization, swelling potential, CBR, lime, DLP

### **INTRODUCTION**

Expansive clays are considered as problematic soils that undergo uncontrolled volume changes due to variations in water content. These volume changes cause severe damages in the superstructures overlying these soils, especially pavement structures [1] and [2]; Nelson and Miller, 1992). Many studies were performed to limit volume changes of these soils; either by replacing them with non-swelling soils as mentioned by Marei [3] or by chemical stabilization using calcium-based agents such as: hydrated lime, Portland cement, and lime/cement mixtures stabilizers as explained by Chen [1].

Undesirable results were observed while treating some formations of expansive clays with lime or cement [4]. Moreover, Kota et al. [5] reported several case studies where infrastructure facilities and highways experienced severe damages due to excessive heave of the underlying lime-treated expansive soils. This was attributed to the high sulfate content in these soil

formations (above 2000 ppm). Sherwood [4] stated that excessive swelling occurs in the sulfate bearing soil when it is stabilized with calcium-based stabilizers.

This paper studies the effect of adding the hydrated lime and dolomitic-limestone waste material (DLP) on the swelling and strength characteristics of an expansive soil with sulfate content. The swelling potential and strength characteristics are evaluated from CBR and free swell tests. In addition, sieve analysis, Atterberg limits, modified Proctor, pH, and chemical analysis are performed.

## MATERIAL AND METHODS

An artificial expansive soil-mixture is used in this study, consisting of 60% bentonite clay and 40% silica sand. The bentonite clay is collected from the International Company for Mining Industries (ICMI) and sand is obtained from a quarry located in Cairo-Suez district. The Hydrated lime is from Torah, while the DLP is a waste material (by-product) obtained during dolomitic-limestone crushing process in Ataqa mountain's quarries.

The chemical composition of the raw materials used in this study are showed in Table 1. Clay consists mainly of Silica, Alumina and Iron with percentages of 49.21%, 23.27%, and 5.60%, respectively. The hydrated lime is composed mainly of Calcium Carbonate (with free Calcium Oxide of 17.2%). Whereas, the DLP contains about 50% of Calcium Carbonate (with free Calcium Oxide of 1%). The chemical reactions are based mainly on the available quantity of the free calcium Oxide existing in the stabilizer. Consequently, hydrated lime is anticipated to be a chemical treatment. However, DLP is anticipated to act mainly as a replacement material, Therefore, higher percentages of DLP are selected for the soil treatment process.

Hydrated lime contents of 3%, 6% and 9% are added to the soil mixture, on the other hand, DLP contents of 12%, 24% and 48% are used. The added amount of each stabilizer is calculated as a percentage of the dry weight of the untreated soil-mixture. The curing period for all treated samples is 3-days in order to allow for chemical reactions between the soil-mixture and stabilizers. Afterwards, a series of laboratory tests is conducted according to ASTM and Indian Standard on the untreated and treated soil mixture including CBR [6], free swell [7], sieve analysis [8], Atterberg Limits [9], Modified Proctor [10], pH test [11] and chemical analysis [12].

Free swell test is adopted to predict swelling potential. In this test, a 10-gm oven-dried soil specimen is poured in a graduated cylinder glass of 100 ml capacity. First, the cylinder is filled with distilled water up to the 100 ml mark and entrapped air is removed by gently shaking the cylinder. Then, the soil is allowed to settle in the cylinder. The same procedure is repeated using kerosene instead of distilled water. In this case, the measuring cylinder should be covered to prevent Kerosene from evaporation. After 24 hours, the final volumes of soils in distilled water ( $V_d$ ) and kerosene ( $V_k$ ) are recorded. The free swell index (FSI) is determined as follows:

$$FSI = \frac{V_d - V_k}{V_k} \times 100 \quad (\text{Eq.1})$$

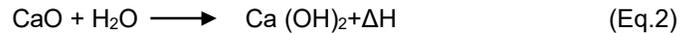
## RESULTS AND DISCUSSIONS

### CHEMICAL ANALYSES RESULTS

Table 2 shows the sulfate and chloride contents of the untreated and treated samples. The results reveal that the effect of adding lime to the soil mixture is more pronounced than adding DLP with respect to increasing the sulfate content. Using lime content of 3%, 6% and 9% to the soil mixture causes the sulfate content to increase by 39%, 70% and 117%, respectively, while adding DLP by 48% to the soil mixture leads to an increase in the sulfate content by 65%. This is attributed to the higher sulfate content in the hydrated lime.

## pH TEST RESULTS

ASTM [11] provides a standard method to obtain the optimum lime content for soil stabilization. The optimum lime content is found to be corresponding to pH value of 12.4 at which the added quantity of lime is sufficient for chemical reactions to take place. The free calcium oxide (CaO) in lime reacts with water (H<sub>2</sub>O) to produce calcium hydroxide (Ca(OH)<sub>2</sub>) which is responsible for increasing the pH of the treated soil system and heat (ΔH). Therefore, by increasing the percent of lime the pH value of the soil mixture increases.



pH tests are conducted on the treated soil-mixture as shown in Fig. 1. Lime content of 6.5% is corresponding to 12.4 pH value. Therefore, lime contents of 3%, 6% and 9% are selected in this study. On the other hand, DLP has an insignificant effect on pH value of the treated soil mixture. Upon using DLP content of 48%, pH value increased only by 2.4%. This is attributed to the low value of free CaO content in DLP (about 1%) compared to the free CaO existing in the hydrated lime (about 17%).

## SIEVE ANALYSIS AND ATTERBERG LIMITS RESULTS

The sieve analysis and hydrometer tests are performed to determine the grain size distribution curves as presented in Fig. 2. According to USCS, sand and DLP are classified as SP (poorly graded sand). For sand, the coefficient of curvature (C<sub>c</sub>) is 0.97 and the coefficient of uniformity (C<sub>u</sub>) is 2.12. For DLP, C<sub>c</sub> is 3.31 and C<sub>u</sub> is 19. The grain size distribution curve of clay shows that 88% of clay particles are less than 0.005 mm. For clay and DLP, the Atterberg limits tests are performed on particles smaller than 0.425 mm. The liquid limit (w<sub>L</sub>), plastic limit (w<sub>P</sub>), and plasticity index (I<sub>p</sub>) of clay are 125%, 42.50% and 82.5%, respectively. Hence, this clay is classified as CH (high plastic clay). For DLP, w<sub>L</sub> is 41.5%, w<sub>P</sub> is 25.4%, and I<sub>p</sub> is 16.1%.

The grain size distribution curves for untreated and treated soil-mixtures are also shown in Fig. 2. The results of the grain size and plasticity analyses indicate that the untreated soil-mixture is classified as CH according to USCS. According to AASHTO [13], this soil is classified as A-7-6 (fair to poor). This is an indication of the necessity for treatment if this soil acts as a subgrade layer.

The effect of the two stabilizers on the Atterberg limits is studied. Increasing lime content leads to a reduction in the soil-mixture liquid limit (w<sub>L</sub>) and plasticity index (I<sub>p</sub>) and an increase in its plastic limit (w<sub>P</sub>). Fig. 3 depicts that for lime content equals to 3%, 6%, and 9%; w<sub>L</sub> is reduced by 7.5%, 10.6%, and 16.0% and w<sub>P</sub> increases by 21.2%, 25.1%, and 30.7%, respectively. Consequently, I<sub>p</sub> reduced from 59.7% to 53.30%, 46.90% and 36.80%, respectively. Thompson [14] found that the reduction in I<sub>p</sub> is attributed to the excess calcium ions (Ca<sup>++</sup>) supplied by the addition of lime. The Ca<sup>++</sup> ions immigrate from hydrated lime to the surface of soil-mixture particles and displace water and other cations on the left side of Ca<sup>++</sup> in the lyotropic series Li<sup>+</sup> < Na<sup>+</sup> < H<sup>+</sup> < K<sup>+</sup> < NH<sub>4</sub><sup>+</sup> < Mg<sup>++</sup> < Ca<sup>++</sup> < Al<sup>+++</sup>. These reactions result in an apparent change in texture of the clay due to the clamping of clay particles together into larger sized aggregates. This process is called the "flocculation and agglomeration" phenomenon as discussed by Negi et al. [15]. Hence, an improvement in the treated soil workability is noticed. The same trend is observed for soil-mixture treated with DLP which is successful in improving the consistency and workability of the soil mixture. I<sub>p</sub> values of samples with DLP content of 12%, 24% and 48% are 48.8%, 44.0% and 42.4%, respectively. This can be attributed to the increase of the granular content in the treated samples due to adding DLP. Moreover, DLP changes the soil-mixture classification. According to AASHTO, soil mixtures treated by DLP contents of 12% and 24% become classified as A-7-6, whereas the stabilized sample by 48% DLP is classified as A-2-7.

## MODIFIED PROCTOR TEST RESULTS

Modified proctor tests are performed on the untreated and treated soil mixture (Fig. 4). The optimum moisture content (OMC) and the maximum dry unit weight (γ<sub>dmax</sub>) of the soil-mixture are

23% and 1.50 gm/cm<sup>3</sup>, respectively. Lime has an insignificant effect on OMC and  $\gamma_{dmax}$  which is consistent with the work of Utami [16]. Using lime content of 9% increases OMC only to 24% and  $\gamma_{dmax}$  to 1.51 gm/cm<sup>3</sup>. However, DLP leads to a noticeable increase in  $\gamma_{dmax}$  and a slight decrease in the OMC as shown in Fig 4. The addition of DLP causes the soil mixture to be coarser, therefore, higher values of  $\gamma_{dmax}$  in addition to lower values of OMC are expected.

### FREE SWELL TEST RESULTS

Free swell index (FSI) all samples (treated/untreated) are plotted in Fig. 5, FSI of the untreated soil-mixture is 165%. It is noted that FSI decreases as the lime content increases until reaching its lowest value at lime content of 6.5% which conforms to the pH test results. Afterwards, FSI begins to increase again as lime content increases. FSI values of samples treated with lime content of 3% and 6% of lime are 109% and 83%, respectively, showing reduction percentages of 33% and 49%. However, upon increasing the lime content up to 9% and 12%, FSI starts to increase again to values of 92% and 125%, respectively. This is attributed to the high sulfate content in the treated soil-mixture (Table 2) which has also been verified by the experimental work of Solanki et al. [17]. Thompson [14] explained this phenomenon in detail. The addition of lime to soil supplies excess calcium ions (Ca<sup>++</sup>) which cause cation exchange to occur. Consequently, the charge potential on the clay surface becomes equilibrated. Hence, the absorption of water into the clay surface decreases and swelling decreases. However, the existing sulfate in the soil mixture along with silicate and alumina react with the calcium in lime to form a highly expansive crystalline of Ettringite. Fig. 6 shows the sequence of Ettringite mineral formation. First, water is added to the lime and the clay particles in the hydration stage. Second, clay particles start to leach at the edges to form a high concentrated silicate (Si) and Alumina (Al) dissolved layer in the dissolving stage. Thirdly, the exchange between the high concentrated dissolved cations from the clay and calcium ions (Ca<sup>++</sup>) from the lime results in the formation of Calcium Silicate Hydrate (CSH), Calcium Aluminum Hydrate (CAH), and Ettringite [18]. The chemical composition of Ettringite is  $Ca_6[Al(OH)_6]_2 \cdot (SO_4)_3 \cdot 26H_2O$ .

For soil-mixture treated with DLP, FSI decreases gradually by increasing DLP content. Samples treated with DLP content of 12%, 24% and 48% show reduction in the FSI by 12%, 16% and 47%, respectively. It can be concluded from Fig. 5 that lime is more efficient than DLP in reducing swelling. For example, adding 11% of lime content is needed to reduce FSI down to a value of 105%, on the other hand, 41% of DLP content is needed to reach the same value.

### CBR TEST RESULTS

CBR tests are used to evaluate the swelling potential (SL) of samples. SL is the change in the sample height after soaking divided by the sample height before soaking. Fig. 6 shows that SL decreases from 28.1% to 14.0% for lime content of 3% (reduction of 50%). By adding 6% lime, SL decreases to 3.0% (reduction of 89%). However, by adding 9% lime SL increases to 7.04%. SL decreases with increasing lime content up to 6.5% after which SL starts to increase again, which agrees with pH and free swell test results. On the other hand, for DLP contents of 12%, 24% and 48%, SL values decrease by 53%, 66%, and 69%, respectively. A rapid reduction rate is observed until reaching DLP content of 24% after which increasing DLP content has an insignificant effect on SL.

CBR tests are also used to evaluate the effect of stabilizers on the soil strength. Fig. 7 shows that lime improves the strength of soil-mixture. Using lime contents of 3%, 6%, and 9% improves CBR value by 171%, 351% and 867%, respectively. This is attributed to the formation of Calcium silicate hydrate (CSH) and Calcium aluminum hydrate (CAH) (Fig. 5). These are cementitious components which are responsible for increasing the strength of the soil-mixture. On the other hand, CBR value increased from 1.4% to 8.7% (521.4% increase) when 48% DLP content is added. Fig. 5 depicts that DLP is most efficient when its content is between 12% and 24%. DLP content less than 12% has an insignificant effect on the soil-mixture strength. At the same time, no significant improvement is noticed using DLP content larger than 24%. This implies that DLP has a limited effect on enhancing the soil-mixture strength. This was verified by performing CBR tests on DLP material. CBR values between 11.0% and 12.1% were obtained.

## CONCLUSION

This research examines the effect of adding two different stabilizing agents on an expansive artificially reconstituted soil-mixture. The hydrated lime is used as a chemical stabilizer. Dolomitic limestone by-product (DLP) is examined as a cheaper stabilizing alternative. It can be concluded that lime is more efficient than DLP stabilizer in reducing swelling and increasing strength. These results are verified from both free swell and CBR tests. However, hydrated lime should be used with great caution in stabilizing expansive soil with high sulfate content. Highly expansive crystalline of Ettringite are formed due to the interaction between sulfate in the soil-mixture and calcium in lime. Ettringite causes excessive heave due to its large volume. Moreover, Lime and DLP are also found to be effective stabilizers in reducing plasticity index ( $I_p$ ), hence, improving the soil workability. Lime has an insignificant effect on the compaction properties of the soil-mixture. However, DLP causes the soil-mixture to be coarser, therefore, compacted soil samples treated with DLP have higher values of  $\gamma_{dmax}$  in addition to lower values of OMC.

**Table 1: Chemical analysis of raw materials**

Chemical compound	Bentonite clay	Hydrated lime	DLP
	Percentage by weight, (%)		
Silica( $\text{SiO}_2$ )	49.21	6.00	11.88
Alumina( $\text{Al}_2\text{O}_3$ )	23.27	2.43	1.83
Ferric oxide ( $\text{Fe}_2\text{O}_3$ )	5.60	1.08	1.11
<b>Silica/Sesquioxide ratio (SSR)</b>			
$\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$	1.70	1.71	4.04
Calcium Carbonate ( $\text{CaCO}_3$ )	1.24	56.82	50.01
Calcium oxide (CaO)	-	17.18	1.01
Magnesium oxide (MgO)	0.76	7.50	13.32
Sodium oxide ( $\text{Na}_2\text{O}$ )	1.22	0.82	0.87
Potassium oxide ( $\text{K}_2\text{O}$ )	0.16	0.16	0.20
Sulfur trioxide ( $\text{SO}_3$ )	0.39	2.04	0.41
Chloride(Cl)	0.80	0.14	0.12
Loss on Ignition	17.22	28.47	40.57
Percentage passing No. 325, %	100	100	100

**Table 2: Sulfate and chloride contents for untreated and treated soil mixtures**

Percentage of stabilizer content %		Sulfate content ( $\text{SO}_3$ ) in ppm	Chloride content (Cl) in ppm
Lime	DLP		
0	0	1553.0	3188.0
3	0	2164.0	3235.0
6	0	2646.0	3267.0
9	0	3381.0	3323.0
0	48	2576.0	3485.0

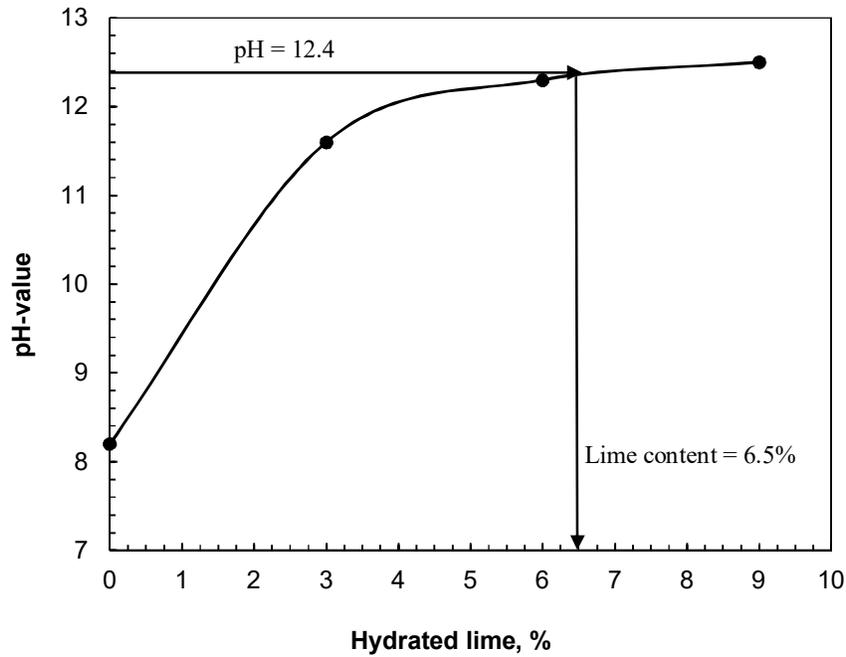


Fig. 1: Variation of pH values with lime content

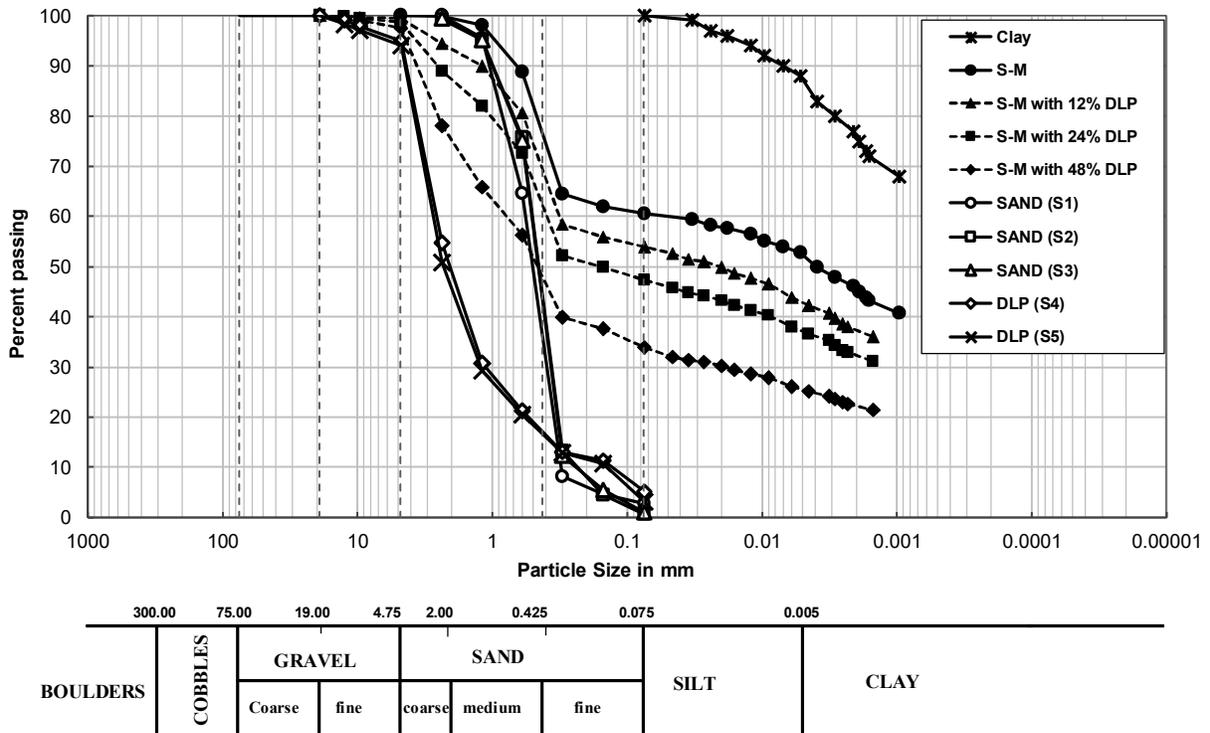


Fig. 2: Grain size distribution curves of raw materials and untreated/treated soil mixtures

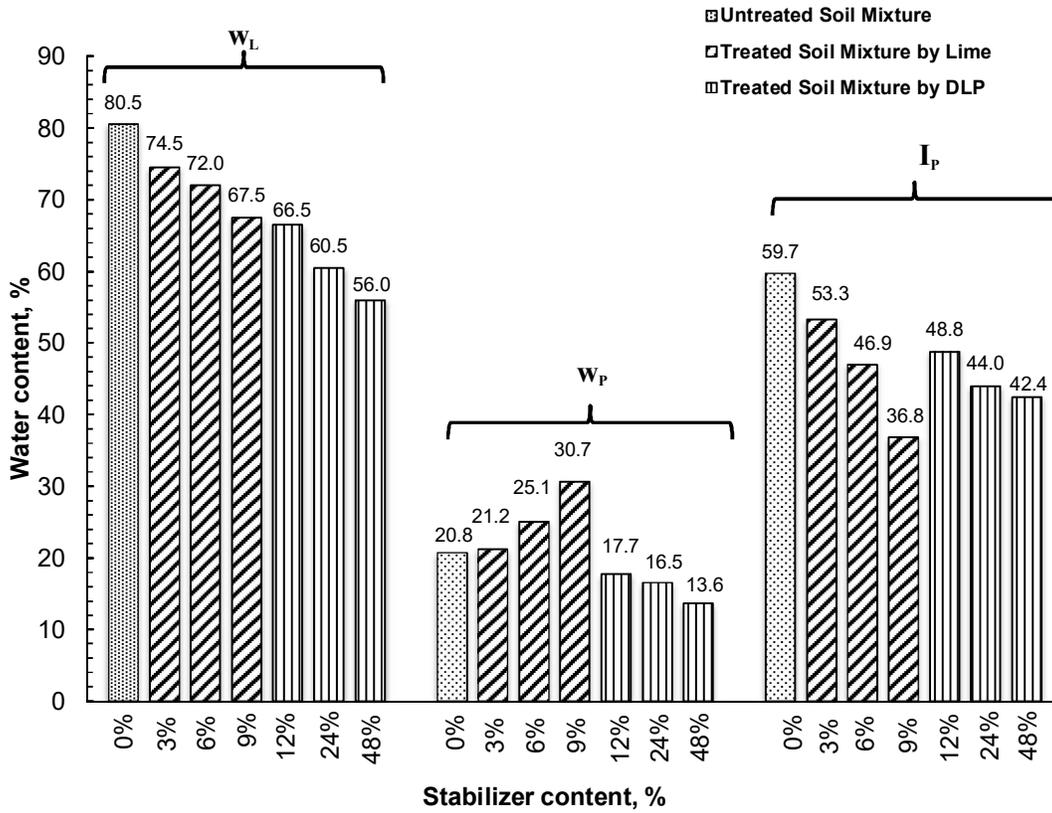


Fig. 3: Atterberg limits for untreated and treated soil-mixtures

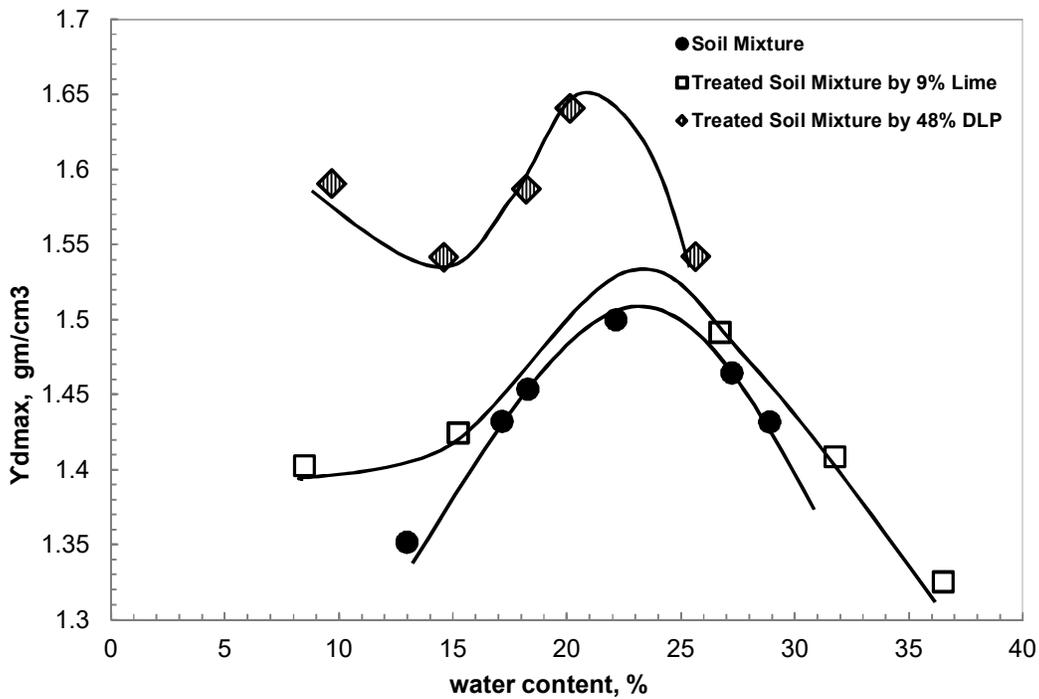


Figure 04. Compaction curves of treated and untreated soil-mixtures

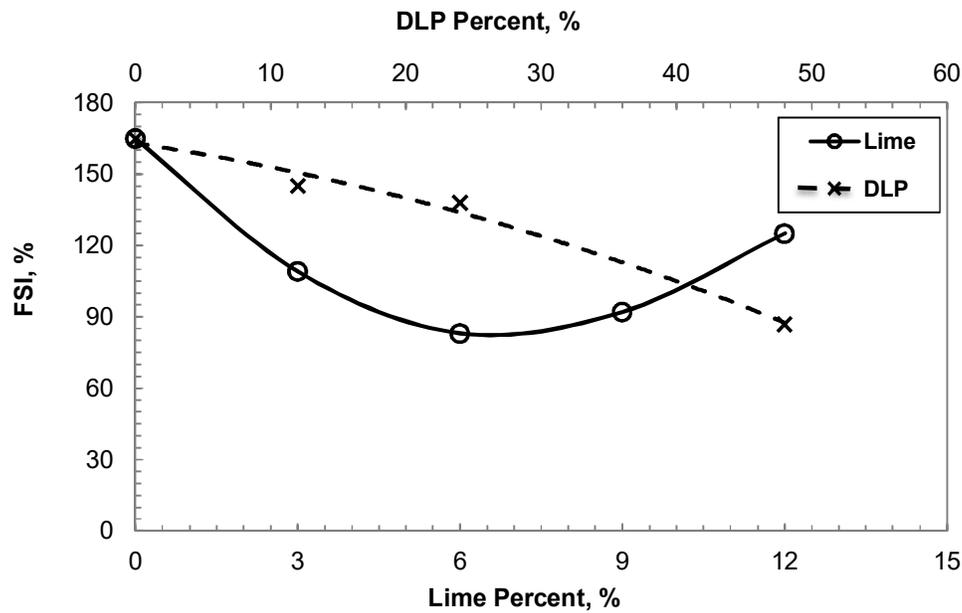


Fig. 5: FSI versus lime and DLP contents

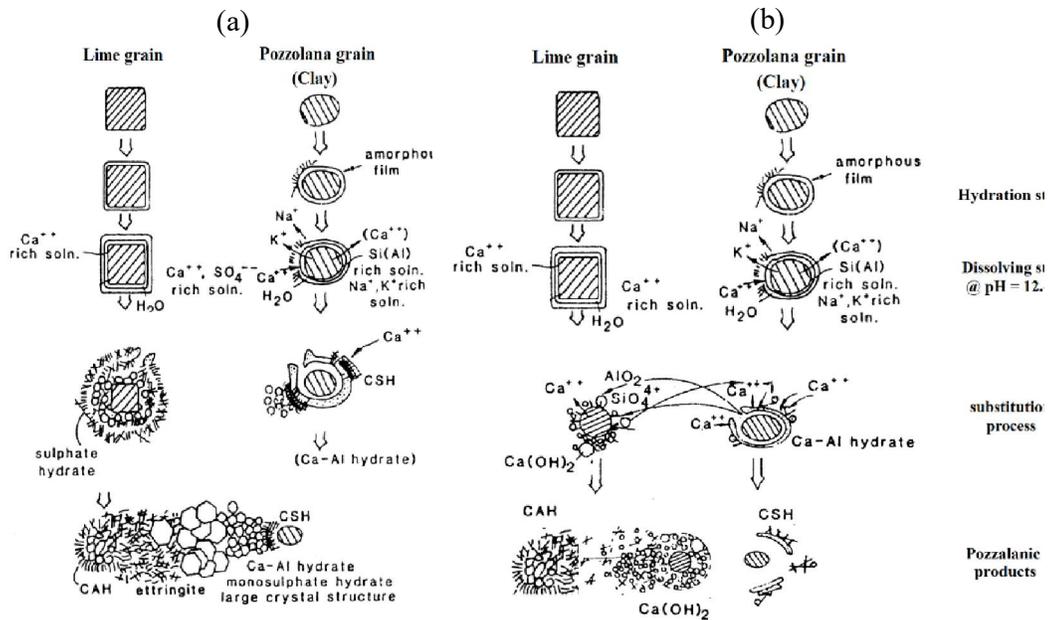


Fig. 6: Schematic diagram showing the formation stages of: (a) Ettringite mineral, (b) cementitious components of CSH and CAH during stabilization of high sulfate soil by lime (Rajasekaran [18])

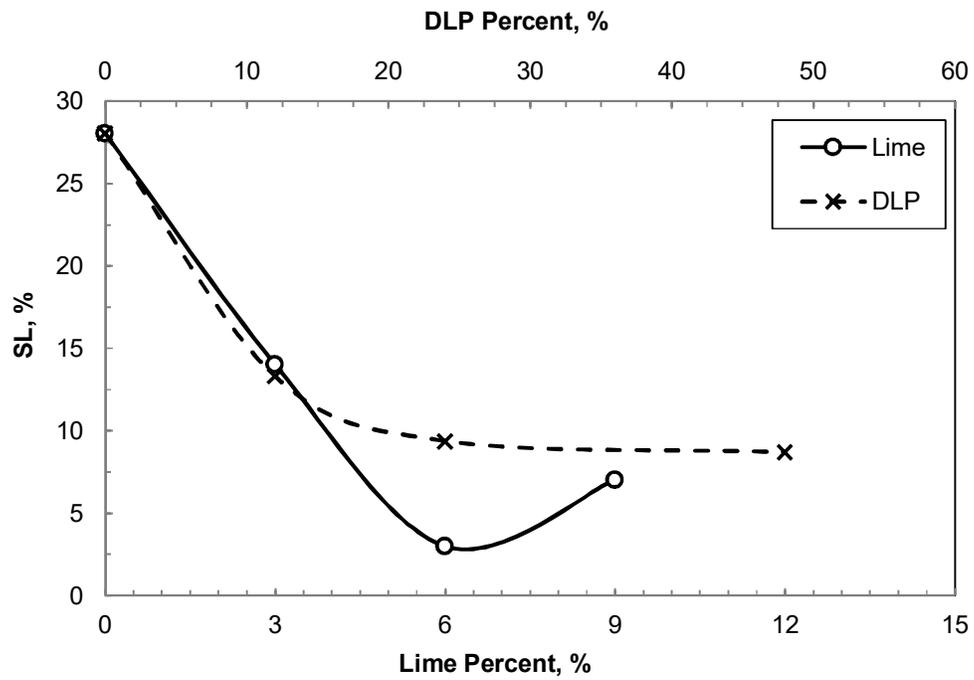


Fig. 7: SL versus lime and DLP contents

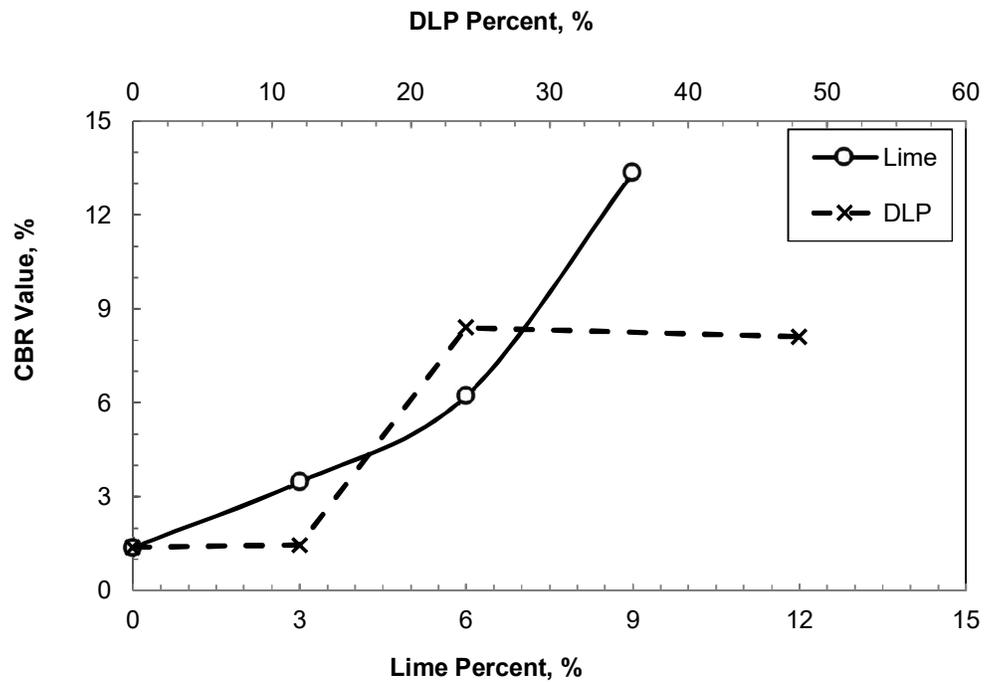


Fig. 8: CBR value versus lime and DLP contents

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