# Comparative Performance of Portland Cement and Lime Stabilization of Moderate to High Plasticity Clay Soils

by Sankar Bhattacharja and Javed I. Bhatty

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**Abstract:** Stabilization, engineering properties, and durability characteristics of clay soils with moderate to high plasticity clay were investigated in the presence of Type I portland cement and hydrated lime. The objective was to perform a direct comparison on the performances of portland cement and lime. The properties investigated were: plasticity indices, unconfined compressive strength, California bearing ratio, strength after vacuum saturation (to evaluate freeze-thaw performance), mass loss in wet-dry test, and hydraulic conductivity and leaching. In order to make a direct comparison, both cement- and lime-stabilized soils were tested under identical conditions. In general, for the moderate Plasticity Index (PI) soils, the performance of portland cement-stabilized soils was superior to lime in all the characterizations performed. For the high PI soils, performance of lime was better at lower dosage levels (3%). However, once this threshold was crossed at higher dosages (6 and 9%), cement-stabilized soils exhibited superior engineering and durability properties.

**Keywords:** Atterberg limits, CBR, California bearing ratio, cement, compaction, compressive strength, hydrated lime, hydraulic conductivity, freeze-thaw, leachate, lime, permeability, portland cement, soil, sulfated soil, soil stabilization, vacuum saturation, wet-dry.

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# Comparative Performance of Portland Cement and Lime Stabilization of Moderate to High Plasticity Clay Soils

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## INTRODUCTION

The modification of clay soils to improve their engineering properties is well recognized and widely practiced. Through stabilization, the plasticity of soil is reduced, it becomes more workable, and its compressive strength and load bearing properties are improved. Such improvements are the result of a number of chemical processes that take place in the presence of a stabilizer.

While both portland cement and lime are capable of providing calcium, the primary ingredient necessary for stabilizing a clay soil, they differ in their chemical nature, mode of reaction in the presence of water, and the resulting reaction products. Based upon the differences involved in these processes, questions can be raised about the ultimate superiority of one over the other. This issue has been addressed in the present investigation. In order to make this an unbiased comparative study, both portland cement- and hydrated lime-stabilized soils were prepared and tested under similar conditions.

A good soil stabilizer should provide calcium ions ($Ca^{2+}$) in sufficient amount so that the monovalent cations, especially $Na^+$, adsorbed on the cleavage surfaces of clay particles are exchanged resulting in a more workable soil with reduced plasticity. In a high pH environment, the solubility of silica and alumina is greatly enhanced, which promotes pozzolanic reaction to form calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H). With portland cement, however, C-S-H and C-A-H are formed immediately upon hydration, and a flocculation process similar to that observed for lime-stabilized soil takes place to produce a soil with improved engineering properties.

Several factors such as plasticity of soil, types and amounts of stabilizers, mixing and compaction methods, curing conditions, etc., affect the performance and durability of a stabilized soil. These issues had previously been discussed at length by the authors in a review article entitled "Stabilization of Clay soils By Portland Cement or Lime – A Critical Review of Literature" (Bhattacharja, Bhatty, and Todres, 2003). In the present investigation, these factors have been investigated on a laboratory scale to provide a one-to-one comparison on the performances of portland cement- and lime-stabilized soils.

## MATERIALS

The soils used in the project were acquired from southern California and Texas. The southern California soil is designated in the text as Cal soil. Two Texas soils were obtained from two separate locations near Dallas and were identified with the assistance of the Texas DOT. These two soils are designated as Texas 1 and Texas 2. Both Cal and Texas 1 soils were procured from locations where no sulfate-related problems were reported and the sulfate contents were low. The Texas 2 soil was obtained from an area where some sulfate-related problems had been reported. However, the sulfate analysis of the soil indicated that the concentration of soluble sulfate in the soil was less than 500 mg/L.

A soil with sulfate content well over this level could not be found for this project. In order to achieve an elevated sulfate level, Cal soil was spiked with sodium sulfate to raise the sulfate level to approximately 20,000 mg/L. This soil is designated in the text as sulfated Cal. Sodium sulfate solution was mixed with Cal soil (passing 4.75 mm sieve) such that the water content of the soil remained about 15%, which is 3% and 5% below the optimum moisture content (OMC) of Cal soil stabilized with portland cement and lime, respectively. The sulfated soil was kept in a closed container for a minimum of two weeks prior to mixing with stabilizers.

Portland cement, hydrated lime, and Class F fly ash were used as the stabilizing agents at various dosage levels. The cement used was a commercially manufactured Type I portland cement. Commercially produced finely ground hydrated lime with 99% passing 75 µm sieve and 97% passing 45µm sieve was used as a stabilizer. Class F fly ash was used in combination with either cement or lime.

## TEST METHODS

Upon procurement, each of the three soils was dried in air, broken into approximately 2 in. (50 mm) pieces, and remixed. Subsequently, the soils were pulverized in a crusher to less than 0.188 in. (4.75 mm) size for testing. In order to stabilize these soils, 3%, 6%, and 9% (by weight) of Type I cement and hydrated lime were used. When Class F fly ash was used in combination with portland cement or lime, fly ash contents were 6 and 12% and the amount of cement or lime was kept constant at 6%. In order to characterize stabilized specimens at different ages, they were placed in two resealable plastic bags and stored in a moist room (100% RH) at room temperature. The moist room curing minimizes any loss of moisture from sample, while the plastic bags prevent any transfer of moisture from outside.

## Plasticity Index and Shrinkage Limit

Plasticity of as-received and stabilized soils was measured following the procedure ASTM D 4318, "Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." The shrinkage limit was also measured following the procedure ASTM D 4943, "Standard Test Method for Shrinkage Factors of Soils by the Wax Method," only when the stabilized soil was plastic. The shrinkage limit determines the dimensional stability as the moisture level in the specimen is changed. It is defined as the percent moisture content (in reference to oven-dried weight) at which no further reduction in volume takes place as the specimen loses moisture. Ideally, the shrinkage limit should be higher than the optimum moisture content. This condition ensures that absorption of further moisture (as determined by the difference between shrinkage limit and optimum moisture) beyond the optimum moisture content (OMC) by a compacted soil will not cause any swelling, or that, a loss of moisture will not cause any shrinkage.

## Optimum Moisture Content and Maximum Dry Density

Optimum moisture content (OMC) at maximum dry density (MDD) was determined for each of the as-received soils without any stabilizers. As this may differ from that of the soil containing a stabilizer, the OMC was determined separately with each of the stabilizers at 6% dosage level. This was considered applicable to the remaining two stabilizer dosages (3% and 9%). While small variations in the stabilizer content may alter the OMC marginally, considering the intrinsic errors involved in preparation and testing, the OMC values obtained at the 6% level were used for 3% and 9% dosage levels. OMC at MDD was determined for soils compacted using standard compactive effort (Proctor test) as per ASTM D 698, "Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort [12,400 ft-lb/ft$^3$ (600 kN-m/m$^3$)]". Molds with 4 in. (102 mm) internal diameter were used for compaction.

In the case of hydrated lime, the soil samples were "mellowed" for 24 hours prior to compaction. When portland cement was used as stabilizer, the soil was compacted immediately after mixing with cement and water. Based upon the practice in the industry, this compaction schedule was selected for the present investigation.

## Unconfined Compressive Strength

The effect on stabilization by the varying dosages of portland cement and lime on the unconfined compressive strength (UCS) of Cal and Texas 1 and 2 soils were investigated. Three dosages of portland cement and lime were separately mixed with the soils at OMC (as determined in the previous section) and the mixtures were compacted using standard compactive effort. Upon demolding, the compacted specimens were stored in the manner described above and tested for UCS at various ages.

As mentioned above, portland cement-stabilized soil samples were compacted immediately after mixing and those stabilized with lime were compacted 24 hours after mixing. The samples were tested for UCS at 3, 7, 28, and 91 days following the procedure ASTM D 2166, "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil."

In order to make a comparison between the immediate and delayed compaction with portland cement, Cal soil was also compacted 24 hours after mixing with cement. UCS of sulfated Cal soil stabilized with both cement and lime was also determined. In addition, sulfated Cal soil was stabilized with portland cement and lime in combination with 6% Class F fly ash. Fly ash was added to determine what effect, if any, fly ash had in reducing expansion in the sulfated Cal soil.

## California Bearing Ratio

California bearing ratio (CBR), both unsoaked and soaked, of all three soils and those stabilized with portland cement and lime was measured following ASTM D 1883, "Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils." The soils were compacted using standard compactive effort at OMC. Portland cement-stabilized soils were compacted immediately after mixing, while lime-stabilized soils were delayed 24 hours before compaction. Two stabilizer dosages, 6% and 9%, were used for all three soils and tested at 91 days. During this period, the compacted specimens in CBR molds were placed in double resealable plastic bags and stored in a moist room at room temperature.

Sulfated Cal soil was also tested for unsoaked and soaked CBR. Any subsequent volume expansion was monitored while the CBR molds with the specimens were soaked in water. The sulfated Cal soil samples were stabilized with either 6% portland cement or lime and compacted at OMC using the standard compactive effort. The amounts of mix water used were the same as those of the corresponding stabilizer for the Cal soil. Samples were stored under identical conditions as described above, and CBR of the stabilized sulfated soil was measured at 91days.

## Vacuum Saturation

The vacuum saturation test was performed based upon ASTM C 593, "Standard Specification for Fly Ash and Other Pozzolans for Use with Lime." This test provides a method by which to evaluate freeze-thaw durability when fly ash or other pozzolans are used with lime. The test was carried out to evaluate the relative performance of cement- and lime-stabilized soils.

Soil samples were compacted at OMC using standard compactive effort and stored in conditions described earlier. The samples were tested at 7 and 91 days. At the end of the curing period, the soil specimens were placed in a chamber (as described in the test procedure) and slowly evacuated over 45 minutes to reach a pressure of 24 in. (610 mm) of Hg. In order to de-air, the specimens were left at this pressure for 30 minutes. Upon de-airing, water was introduced into the chamber, the vacuum was released, and the entire sample was soaked for one hour. Subsequently, the unconfined compressive strength (UCS) was measured (ASTM D 2166) after draining the surface water for approximately 2 minutes.

## Wet-Dry Test

The wet-dry test was performed on all three soils stabilized separately with portland cement and lime. Following compaction at OMC using standard compactive effort, the stabilized soil samples were stored in double resealable plastic bags in a moist room (100% RH) at room temperature. The wet-dry test was performed at different ages, 7 and 91 days after mixing with the stabilizers. The test procedure used was a slight modification of ASTM D 559, "Standard Test Method for Wetting and Drying Compacted Soil-Cement Mixtures." In order to make a direct comparison with the lime-stabilized soils, the application of wire scratch brush, as prescribed in the standard test method, was not made in this test. Specimens stabilized with either portland cement or lime were prepared from soils passing a 0.188 in. (4.75 mm) sieve and tested in exactly the same manner.

With time, many of the specimens started losing significant weight making the dimension measurements unreliable. Also, many of the samples failed prior to the 12 wet-dry cycles prescribed in the test procedure.

## Hydraulic Conductivity of Stabilized Soils

Hydraulic conductivities were measured for all three soils stabilized separately with different amounts of cement and lime. The soil specimens used for hydraulic conductivity measurements were compacted at OMC using the standard compactive effort. While the specimens were in the compaction mold, a 2.875 in. (73 mm) diameter specimen was cored out for measurement. A steel sleeve with a 2.875 in. (73 mm) internal diameter and sharpened edge was used for coring. The specimens were placed in two resealable plastic bags and stored in a moist room at room temperature for 35 days. The dimensions of these specimens were approximately 4.5 in. (110 mm) long and 2.875 in. (73 mm ) in diameter. On the 35th day, measurements for hydraulic conductivity were started. The test procedure followed was ASTM D 5084, "Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter." The specimens were saturated using backpressure and the falling head and rising tailwater method was used to measure the hydraulic conductivity.

Measurements were performed for a period of 60 days or more. In some cases of low permeability samples, a differential pressure between two ends of specimen was used to promote flow and shorten testing time. However, the hydraulic gradient used in the measurement was always below the limits prescribed in the test method D 5084. Periodically, a sample of effluent liquid was collected and analyzed for pH and concentrations of calcium, sodium, and potassium ions. The concentrations of these ions in the influent water were also measured to compare with those in the leachate. The cumulative volume of the effluent was also monitored during the entire testing period.

## RESULTS AND DISCUSSION

The classification and grain size analysis of the as-received soils are presented in Table 1. Table 2 provides information on Atterberg and shrinkage limits, optimum moisture content (OMC), and maximum dry density (MDD). The OMC and MDD of the soil samples were determined using standard compactive effort and are shown in

**Table 1. Classification and Grain Size Analysis of As-Received Soils**

| | | | Gradation (% passing specific sieve size) | | | | |
|---|---|---|---|---|---|---|---|
| Soil ID | Textural classification | AASHTO soil group | No. 4 (4.75 mm) | No. 10 (2.00 mm) | No. 40 (425 μm) | No. 100 (150 μm) | No. 200 (75 μm) |
| Cal | Sandy clay | A-7-6 | 100 | 90 | 89 | 80 | 65 |
| Texas 1 | Clay | A-7-6 | 100 | 94 | 93 | 91 | 88 |
| Texas 2 | Clay | A-7-6 | 100 | 97 | 96 | 92 | 86 |

**Table 2. Atterberg and Shrinkage Limits, Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the As-Received Soils**

| Soil ID | Atterberg limits | | | Shrinkage limit | OMC (%) | MDD (pcf) |
|---|---|---|---|---|---|---|
| | Liquid limit | Plastic limit | Plasticity index | | | |
| Cal | 43 | 18 | 25 | 25 | 17 | 100.1 |
| Texas 1 | 63 | 21 | 42 | 18 | 25 | 88.4 |
| Texas 2 | 61 | 24 | 37 | 20 | 23 | 88.1 |

Figure 1. Table 3 includes information on UCS and CBR of the as-received soils.

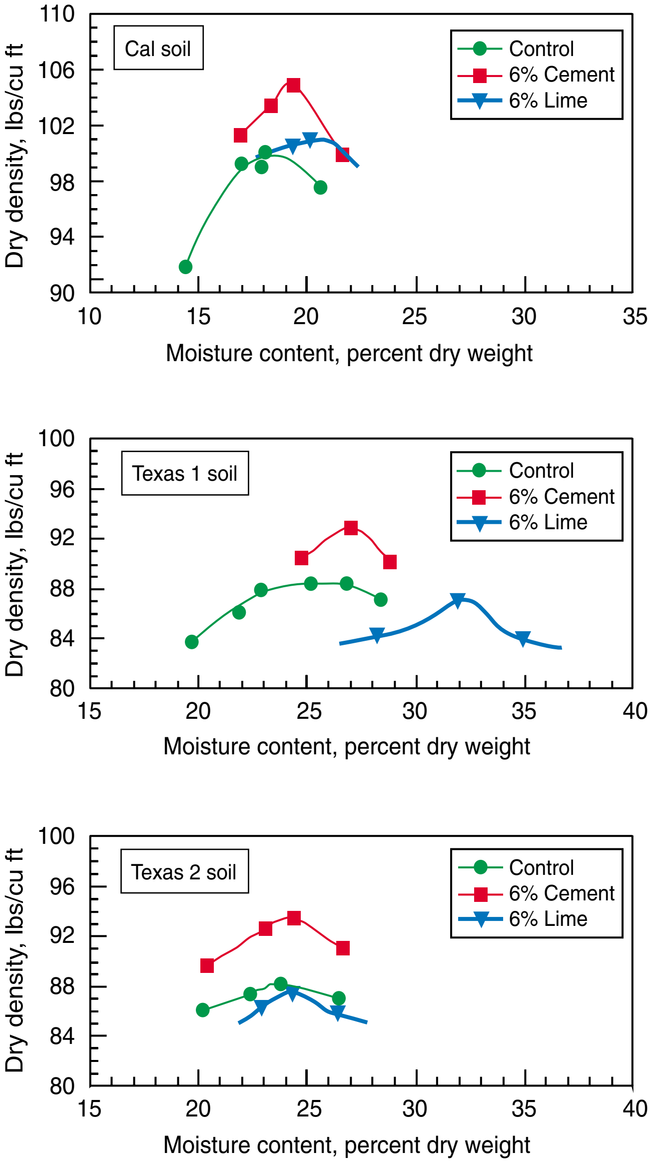


**Figure 1. Moisture-density relationship of the as-received and stabilized soils.**

**Table 3. Unconfined Compressive Strength and CBR of As-Received Soils**

| Soil ID | Strength (psi) | Unsoaked CBR (%) | Soaked CBR (%) |
|---|---|---|---|
| Cal | 60 | 8 | 5 |
| Texas 1 | 54 | 12 | 4 |
| Texas 2 | 57 | 10 | 4 |

## Plasticity Index and Shrinkage Limit

The Plasticity Index of the as-received Cal soil was 25. In the presence of 3% portland cement or lime this soil became nonplastic at 1 day. Texas 1 soil having a PI of 42, however, remained plastic at 1 day after addition of 3% cement or lime. The change in PI of Texas 1 soil with stabilizer dosage and time is shown in Table 4. The values shown in Table 4 are samples that remained plastic; 3% cement and lime up to 91 days and 6% cement at 1 day. At all other dosage levels the Texas 1 soil became nonplastic at 28 and 91 days. It is evident that for this highly plastic soil, the addition of 3% stabilizer is not enough to make it nonplastic. However, at higher dosages and prolonged curing, the soil becomes nonplastic in the presence of either stabilizer. A substantial increase in shrinkage limit is also evident in the stabilized specimens.

Texas 2 soil had a PI of 37, and 3% lime was adequate to make it nonplastic. The PIs and shrinkage limits for Texas 2 soil stabilized with portland cement are shown in Table 5. At 28 and 91 days, the portland cement-stabilized soils were nonplastic and are not included in the table.

The behavior of sulfated Cal soil stabilized with portland cement and lime differs slightly from the as-received Cal soil stabilized with the same ingredients. Only 6% and 9% stabilizer were used in stabilizing the sulfated Cal soil; their PIs and shrinkage limits are given in Table 6. Cal soil was nonplastic in the presence of lime or portland cement at 1 day. However, the lime treated sulfated Cal soil remained plastic at 1 day even with 9% lime.

## Table 4. Liquid Limit (LL), Plastic Limit (PL), Plasticity Indices (PI) and Shrinkage Limits (SL) of Stabilized Texas 1 Soil*

| Stabilizer dosage | 3% stabilizer | | | | | | | | | | | | | | | | 6% stabilizer | | | | | 9% stabilizer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specimen age (day) | 1 day | | | | 7 days | | | | 28 days | | | | 91 days | | | | 1 day | | | | 7 days | 1 day |
| | LL | PL | PI | SL | LL | PL | PI | SL | LL | PL | PI | SL | LL | PL | PI | SL | LL | PL | PI | SL | — | — |
| Cement | 53 | 37 | 16 | 27 | 49 | 37 | 12 | 31 | 49 | 40 | 9 | 32 | 50 | 41 | 9 | 29 | 47 | 40 | 7 | 30 | NP | NP |
| Lime | 48 | 38 | 10 | 35 | 54 | 43 | 11 | 34 | 53 | 44 | 9 | 35 | 54 | 48 | 6 | 36 | — | NP | NP | NP | NP | NP |

* The stabilized soils turned nonplastic at all other dosages and ages, and are excluded from the table.

## Table 5. Atterberg and Shrinkage Limits of Cement-Stabilized Texas 2 Soil*

| Stabilizer dosage | 6% stabilizer | | | | | | | | 9% stabilizer |
|---|---|---|---|---|---|---|---|---|---|
| Specimen age | 1 day | | | | 7 days | | | | 1 day |
| | LL | PL | PI | SL | LL | PL | PI | SL | — |
| Cement | 48 | 38 | 10 | 33 | 47 | 36 | 11 | 31 | NP |
| Lime | NP | | | | | | | | |

* The stabilized soils turned nonplastic at all other dosages and ages, and are excluded from the table.

## Table 6. Atterberg and Shrinkage Limits of Sulfated Cal Soil Stabilized with Various Dosages of Portland Cement and Lime

| Sulfated Cal soil | | | | Stabilized sulfated Cal Soil | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Stabilizer | Dosage (%) | 1 day | | | | 7 days |
| | | | | | | LL | PL | PI | SL | |
| LL | PL | PI | SL | Cement | 6 | NP | | | | NP |
| | | | | | 9 | | | | | |
| 43 | 16 | 27 | 20 | Lime | 6 | 48 | 30 | 18 | 33 | NP |
| | | | | | 9 | 51 | 30 | 21 | 30 | NP |

The Atterberg limits of the sulfated Cal soil (given in Table 6) are approximately the same as those of the as-received soil. However, in the presence of 6 and 9% lime, it remained plastic after 1 day. Whereas, with the same dosages of cement, it was nonplastic. This observation may be attributed to the consumption of calcium released from lime to form calcium sulfate hydrates. In such a case, calcium was not readily available for soil stabilization. A similar situation may also be applicable to the calcium released from the hydration of portland cement. As hydration of cement helps soil to agglomerate and the original Cal soil is a sandy clay, sulfated Cal soil may have became nonplastic in the presence of cement. This behavior may also have influenced the strength of the stabilized sulfated soil, which is discussed later.

## Optimum Moisture Content and Maximum Dry Density

The moisture-density plots for the three soils stabilized with 6% cement or lime are shown in Figure 1. In all three cases, portland cement-stabilized soils exhibited higher maximum dry density than that achieved with lime addition. The OMC and MDD values are also shown in Table 7. These values were determined at standard compactive effort. The average difference between the shrinkage limit and OMC for Texas 1 soil stabilized with either lime or portland cement is 4%. This suggests that, at 3% dosage level, the Texas 1 soil stabilized with either cement or lime will have similar dimensional stability. In the case of Texas 2 soil with 3% cement, the difference between average shrinkage limit and OMC is 9%, indicating a higher dimensional stability compared to Texas 1 at the same stabilizer dosage level. At all other ages and dosage levels, the soils were nonplastic. The OMC values used in compacting the sulfated Cal with portland cement and lime were respectively the same as those determined for Cal soil at 6% dosage level.

## Unconfined Compressive Strength

For all soil-cement combinations, the unconfined compressive strength increased at all ages with cement dosages. The strength gain was very pronounced with the Cal soils (PI of 25) when compacted immediately after mixing as compared to delayed compaction (see Table 8 and Figure 2). It is evident from Table 8 that Texas 1 soil with a PI of 42 also shows a similar trend. The results indicate that

**Table 7. Optimum Moisture Content at Maximum Dry Density of Three Soils Stabilized with 6% Cement and Lime and Compacted with Standard Compactive Effort (ASTM D 698)**

| Soil | Cal | | | | Texas 1 | | | | Texas 2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OMC of as-received soil | 17% | | | | 25% | | | | 23% | | | |
| Stabilized Soil (6% stabilizer) | Cement | | Lime | | Cement | | Lime | | Cement | | Lime | |
| | OMC (%) | MDD (pcf) | OMC (%) | MDD (pcf) | OMC (%) | MDD (pcf) | OMC (%) | MDD (pcf) | OMC (%) | MDD (pcf) | OMC (%) | MDD (pcf) |
| | 18 | 104.8 | 20 | 101.0 | 26 | 92.7 | 31 | 89.0 | 23 | 93.4 | 23 | 87.5 |

**Table 8. Unconfined Compressive Strength (psi) of Cal and Texas 1 Soils Stabilized with Portland Cement and Compacted at OMC Immediately and 24-Hour Delay After Mixing**

| Cement | 3% | | 6% | | 9% | |
|---|---|---|---|---|---|---|
| Compaction | Immediate | 24-hr delay | Immediate | 24-hr delay | Immediate | 24-hr delay |
| | Cal soil | | | | | |
| Age 1 day | 140 psi | 50 psi | 240 psi | 55 psi | 385 psi | 45 psi |
| 7 | 175 | 40 | 425 | 80 | 590 | 80 |
| 28 | 220 | 85 | 440 | 125 | 770 | 115 |
| 91 | 290 | 55 | 500 | 140 | 1090 | 150 |
| | Texas 1 soil | | | | | |
| Age 7 days | 90 psi | 55 psi | 190 psi | 60 psi | 250 psi | 70 psi |
| 91 | 110 | 35 | 280 | 70 | 360 | 75 |

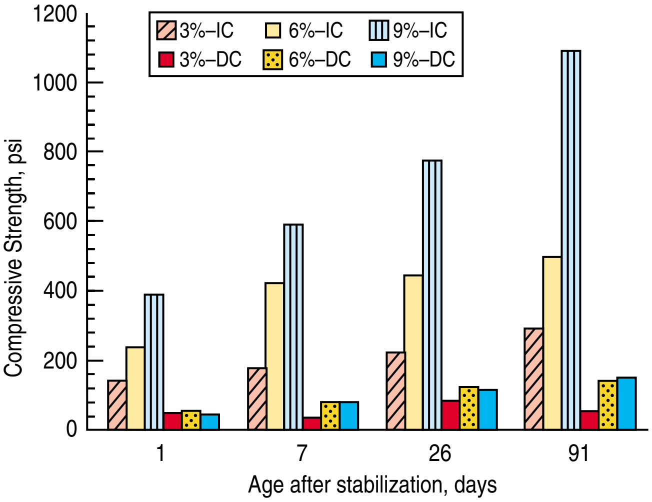


**Figure 2. Unconfined compressive strengths of Cal soil stabilized with 3%, 6%, and 9% cement.**

compaction of cement-stabilized soil immediately after mixing significantly increases the strength. A similar observation was also made by Christensen [1969] in his investigation on the modification of clay soils by cement.

The achievement of stronger material with immediate compaction can be attributed to the physicochemical phenomenon resulting from the hydration of portland cement. Within a short time after mixing portland cement with soil, the mixture becomes granular due to agglomeration, which primarily results from the hydration of the cement grains and helps form a network. If the compaction is delayed, the network is broken during compaction, leading to a weaker mass. However, compaction prior to such granulation is more efficient and provides a stable network with superior engineering properties. The granular nature of soil particles also makes the compaction inefficient. The difference between the UCS of samples compacted immediately and those compacted 24-hour after mixing increases with age and dosage. This is because the UCS of delayed compaction specimens remains approximately invariant with respect to dosage of cement and age. This suggests that the bonds that were broken during delayed compaction were never re-established during the time period of 91 days of testing. In all remaining tests, portland cement-stabilized soils were compacted immediately after mixing and lime-stabilized soils were compacted 24 hours after mixing.

For comparison, the performances of all three soils stabilized separately with portland cement and lime and compacted at OMC using standard compactive effort are shown in Table 9. These results are also shown in Figure 3. The data clearly indicates the superiority of portland cement addition for Cal soil with moderate plasticity. For the high plasticity Texas 1 and 2 soils, the addition of 3% lime provides only a marginally better strength than 3% cement addition. Again, that trend changes drastically at 6% and 9% dosages, where portland cement-stabilized

**Table 9. Unconfined Compressive Strength of Three Soils Stabilized with Three Dosages of Portland Cement and Lime and Compacted at Respective OMC**

| Dosage | 3% | | 6% | | 9% | |
|---|---|---|---|---|---|---|
| Stabilizer | Cement | Lime | Cement | Lime | Cement | Lime |
| | Cal soil | | | | | |
| Age 1 day | 140 psi | 45 psi | 240 psi | 75 psi | 385 psi | 55 psi |
| 7 | 175 | 95 | 425 | 120 | 590 | 95 |
| 28 | 220 | 150 | 440 | 175 | 770 | 190 |
| 91 | 290 | 230 | 500 | 260 | 1090 | 515 |
| | Texas 1 soil | | | | | |
| Age 7 days | 80 psi | 50 psi | 160 psi | 58 psi | 210 psi | 60 psi |
| 7 | 90 | 115 | 190 | 110 | 250 | 90 |
| 28 | 110 | 150 | 240 | 200 | 330 | 170 |
| 91 | 110 | 150 | 280 | 320 | 360 | 320 |
| | Texas 2 soil | | | | | |
| Age 7 days | 100 psi | 60 psi | 180 psi | 60 psi | 250 psi | 65 psi |
| 7 | 110 | 95 | 200 | 75 | 300 | 100 |
| 28 | 110 | 120 | 280 | 135 | 320 | 130 |
| 91 | 110 | 135 | 310 | 180 | 365 | 190 |

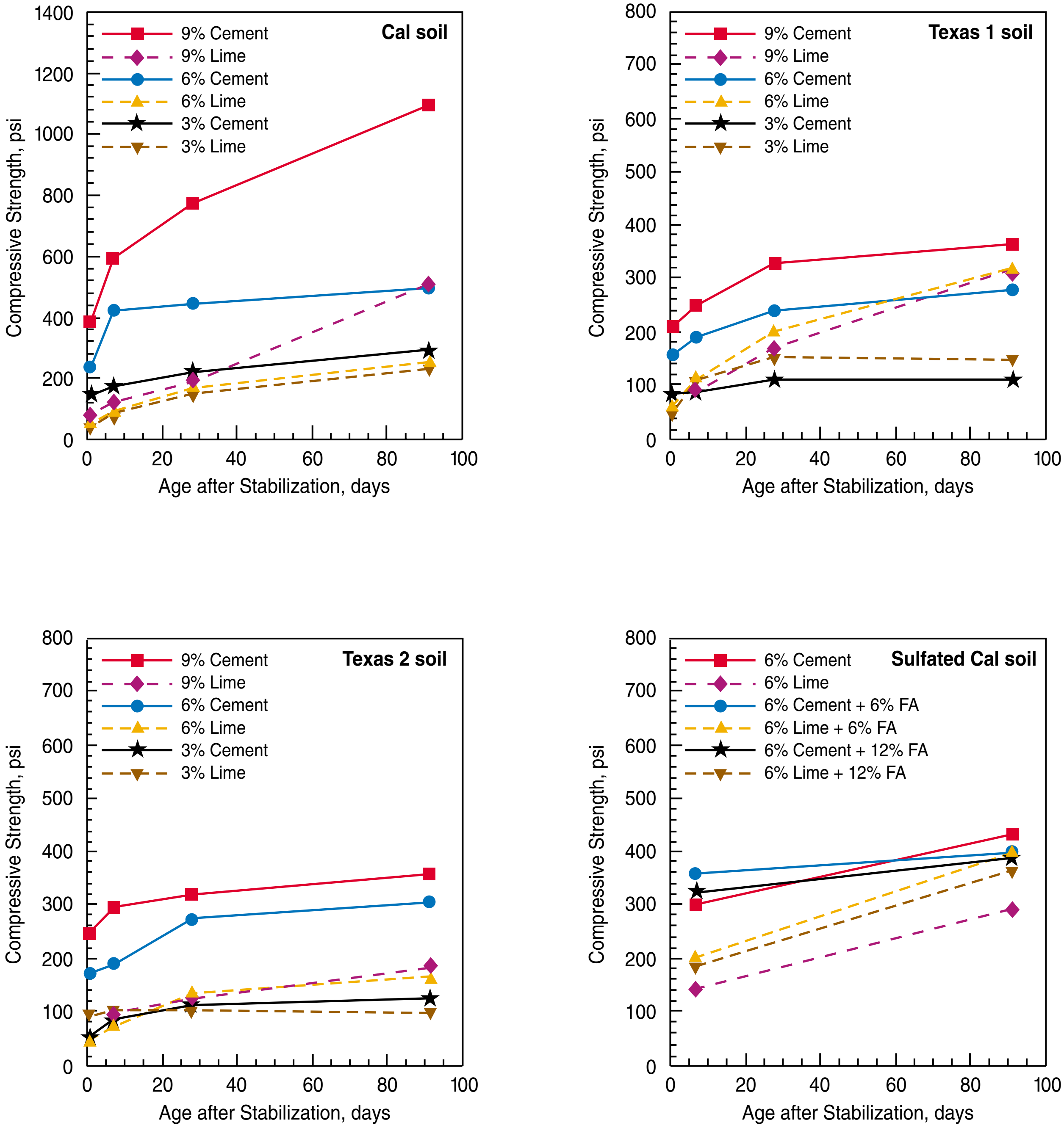


**Figure 3. Unconfined compressive strengths of soils stabilized with various dosages of portland cement and lime. (Note the expanded ordinate for the stabilized Cal soil.)**

specimens exhibit significantly better UCS values. This suggests that for clay soils with high plasticity, portland cement is about equivalent to lime at low dosages (3%). However, at higher dosages of 6% to 9%, cement addition produces a much stronger stabilized product.

It is also noticeable that the cement-stabilized soils exhibit higher initial UCS values than those stabilized with lime. Cement-stabilized soils (with an exception to Texas 1 and 2 at 3% dosage) also have a higher strength at 91 days. However, the rate of increase in UCS between 1 and 91 days for lime-stabilized soil suggests that the strength gain of lime-stabilized soils is very much dependent on the pozzolanic reactions.

UCS values of sulfated Cal soils stabilized with portland cement and lime with and without the combination with 6% Class F fly ash are shown in Tables 10 and 10a. It

**Table 10. UCS of Sulfated Cal Soil Stabilized with Cement and Lime**

| Dosage | 6% | | 9% | |
|---|---|---|---|---|
| Stabilizer | Cement | Lime | Cement | Lime |
| Age 7 days | 305 psi | 145 psi | 455 psi | 170 psi |
| 91 | 435 | 300 | 540 | 390 |

**Table 10a. UCS of Sulfated Cal Soil Stabilized with Cement and Lime in Combination with Two Dosages of Class F Fly Ash**

| Stabilizer | Cement + Fly Ash | | Lime + Fly Ash | |
|---|---|---|---|---|
| Dosage, % | 6 + 6 | 6 + 12 | 6 + 6 | 6 + 12 |
| Age 7 days | 360 psi | 325 psi | 205 psi | 185 psi |
| 91 | 400 | 390 | 400 | 370 |

appears that cement-stabilized sulfated Cal soils are weaker than Cal soil stabilized with the same amount of cement. Lime-stabilized sulfated Cal soil, on the other hand, exhibits a slight increase in UCS at 7 days compared to Cal soil containing the same amount of lime. However, there is no clear difference in behavior for lime-stabilized sulfated Cal soil at 91 days. The cement-stabilized sulfated Cal soils are obviously stronger than lime-stabilized soil, as observed earlier for unadulterated Cal soil. In order to make a comparison, strengths of sulfated Cal soils are also shown in Figure 3.

When Class F fly ash is added to cement or lime at two dosages, 6 and 12% by dry mass of soil, for portland cement, the UCS values remained approximately invariant with and without the addition of fly ash. For lime, the UCS values with and without fly ash are similar although slightly higher values are apparent in the presence of fly ash. The lime-fly ash combination may have prompted pozzolanic reactions.

It is seen that with identical additions of lime or cement, Cal soil (PI = 25) produces higher strength at all ages and additions than both the Texas 1 and 2 soils with PIs of 42 and 37, respectively. Furthermore, within each soil, the addition of cement produces higher strengths than lime. With the three types of soils examined in the present investigation, the cement addition to soils with immediate compaction produced equal or stronger soils relative to lime stabilization, with strength improvement evident from the early age.

## California Bearing Ratio

The CBR values for both unsoaked and soaked stabilized specimens were measured at 91 days. The results for all three soils are given in Table 11 and the typical penetration vs. stress plots are shown in Figure 4 for two of the soils.

The portland cement-stabilized Cal soils show significantly higher CBR values than the lime-stabilized Cal soils at both 6 and 9% dosages. In fact, the soaked CBR values are even higher than the unsoaked values for the cement-stabilized Cal soil. On the other hand, the unsoaked and soaked values for the lime-stabilized Cal soils are almost unchanged.

The cement-stabilized Cal and Texas 1 soils showed an increase in the soaked CBR value, while that of all lime-stabilized soils (with an exception of Texas 1 soil with 9% lime) and only one cement-stabilized Texas 2 was reduced. This increase in soaked CBR values may be attributed to a

**Table 11. California Bearing Ratio (CBR) at 91 Days for Soils Stabilized with Portland Cement and Lime**

| Soil ID | Stabilizer dosage (%) | Stabilizer | Unsoaked CBR (%) | Soaked CBR (%) | Soaked moisture (%) | Moisture at compaction (%) |
|---|---|---|---|---|---|---|
| Cal | 6 | Cement | 240 | 370 | 19 | 18 |
| | | Lime | 130 | 130 | 28 | 20 |
| | 9 | Cement | 290 | 460 | 23 | 18 |
| | | Lime | 150 | 140 | 26 | 20 |
| Texas 1 | 6 | Cement | 190 | 200 | 24 | 26 |
| | | Lime | 140 | 120 | 28 | 31 |
| | 9 | Cement | 190 | 260 | 23 | 26 |
| | | Lime | 140 | 160 | 25 | 31 |
| Texas 2 | 6 | Cement | 130 | 100 | 23 | 23 |
| | | Lime | 110 | 100 | 30 | 23 |
| | 9 | Cement | 220 | 190 | 23 | 23 |
| | | Lime | 160 | 160 | 27 | 23 |

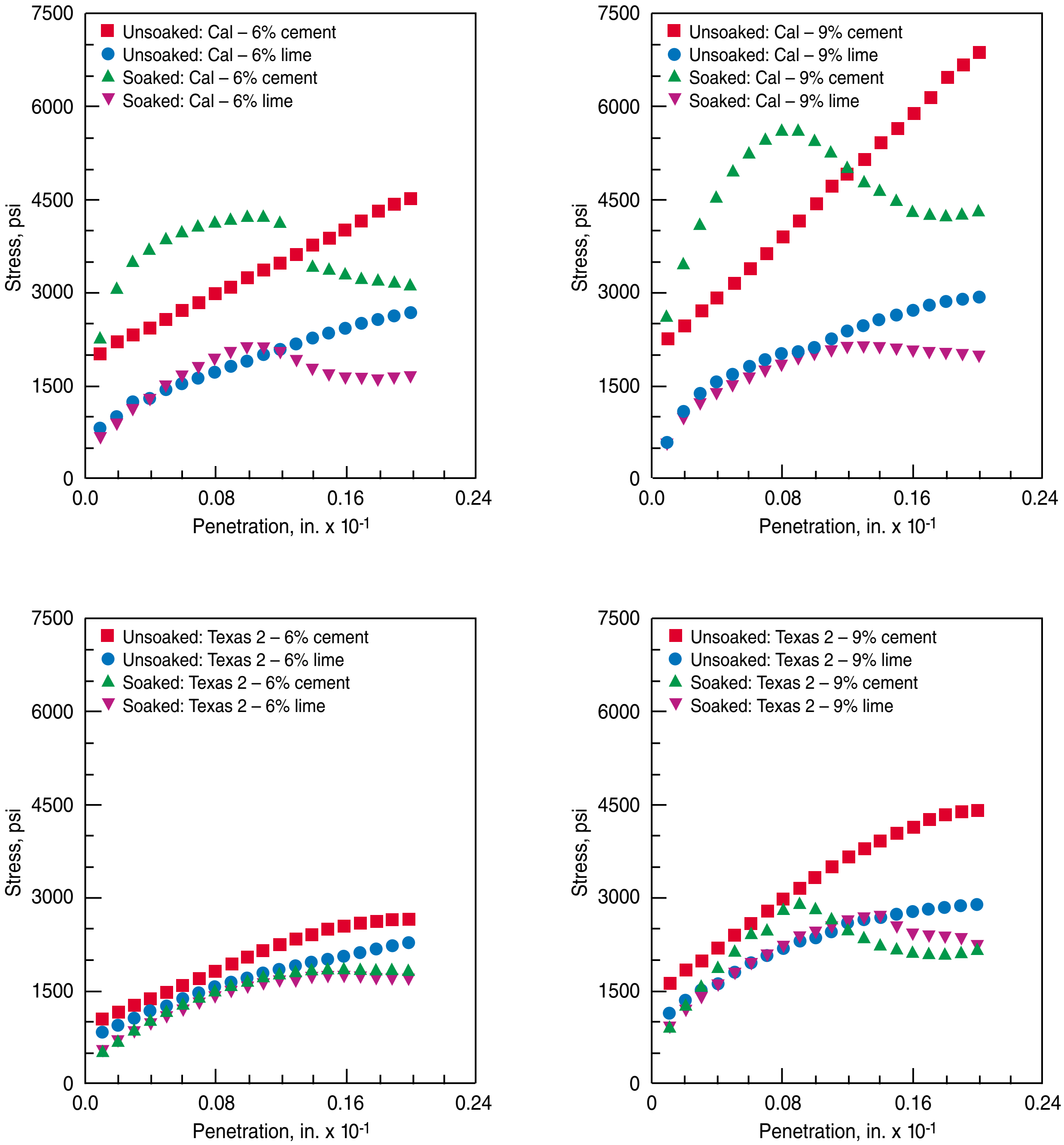


**Figure 4. Penetration vs. stress plots from the measurements of California Bearing Ratio of Cal and Texas 2 soils stabilized with 6 and 9% portland cement and lime.**

renewed hydration of the core of the relatively larger cement grains, which may take more than 91 days. An increase in cement content from 6% to 9% resulted in significant increase in CBR values of Cal and Texas 2 soils. However, the increase with lime content is small in all cases. The invariance in the unsoaked CBR values with the stabilizer content in Texas 1 soil may stem from its high plasticity.

The moisture contents (column six in Table 11) measured after performing soaked CBR show lower water absorption by cement-stabilized soils. A comparison between the moisture contents of the soaked samples and the OMC of the compacted specimens suggests that cement-stabilized soils, in most cases, did not absorb water. On the other hand, lime-stabilized Cal and Texas 2 soils absorbed as much as 8% and 7% additional water, respectively. The loss of water from stabilized Texas 1 specimens may be due to high initial moisture content. This may be a reason for the superior performance observed for the cement-stabilized soils in wet-dry and vacuum saturation tests (discussed in the forthcoming sections).

It is apparent from Figure 4 that unsoaked cement-stabilized Cal soil specimens do not deform until the load is high enough; a behavior generally observed for mortar and concrete. However, soaked specimens and lime-stabilized Cal soils exhibit behavior that is typical for untreated soils (see Figure 4 for stabilized Texas 2 soils). The profiles of the stress as a function of penetration for the Texas 1 soil stabilized with portland cement and lime are similar to that of the stabilized Texas 2 soils. Even for the two highly plastic soils, Texas 1 and Texas 2, cement stabilization, in general, has resulted in higher CBR values (both unsoaked and soaked) than those stabilized with lime. This behavior was, however, much more pronounced for Cal soil. Consequently, it is apparent that cement-stabilized soils are mechanically stronger and can sustain higher bearing loads than lime-stabilized soils.

It is noticeable that an increase of about 150% in soaked CBR values compared to unsoaked for cement-stabilized Cal soil is not present in the case of the two highly plastic Texas soils. The unsoaked CBR values for all the lime-stabilized soils presented in Table 11 range between 110 and 160%. On the other hand, for Cal with a PI of 25, cement-stabilized soils have unsoaked CBR values of 240% and 290%, and those for Texas 1 and 2 range between 130% and 220%. This suggests that cement stabilization significantly improves the bearing ratio of moderate PI soil. For high PI soils, cement-stabilized soils also have higher bearing ratios than the lime-stabilized ones. The dosage of lime used in stabilization appears to have little influence on the CBR results for all three soils used.

The CBR values for sulfated Cal soil stabilized with 6% portland cement and lime are given in Table 12. These values are comparable to those observed for Cal soil, as presented in Table 11. Following the measurements of soaked CBR, the stabilized sulfated Cal specimens, while in the molds, were resoaked in water for 4 weeks without removing the surcharge (weighing 10 lbs [4.5 kg]). During this period, calipers were used to monitor any change in sample volume. No increase in sample height was observed for the cement-stabilized soil. However, an increase of 0.35% in height was registered in the caliper for the lime-stabilized sulfated Cal soil. The moisture content of these specimens was measured at the end of soaking and is reported in column 4 of Table 12.

The amount of water absorbed during this extended soaking period appears to be slightly higher for the sulfated Cal Soil stabilized with portland cement. The reverse was true for all other soils (shown in Table 11) after 96 hours of soaking. However, as observed earlier, the soaked CBR value for cement-stabilized soil is higher than the unsoaked CBR value, and those for the lime-stabilized soil remained virtually unchanged. It is anticipated that the reduced water content of lime-stabilized sulfated Cal soil stems from the loss of free water due to conversion to hydrates that are responsible for causing expansion.

## Vacuum Saturation

The unconfined compressive strength (UCS) values for Cal soil stabilized with portland cement and lime are given in Table 13 and illustrated in Figure 5. It is obvious that a significant loss of unconfined compressive strength was experienced by most of the samples in the vacuum saturation test. The unconfined compressive strength of Cal soil stabilized with portland cement was significantly higher than those of the lime-stabilized soils before vacuum saturation (see Figure 5 and column 4 of Table 13). A similar trend is also apparent in the UCS measured following the vacuum saturation test.

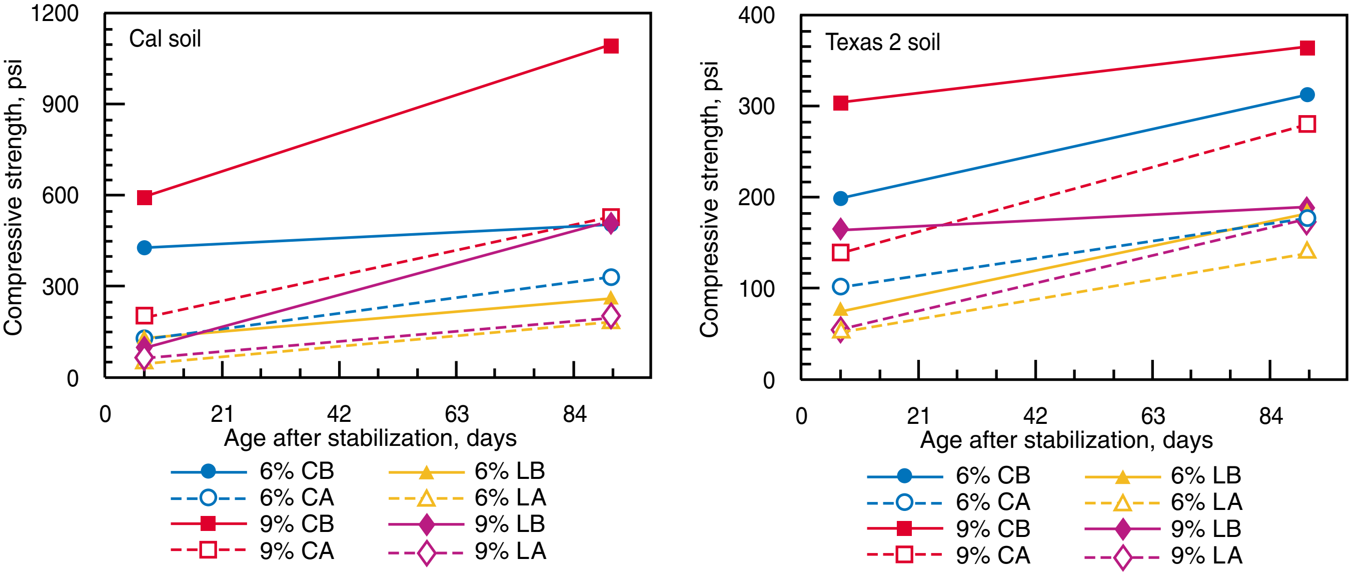
Vacuum saturation itself is a severe test, and removing the water during evacuation step and then forcing water into the specimen to saturate it can do significant damage. The UCS measured after vacuum saturation with water is influenced significantly by the pore structure and the mechanical strength (tensile and compressive strengths) of the sample. Pore walls may collapse during rapid removal and subsequent infiltration of water. Therefore, how all these parameters individually affect the results is not discernable. Both cement- and lime-stabilized soils are dynamic, as the microstructural changes continue through the testing period of 7 and 91 days. Consequently, the combination of the strength and pore structure at 7-day is expected to be different from that at 91-day. This combination may have resulted in significant strength loss at 7-days but not at 91-days. However, the following inferences can

**Table 12. California Bearing Ratio (CBR) at 91 Days for Sulfated Cal Soil Stabilized with Portland Cement and Lime**

| Stabilizer (6%) | Unsoaked CBR (%) | Soaked CBR (%) | Soaked moisture content (%) | Swelling after 4 weeks of soaking (%) |
|---|---|---|---|---|
| Cement | 230 | 280 | 28 | 0 |
| Lime | 160 | 150 | 22 | 0.35 |

**Table 13. Unconfined Compressive Strength of Stabilized Cal Soil Before and After Vacuum Saturation**

| Stabilizer | Age (day) | Dosage (%) | UCS before vacuum saturation (psi) | UCS after vacuum saturation (psi) |
|---|---|---|---|---|
| Cement | 7 | 6 | 425 | 125 |
| | | 9 | 590 | 200 |
| | 91 | 6 | 500 | 325 |
| | | 9 | 1090 | 525 |
| Lime | 7 | 6 | 120 | 50 |
| | | 9 | 95 | 60 |
| | 91 | 6 | 260 | 175 |
| | | 9 | 515 | 190 |



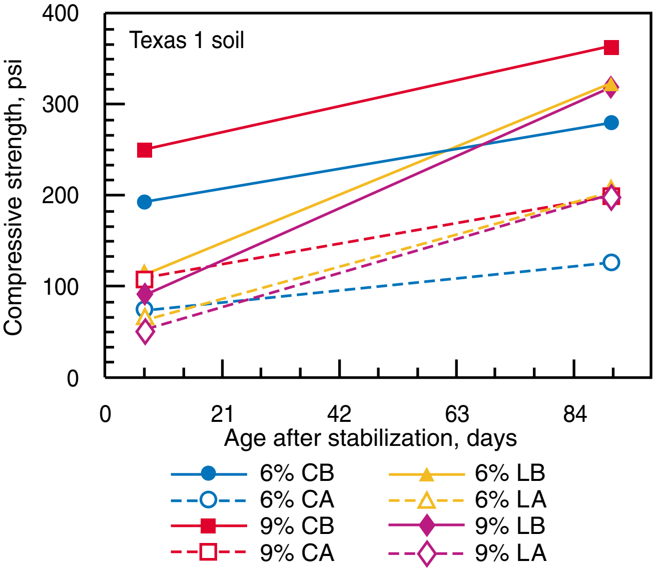


**Figure 5. Compressive strength of stabilized soils before and after vacuum saturation. (Note the expanded ordinate for Cal soil).**

- **CB and LA = before vacuum saturation**
- **CA and LA = after vacuum saturation**
- **Broken lines connect post vacuum saturation strength data**

be drawn from the post vacuum saturation UCS data given in Table 13: (i) portland cement-stabilized Cal soils exhibit significantly higher UCS than the lime-stabilized Cal soil and (ii) cement-stabilized soils show both dosage- and time-dependent improvement in the UCS, while lime-stabilized soils mostly show a time-dependent increase and only a limited influence from the dosage.

The minimal influence of lime content especially at early ages, and to some extent at later ages, stems from the fact that these engineering properties depend on the mechanical strength of the material. The formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) in both cement and lime-stabilized soil contributes to strength development. In the case of portland cement, these hydrates are produced from both hydration and pozzolanic reactions, and may continue to form for a long time. However, in the case of lime, these hydrates are formed from pozzolanic reaction alone. As this reaction is a relatively slower process compared to hydration of cement, the dependence on dosage is not apparent at early ages. Furthermore, often this dependence is not very pronounced at later ages because pozzolanic reaction is a through solution process (presence of free water is needed for this reaction) and the low solubility of calcium hydroxide (approximately 1.2 g per liter) controls the amount of calcium available in the pore solution.

The UCS values for Texas 1 and Texas 2 soils are given in Table 14 and also plotted in Figure 5. Although these soils have a high PI, the data presented show a trend similar to that discussed above for the Cal soil. The post saturation UCS values achieved for all three lime-stabilized soils are very similar. While, those for cement-stabilized soils relate to the soil plasticity, the strongest being the cement-stabilized Cal soil. Even with these highly plastic soils, the post saturation UCS values for portland cement-stabilized soils are in most cases superior to those for lime-stabilized soils. This suggests that regardless of the soil plasticity range used in this investigation, the strength of the cement-stabilized soils after vacuum saturation is clearly superior to those of the lime-stabilized soils. Consequently, portland cement-stabilized soils are expected to be more durable than lime-stabilized soils in freeze-thaw conditions.

## Wet-Dry Test

The durability of soil upon repeated wetting and drying primarily depends on the pore structure and tensile strength of the material. Other parameters, such as interparticle friction and cohesion may also influence the material loss in this testing. Similar to vacuum saturation test, as water moves in and out of pore network of the specimen during wetting and dying, the pore walls experience capillary pressure and may collapse. As a result, in the present investigation, stabilized soils suffered from small to significant material loss during the wet-dry testing, and in many cases, disintegrated prior to completion of 12 cycles, as specified in the test procedure.

The performance of stabilized Cal soil compacted at OMC using standard compactive effort is shown in Figure 6. All Cal soil specimens stabilized with either cement or lime lasted 12 cycles of wetting and drying. The data clearly indicates that portland cement-stabilized soil exhibits superior performance to that compacted with hydrated lime.

Stabilized Texas 1 soil performed poorly as compared to stabilized Cal soil, and all of its specimens failed prior to reaching the 12th cycle. This inferior performance is

**Table 14. Unconfined Compressive Strength of Stabilized Texas 1 and Texas 2 Soils Before and After Vacuum Saturation**

| Soil | Stabilizer | Age (day) | Dosage (%) | UCS before vacuum saturation (psi) | UCS after vacuum saturation (psi) |
|---|---|---|---|---|---|
| Texas 1 | Cement | 7 | 6 | 190 | 70 |
| | | | 9 | 250 | 110 |
| | | 91 | 6 | 275 | 125 |
| | | | 9 | 360 | 200 |
| | Lime | 7 | 6 | 110 | 60 |
| | | | 9 | 90 | 50 |
| | | 91 | 6 | 320 | 200 |
| | | | 9 | 348 | 205 |
| Texas 2 | Cement | 7 | 6 | 200 | 100 |
| | | | 9 | 300 | 140 |
| | | 91 | 6 | 310 | 175 |
| | | | 9 | 365 | 280 |
| | Lime | 7 | 6 | 75 | 50 |
| | | | 9 | 100 | 55 |
| | | 91 | 6 | 180 | 140 |
| | | | 9 | 190 | 180 |

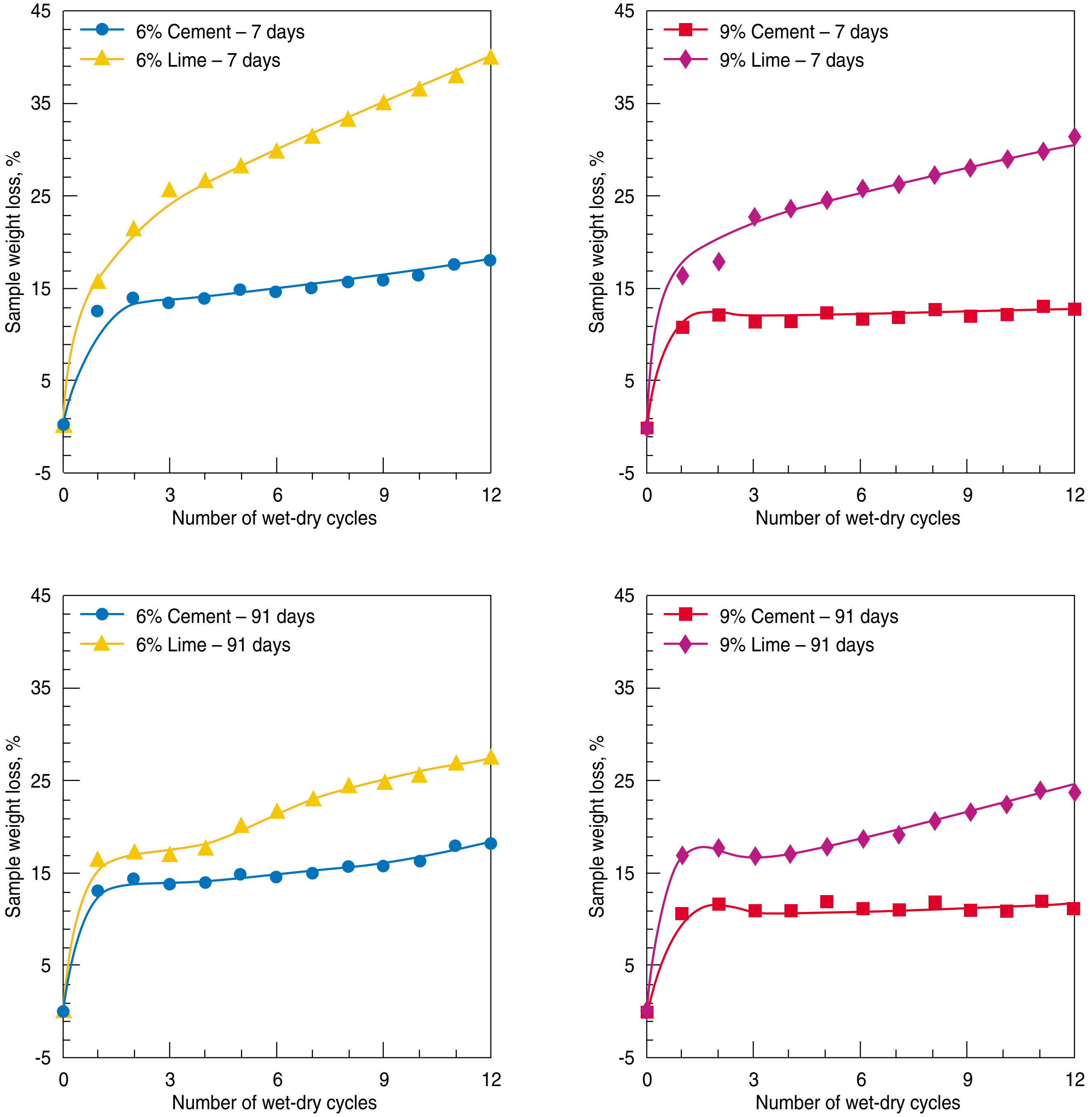


**Figure 6. Weight loss in wet-dry durability testing of Cal soil stabilized with 6 and 9% portland cement and lime.**

observed with both the stabilizers as shown in Table 15. Comparing with Cal soil, it is apparent that the high PI soil suffers more severely in the wetting and drying situations. From the data shown in Table 15 it is evident that increasing the stabilizer dosage minimizes the degradation, and this is more applicable to portland cement than lime. By increasing the dosage from 6% to 9%, the number of cycles to reach failure increased by seven for cement as compared to two to three for lime. While at the 6% level both the stabilizers exhibit similar performances, at the 9% level, superiority of portland cement over lime addition is discernable.

**Table 15. Performance of Portland Cement and Lime-Stabilized Texas 1 and Texas 2 Soils in Wet-Dry Test**

| Soil | Stabilizer | Testing age (day) | Stabilizer dosage (%) | Percent weight loss at the end of failing cycle | End of the cycle when sample failed |
|---|---|---|---|---|---|
| Texas 1 | Cement | 7 | 6 | 52 | 3 |
| | | | 9 | 55 | 10 |
| | | 91 | 6 | 45 | 4 |
| | | | 9 | 53 | 11 |
| | Lime | 7 | 6 | 58 | 4 |
| | | | 9 | 46 | 7 |
| | | 91 | 6 | 34 | 3 |
| | | | 9 | 33 | 5 |
| Texas 2 | Cement | 7 | 6 | 36 | 2 |
| | | | 9 | 53 | 10 |
| | | 91 | 6 | 40 | 3 |
| | | | 9 | 51 | 12 |
| | Lime | 7 | 6 | 57 | 6 |
| | | | 9 | 53 | 10 |
| | | 91 | 6 | 49 | 5 |
| | | | 9 | 55 | 10 |

The data presented for Texas 2 soil stabilized with portland cement and lime show a similar performance as described for Texas 1 soil. This most likely stems from the similarity in plasticity of these two soils. It is noticeable in Table 15 that there is little difference in performance between 7 and 91 days, regardless of the stabilizer used. This suggests that for high PI soil, contribution of the stabilizer dosage is more significant than age. However, the unconfined compressive strength, before and after vacuum saturation (discussed earlier), improved with time. This may be due to the physical parameters that dominate the performance in these tests. In the compressive strength test, specimens are under compressive load, although during vacuum saturation, pore walls of the specimens experience some tensile force. In the wet-dry test, tensile force is applied exclusively on the pore walls as water moves in and out of the pore network.

Both Texas soils, stabilized with 9% cement, distinctly performed better than the corresponding lime-stabilized soils. As mentioned above, a similar trend was also observed in the case of Cal soil. The observation of relatively better performance for portland cement than lime suggests that although both supply $Ca^{2+}$ ions, the ingredient necessary for stabilization, the physicochemical processes involved are not entirely similar, and the wet-dry durability is, more than likely, dictated by this difference.

## Hydraulic Conductivity of Stabilized Soils and Leaching

The hydraulic conductivity measurements were performed on three soils stabilized separately with equal dosages of cement and lime. During the measurements, effluent liquid was collected periodically for chemical analysis. All three soils were analyzed for pH and water-soluble calcium, sodium, potassium, and sulfate ions. These data are shown in Table 16. The concentrations of these ions present in the influent water are also included in the table. These soils were compacted at OMC and the measurements started when the specimens were 35 days old.

**Table 16. Concentration of Water-Soluble Ions from the Three as-Received Soils and the Influent Water Used for Hydraulic Conductivity Measurements**

| | Concentration (mg/L) | | | | | |
|---|---|---|---|---|---|---|
| Soil | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $So_4^{2-}$ | pH |
| Cal | 280 | 2 | 40 | 20 | 115 | 8.0 |
| Texas 1 | 20 | 1 | 210 | 10 | 170 | 7.5 |
| Texas 2 | 10 | 3 | 320 | 10 | 470 | 7.9 |
| Influent | 10 | 1 | 30 | — | — | 6.5 |

The hydraulic conductivity plots for the stabilized Cal soils, shown in Figure 7, clearly indicate that the permeability of cement-stabilized Cal soils is one to two orders of magnitude lower than those of the lime-stabilized Cal soils. Over a particular length of time, due to lower permeability, the effluent volume from the cement-stabilized Cal soil is significantly less than that from the lime-stabilized Cal soil. The closeness in hydraulic conductivity values at both cement dosages suggests that the tortuosity or the pore connectivity developed in the stabilized system is similar. The hydraulic conductivity values for the lime-stabilized Cal soil are different initially, but became similar during the test. After about forty days, the pozzolanic reaction in the 6% lime-stabilized sample may have been adequate enough to make the permeability similar to that achieved with 9% lime.

Stocker [1975] reported that only 0.5% $Ca(OH)_2$ is sufficient to produce a unit layer of reaction product and eliminate swelling. Subsequently, the process becomes diffusion dependent, as $Ca^{2+}$ ions have to diffuse through the reaction product. As the solubility of calcium hydroxide, either formed due to the hydration of portland cement or supplied by the hydrated lime, is low (1.2 g per liter of water), Stocker's observation suggests that by increasing the stabilizer dosage, the gain in the long-term properties may not be significantly different. Figure 7 shows that at later ages, the hydraulic conductivities are similar at both dosage levels. In Cal soil, a sandy clay, the cementing action from portland cement hydration resulted in significant reduction in the hydraulic conductivity compared to those achieved by lime addition.

The hydraulic conductivity results of Texas 1 soil stabilized with 3%, 6%, and 9% cement or lime are shown in Figure 8. The behavior observed here is different from that observed for the stabilized Cal soil. At the 3% dosage level, the hydraulic conductivities of the cement- or lime-stabilized soils are of the same magnitude and relatively high, although cement-stabilized soil is slightly less permeable. At the 6% level, both the cement- and lime-stabilized soils start with a similar permeability, and a time-dependent reduction in permeability is exhibited by the lime-stabilized soil. At the 9% level, on the other hand, the cement-stabilized soil has a significantly lower permeability. This behavior indicates that at higher cement content, Texas 1 soil performs similarly or better than the same dosage of lime. For a highly plastic clay, a higher amount of calcium is necessary for stabilization. It is also known that the amount of $Ca(OH)_2$ generated from hydration of portland cement is typically 31% of the weight of cement. As a result, 3% or 6% cement may not have been adequate to reduce the permeability. However, with an increased cement content, that requirement is satisfied. Furthermore, an additional benefit was provided by the network formation due to the hydration of the cement particles.

The hydraulic conductivity results, shown in Figure 9, for stabilized Texas 2 soil indicate some similarities to those

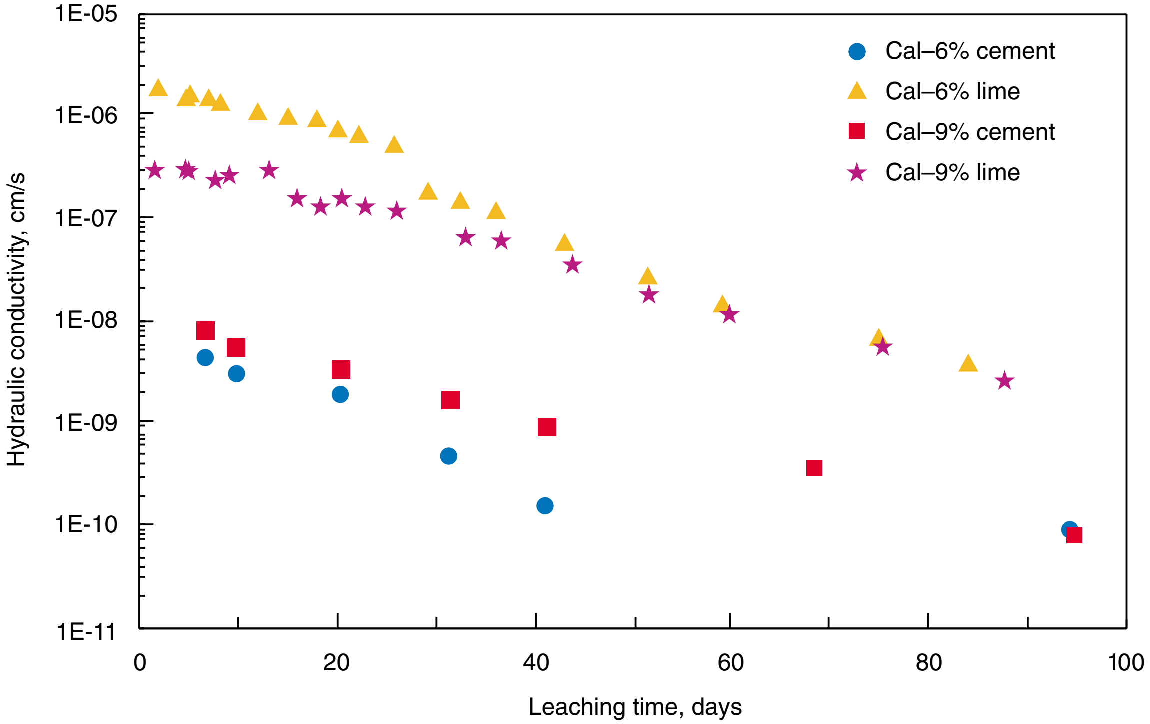


**Figure 7. Change in hydraulic conductivity with time for Cal soil stabilized with 6% and 9% portland cement and lime.**

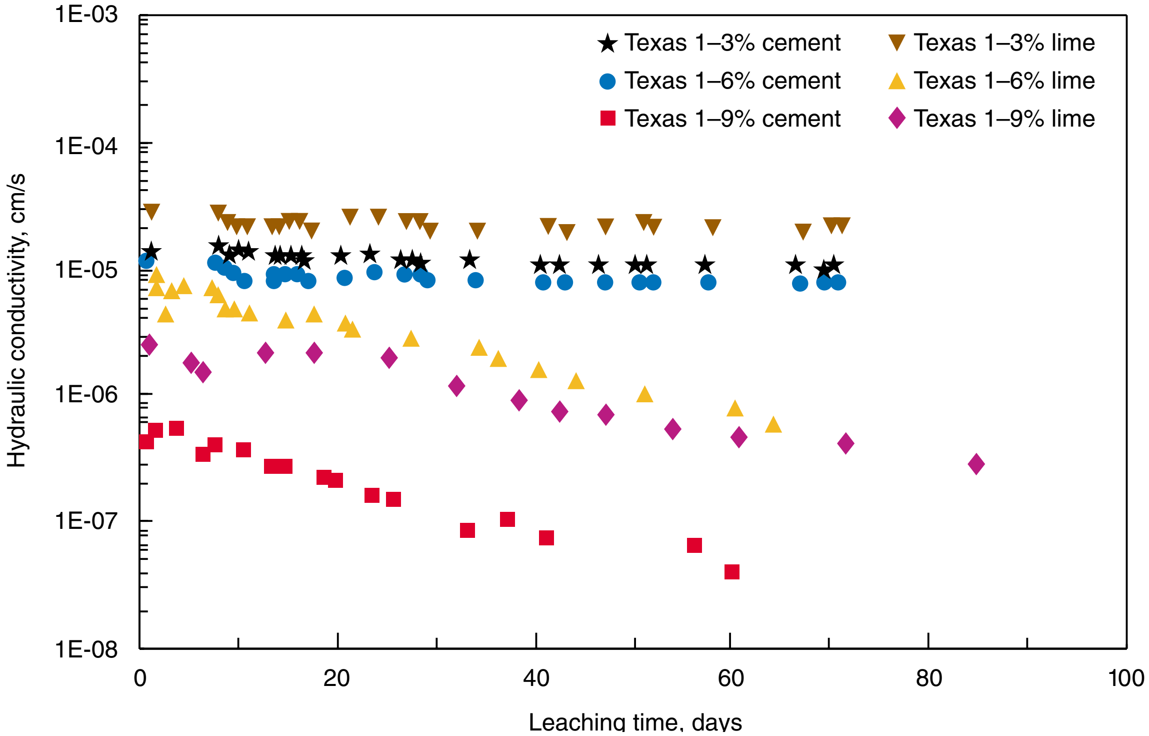


**Figure 8. Change in hydraulic conductivity with time for Texas 1 soil stabilized with 3%, 6%, and 9% portland cement and lime.**

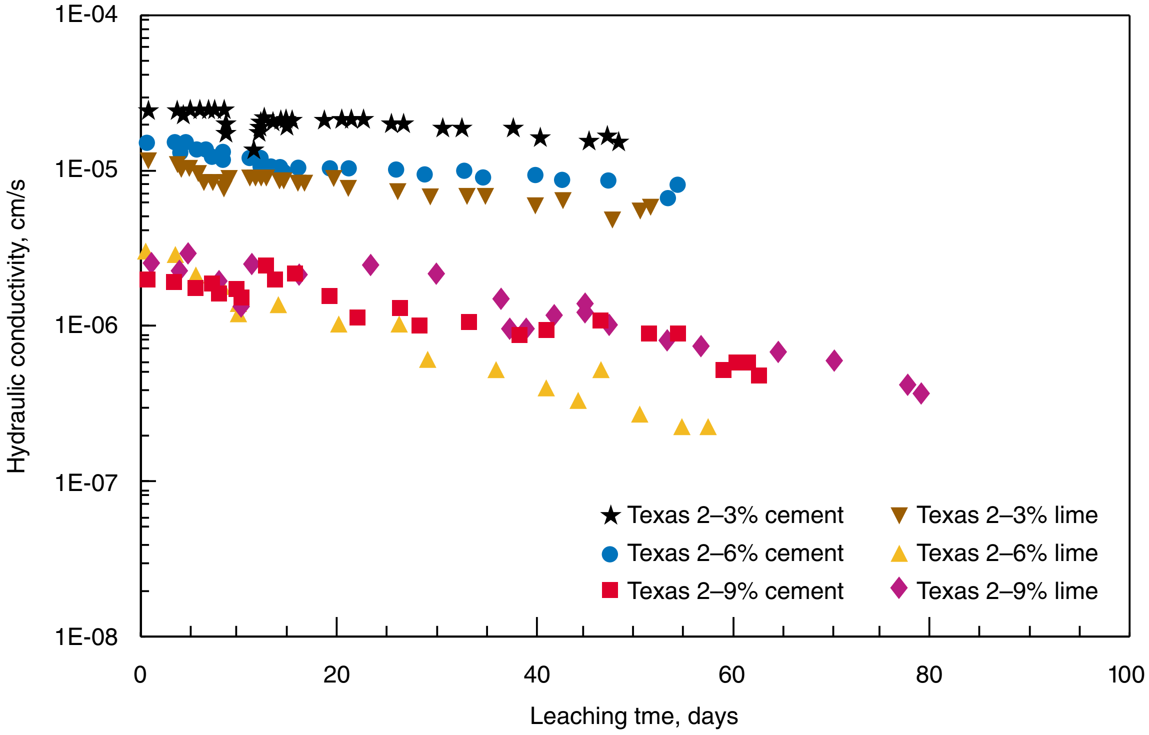


**Figure 9. Change in hydraulic conductivity with time for Texas 2 soil stabilized with 3%, 6%, and 9% portland cement and lime.**

observed for the stabilized Texas 1 soil. The hydraulic conductivities of the soil stabilized with either 3% portland cement or lime is of the same order of magnitude, and at 6% addition, lime-stabilized soil is less permeable than cement-stabilized soil. This behavior changes at a higher dosage level, and at the 9% level, the hydraulic conductivity values are essentially the same for both portland cement and lime.

The changes in the concentrations of $Ca^{2+}$ ions in the effluent during the course of experiments are shown in Figures 10, 11, and 12 for the three soils. The concentration of $Ca^{2+}$ ions in the effluent liquid from all lime-stabilized soils remained higher than that from cement-stabilized soils throughout the testing period. Furthermore, at a higher lime dosage, the $Ca^{2+}$ ion concentration in the effluent is elevated and the level is maintained over a longer period. On the other hand, the $Ca^{+}$ ion concentration in the effluent from cement-stabilized soils does not show much of a dose dependency. Consequently, the cumulative loss of calcium from the lime-stabilized soils will be higher due to higher permeability.

The concentration of $Na^{+}$ and $K^{+}$ ions in all cases, with the exception of Cal soil, remained approximately 50 mg/L or less throughout the testing period. The higher $Na^{+}$ ion concentration in leachates from stabilized Cal soil (shown Figure 10) may be attributed to higher $Na^{+}$ ion concentration (approximately 300 mg/L) in the as-received soil. The pH of the leachates collected from the stabilized soils during testing was approximately 12 in all cases, and no particular trend with testing time was observed. The higher calcium concentration in leachate, particularly from the lime-stabilized soils suggests that due to low solubility, a portion of the hydrated lime used for stabilization remains unreacted and washes out with the effluent liquid.

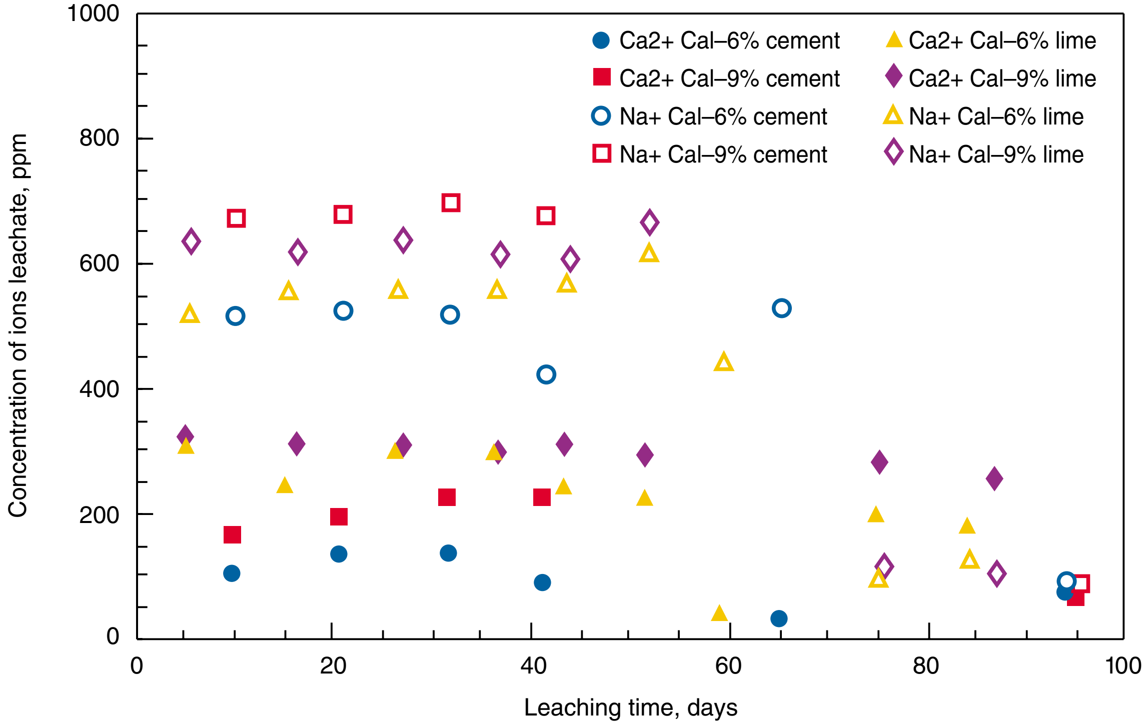


**Figure 10. Concentration of calcium and sodium ions in leachates collected during measurements from Cal soil stabilized with 6% and 9% portland cement and lime.**

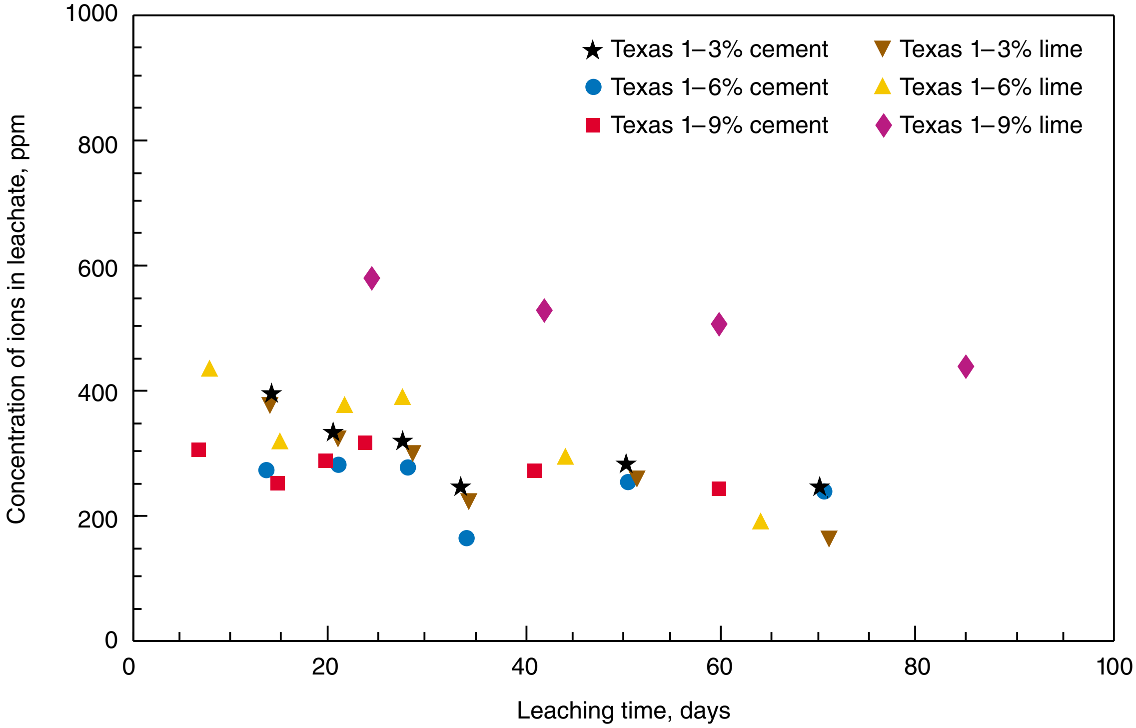


**Figure 11. Concentration of calcium ions in leachates collected during measurements from Texas 1 soil stabilized with 3%, 6%, and 9% portland cement and lime.**

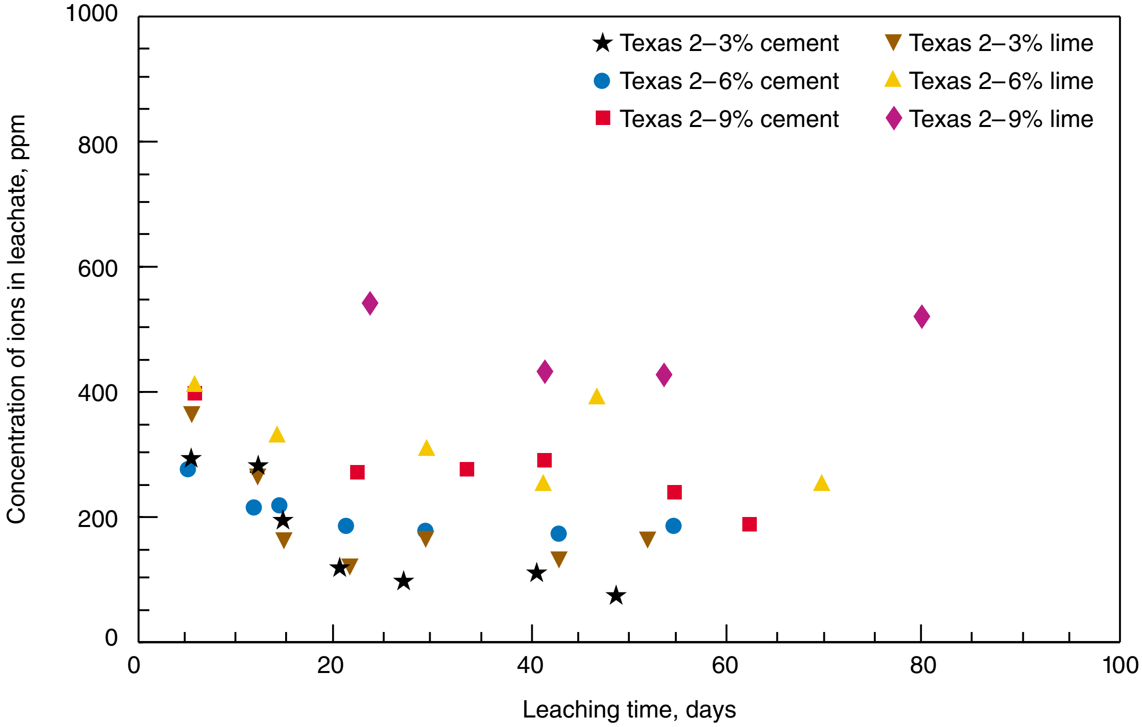


**Figure 12. Concentration of various calcium ions in leachates collected during measurements from Texas 2 soil stabilized with 3%, 6%, and 9% portland cement and lime.**

## CONCLUSIONS

This investigation was performed to evaluate the performance of portland cement and hydrated lime in stabilization and in improving engineering properties of several soils. Three soils with PI values ranging from 25 to 42, obtained from California and Texas, were used. In order to make a one-to-one comparison between the performances of portland cement and hydrated lime as stabilizer, the dosages and testing methods were kept the same. Several characteristics, including engineering properties and long-term durability, were investigated. The following general conclusions can be drawn based upon the investigation performed.

1. Both portland cement and hydrated lime are effective stabilizers for moderate to high plasticity clay soils. For the moderate PI soil (PI=25), portland cement performs better than lime even at dosages as low as 3%. For the high PI soils (PI 37 and 42), the performance improved significantly when the cement dosage was increased to 6% or more. At this dosage level, the performance of lime-stabilized soils, in general, was inferior to the cement-stabilized soil.
2. The maximum dry density of all three soils stabilized with portland cement attained higher maximum dry density than the lime-stabilized soils. Optimum moisture content (OMC) for the three stabilized soils increased from 0% to 3% except for the lime stabilized Texas 1 soil which increased 6%.
3. The unconfined compressive strength (UCS) of moderate PI soil stabilized with cement is almost always higher than that of lime-stabilized soil. For high PI soil, lime stabilization produces a stronger product at 3% dosage level. However, at 6% and 9% dosages, cement-stabilized soils have generally higher UCS. In order to achieve high UCS, portland cement-stabilized soils should be compacted immediately after mixing. Delaying compaction by a day, which is practiced for lime stabilization, considerably reduces the UCS of portland cement-stabilized soils.
4. Strength of cement-stabilized soil is generally higher than lime-stabilized soil at all ages. Lime-stabilized soil starts weaker but gains strength with time. The increase in UCS of lime-stabilized soil is more dependent on time rather than dosage. The improvement in performance with higher dosage of cement is clearly noticeable. This suggests the dependence of pozzolanic reaction for strength gain in the lime-stabilized soils.
5. California Bearing Ratios (CBR) measured for all three soils stabilized with 6% and 9% cement or lime, clearly indicate that cement-stabilized soils have superior load bearing capacity. Even for the high PI soils, cement stabilization produced a stronger material.
6. The vacuum saturation test relates to the performance in freeze-thaw conditions. Over the soil PI range of 25 to 42, soils stabilized with 6% and 9% cement had significantly higher strength than lime-stabilized soils after the vacuum saturation test, although significant loss of strength was encountered for both the stabilizers, which is expected.
7. The physicochemical nature of cement-stabilized soils, particularly the moderate PI soil, results in better wet-dry durability. For high PI soils, cement-stabilized soils performed very similarly to those stabilized with lime at lower dosage level. However, at higher dosage level, the performance of cement-stabilized high PI soils is, in general, superior.
8. Hydraulic conductivities of cement-stabilized moderate PI soils are significantly lower than lime-stabilized ones at all dosage levels. For high PI soils at a higher dosage (above 6%) level, permeability of cement-stabilized soils is generally lower than the lime-stabilized soils. At lower dosage levels (3% to 6%), hydraulic conductivity of cement-stabilized high PI soils is about the same as lime-stabilized soils.
9. The concentration of calcium ions in leachates from lime-stabilized soils is generally higher (as much as 2 to 3 times at 9% dosage level) than those from cement-stabilized soils. Depending on the permeability, the cumulative loss of calcium from lime-stabilized soil is higher, although the availability of calcium content is more than that in soil stabilized with an equal dosage of cement.
10. An artificial increase of sulfate level of Cal soil apparently made the soil more plastic. This resulted in loss of UCS compared to the same stabilizer dosages used for the unsulfated Cal soil. Such spiking with sodium sulfate solution may not produce a sulfated soil similar to that found in the field. However, sulfate-related expansion was measured for lime-stabilized sulfated Cal soil, and the corresponding cement-stabilized sulfated soil did not register such an activity.

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