Effectiveness of Portland Cement and Lime in Stabilizing Clay Soils

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Pavement subgrades constructed with clay soils can cause significant pavement distress because of moisture-induced volume changes and low subgrade support values. Lime is well known for its ability to stabilize plastic clays; however, portland cement also provides highly effective clay stabilization, usually with the added benefit of higher strength gain. Stabilizing clays with cement or lime can improve subgrade properties at a lower cost than either removing and replacing material or increasing the base thickness to reduce subgrade stress. The clay soil stabilization mechanism for the calcium-based stabilizers portland cement and lime is reviewed. These materials modify soil properties through cation exchange, flocculation and agglomeration, and pozzolanic reaction. Additionally, cement provides hydration products, which increase the strength and support values of the subgrade materials as well as enhance the permanence of the treatment. Comparative laboratory and field performance studies by others, focusing on stabilization of clay soils with portland cement or lime, are critically reviewed. Several factors affecting stabilization are discussed, including stabilizer test procedures, dosage effects to soil properties, mixing, compaction, and gradation and pulverization. Additionally, durability of cement and lime as stabilizers is reviewed, including wetting and drying, freezing and thawing, leaching, and long-term field performance. The research reviewed indicates that, if proportioned and applied properly, both cement and lime can effectively improve the engineering properties of clay soils over the life of a pavement. The results presented provide a guide to the engineer about the property changes to expect when using portland cement and lime with regard to volume stability, strength, and durability.

Clay soils present unique problems to engineers in the construction of durable roads. The two principal concerns are shrinking and swelling of clays and changes in material properties under a range of moisture conditions. Volume change in clays can be significant and occur as the moisture content changes. Low-volume roads constructed on clay subgrades are a particular challenge to engineers because the volumetric changes cause instability of the road, resulting in an uneven pavement surface, detrimental cracking, and, ultimately, premature deterioration and replacement. Property changes of the clays are also problematic. When dry, clays are quite strong. However, as moisture increases, plasticity of the clay increases and strength decreases. Support of the pavement base layer by the clay subgrade is dramatically reduced and often results in poor pavement performance such as base failure, alligator cracking, uneven pavement, rutting, and potholes. Significant maintenance or premature road replacement is often necessary.

Solutions to the problems presented by clay subgrades include excavating and replacing a thickness of clay with a select fill material and increasing the base thickness layer to decrease subgrade stresses and minimize moisture changes. Both solutions are inherently

expensive and wasteful because they require disposal of significant quantities of inferior materials or the use and transportation of additional virgin materials. For low-volume roads, this expense is especially high because, frequently, the distance of the road project to sources of suitable materials is quite far. A more economic alternative is to stabilize the in situ materials with a calcium-based stabilizer. For decades both portland cement and lime have been used successfully for clay subgrade stabilization. However, engineers and constructors often believe that lime is their only alternative; cement is mistakenly assumed to be effective only in soils with a plasticity index (PI) of 20 or less. Significant research reviewed in this paper indicates that cement is at least as effective as lime in stabilizing soils from moderate to high plasticity (PI values up to 50). Generally only small amounts of stabilizer are required to dramatically enhance the engineering properties of clays. Although some similarity exists between cement and lime with regard to stabilization, there are differences that also must be considered by an engineer when choosing a stabilizer. These differences may include important properties such as strength, time dependence of strength development, curing, and durability and permanence of the treatment.

OBJECTIVE

Numerous researchers have investigated the ability of cement and lime to stabilize clay soils. Several have performed comparative studies on these stabilizers. The objective of this paper is to

1. Critically review relevant research performed to date on lime and cement as stabilizers;
2. Discuss similarities and differences between cement and lime with regard to the stabilization mechanism, its effect on engineering properties, and durability of the stabilized clays; and
3. Provide engineers and constructors with two effective stabilizers—cement and lime—which obviate the need for either removing or replacing inferior clay subgrade soils or increasing pavement sections to reduce subgrade stresses.

STABILIZATION MECHANISM

Improvement of clay soils with calcium-based stabilizers, such as portland cement and lime, involves four distinct processes:

- Cation exchange,
- Flocculation and agglomeration,
- Cementitious hydration, and
- Pozzolanic reaction.

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Portland cement provides the compounds and chemistry necessary to achieve all four processes. Lime can accomplish all the processes except cementitious hydration.

Source of Calcium

The most important factor in the initial timely stabilization of clayey soils is the ability of the stabilizer to supply an adequate amount of calcium. Both portland cement and lime can supply this necessary ingredient, and both, when used properly, can effectively stabilize clay soils. However, lime and portland cement are inherently different materials, and the calcium provided by each is supplied to the soil-stabilizer system in a somewhat different manner.

Portland Cement

Portland cement is a finely divided material that results from inter-grinding clinker and gypsum. Clinker is a pyroprocessed hydraulic material composed of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) (in cement chemistry notation, $C = Ca$, $S = SiO_2$, $A = Al_2O_3$, and $F = Fe_2O_3$). The two calcium silicate phases are the most important with regard to soil stabilization. Upon hydration, these two phases produce both calcium hydroxide, which provides available calcium for cation exchange and flocculation and agglomeration, and calcium silicate hydrate (C-S-H), which provides strength and structure in the soil matrix:

$$2C_3S + 6H \rightarrow C\text{-}S\text{-}H + 3Ca(OH)_2 \tag{1}$$

$$2C_2S + 4H \rightarrow C\text{-}S\text{-}H + Ca(OH)_2 \tag{2}$$
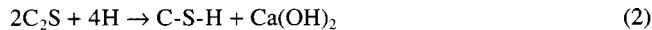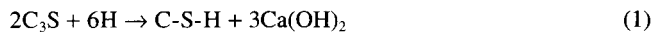
where $H = H_2O$ and $C\text{-}S\text{-}H = C_3S_2H_3$.

When portland cement is mixed with water, hydration is initiated and calcium concentration in the soils builds up quite rapidly. The solution becomes saturated with calcium hydroxide within 12 min of water-cement contact (*1*). As calcium ions (Ca^{2+}) are released in solution, they are available for stabilizing the clayey soil. A drop in calcium content after 12 h is attributed to the setting of cement, where a substantial amount of calcium and water are consumed to form C-S-H and $Ca(OH)_2$ (*2*). Initial absorption of calcium by the clay is rapid and then slows as it becomes increasingly diffusion dependent. Calcium hydroxide, however, is a product of these reactions; thus calcium is replenished as the initial supply due to unhydrated cement is depleted. The calcium hydroxide crystals that form are so highly dispersed in a cement-soil system that they remain in the form of very fine and highly reactive particles of pure "hydrated lime." Herzog and Mitchell (*3*) have described these crystals as being "more reactive than ordinary lime." The calcium in the crystals and in the pore solution is available to the clay for continued stabilization of the soil particles.

Normally, for Type I and II cements, 75 percent of the weight of cement is C_3S and C_2S. Hydration can continue at an ever-slowing pace over many years, and therefore calcium hydroxide is produced during this time. This helps maintain the high pH levels of about 12.5 in mortar and concrete systems. Maintaining a high pH in a soil-stabilizer system is important because high pH is necessary for long-term pozzolanic reactions to occur.

Lime

Lime, as a stabilizer, is manufactured in various forms. Those most typically used in stabilization applications are hydrated high-calcium lime [$Ca(OH)_2$], hydrated dolomitic lime [$Ca(OH)_2 \cdot Mg(OH)_2$], quicklime (CaO), and dolomitic quicklime ($CaO \cdot MgO$). The availability of lime varies in accordance with its composition and solubility. For instance, as magnesium hydroxide is significantly less soluble than calcium hydroxide, high-calcium lime provides more free calcium for stabilization. Quicklime comes in various sizes from 2- to 3-in. (5.08- to 7.62-cm) lumps to pulverized form (85 to 95 percent passing a No. 100 sieve). Quicklime consumes a considerable amount of water when it hydrates in an exothermic reaction. Hydrated lime normally comes as a powder or in a slurry. In either form, when hydrated lime is added to a soil system it consumes no additional water.

The rate of dissolution of lime depends principally on particle size, with finer gradations going into solution faster because of the higher exposed surface area. Small concentrations of lime increase the pH of neutral water from 7 to >11. Approximately 1.8 g of calcium hydroxide is adequate to increase the pH of 1 L of water to 12.45 when it reaches its saturation limit. Maintenance of the high pH environment is especially important for lime-stabilized systems because cementitious material is formed only through long-term pozzolanic reactions and not through formation of cementitious compounds during hydration, as occurs in cement.

Cation Exchange

Cation exchange initiates the stabilization process very quickly, and it is followed by flocculation and agglomeration. Plasticity of a soil is determined by the amount of expansive clay, principally montmorillonite, present. This clay mineral forms by stacking of silica tetrahedra and alumina octahedra layers through ionic and covalent bonds. The 2:1 (two silica tetrahedra to one alumina tetrahedron) basic units stack to form montmorillonite. The cleavage surfaces of this stacking are deficient in the charge because of substitution of aluminum by magnesium. To neutralize the charge deficiency in the crystal structure of this clay, cations and water molecules (which are dipolar) are attracted to the negatively charged cleavage surfaces. This results in a diffused separation of two charged surfaces, commonly called a "double layer." The double layer acts as a lubricant: The thicker the double layer, the more active and plastic the soil. Monovalent cations such as sodium and potassium (Na^+ and K^+) are the prevalent cations that form the double layer, along with water molecules.

However, the monovalent cations can be readily exchanged with cations of higher valence such as calcium. Numerous cations can exchange for sodium in the following preferential order (*4*): $Na^+ < K^+ < Ca^{2+} < Mg^{2+} < Al^{3+}$.

A calcium-based soil stabilizer, of course, will provide sufficient calcium ions so that the monovalent cations are exchanged. Upon ion exchange, the higher charge density of di- or trivalent ions results in a significant reduction of the double-layer thickness. This ion-exchange process is generally quite rapid (usually within a few hours) and is presented in Figure 1.

As both cement and lime provide calcium ions when mixed in a soil-water system, both have the ability to accomplish cation exchange.
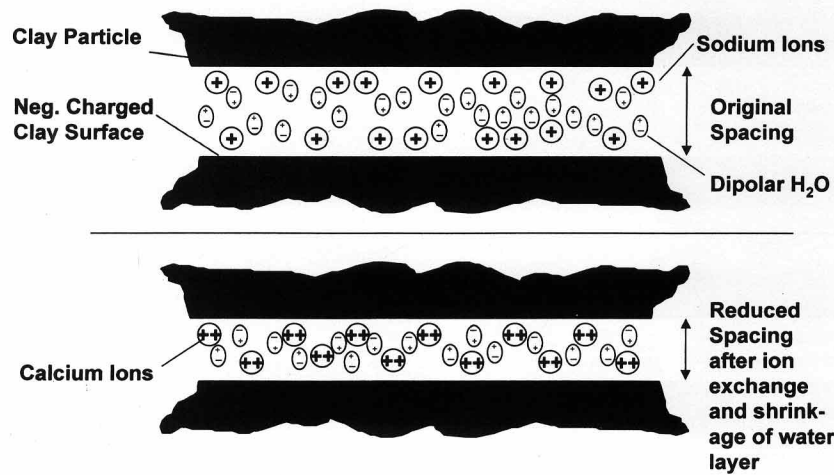
FIGURE 1 Cation exchange.

Flocculation and Agglomeration

Flocculation and agglomeration change the clay texture from that of a plastic, fine-grained material to that of a granular soil. Flocculation is the process of clay particles altering their structure from a flat, parallel structure to a more random edge-to-face orientation. Flocculation has been attributed to the high electrolyte content, the high pH, and the reduction in the double-layer thickness through cation exchange (3).

Agglomeration is speculated to occur as the flocculated clay particles begin to form weak bonds at the edge-surface interfaces of the clay particles because of the deposition of cementitious material at the clay-particle interfaces. The flocculation and agglomeration process is presented in Figure 2. Agglomeration begins the formation of larger aggregates from finely divided clay particles and further improves the texture of the clay soil.

The reduced size of the double layer due to cation exchange, as well as the increased internal friction of clay particles due to flocculation and agglomeration, result in a reduction in soil plasticity, an increase in shear strength, and an improvement in texture.

As with cation exchange, flocculation and agglomeration are relatively rapid; the most significant changes occur within several hours of mixing.

Cementitious Hydration

Cementitious hydration (Figure 3) is a process that is unique to cement but not lime. Cement hydration produces cementitious mate-
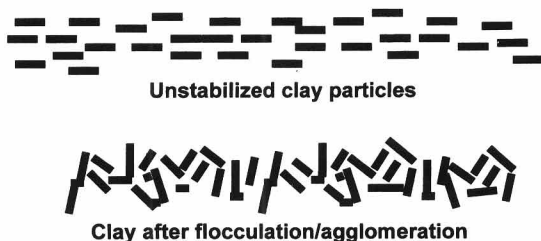
rial, as indicated in Equations 1 and 2. In addition to C-S-H, portland cement, when hydrated, also forms calcium-aluminum-hydrate (C-A-H) and $Ca(OH)_2$. C-S-H and C-A-H form a network and serve as the "glue" that provides structure and strength in a cement-modified clay. The hydrates help to stabilize the flocculated clay particles through cementation. The most rapid strength increases occur between one day and one month; smaller gains in strength—due to continued hydration and formation of cementitious material—continue to occur for years.

The formation of a network of cementitious material within the first month after mixing contributes to a significant increase in strength of the cement-soil system. The cement develops strong bonds between the hydrating cement and clay particles, forming the products into a high-strength mass. It also improves the gradation of the stabilized clay soil by forming larger aggregates from fine-grained particles. In addition, some evidence suggests that formation of cementitious bonds reduces the leaching potential of calcium hydroxide when the soil is subjected to seasonal wetting and drying cycles or when ground water moves through the stabilized soil.

Pozzolanic Reaction

Pozzolanic reaction (Figure 4) is a secondary process of soil stabilization and is applicable to both lime- and cement-soil systems. The
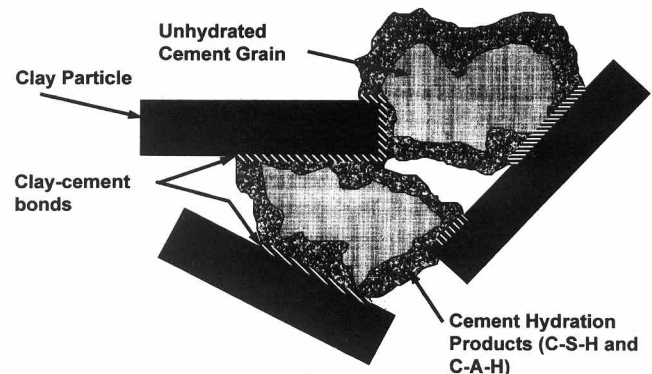

FIGURE 2 Flocculation and agglomeration.
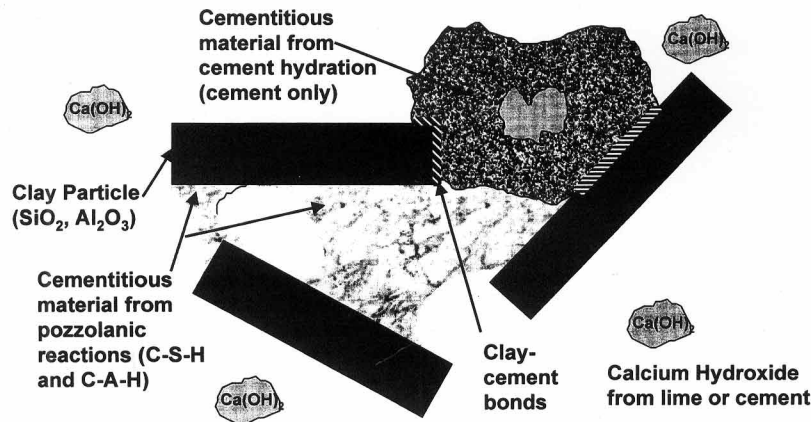

FIGURE 3 Hydration (cement only).

FIGURE 4 Pozzolanic reaction.

high-pH environment of a calcium-stabilized system increases the solubility and reactivity of the silica and alumina present in clay particles (*3,5*). It is postulated that calcium ions combine with silica and alumina dissolved from the clay lattice to form additional cementitious material (C-S-H and C-A-H) (*6*). Although it is a through-solution process, others have claimed a direct reaction of calcium hydroxide with adjacent clay surfaces, with the pozzolanic products formed as precipitates (*7*). This helps explain the agglomeration process. The basic pozzolanic reactions are

$$Ca(OH)_2 + SiO_2 \rightarrow C\text{-}S\text{-}H \qquad (3)$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow C\text{-}A\text{-}H \qquad (4)$$

The pozzolanic reactions take place slowly, over months and years, and can further strengthen a modified soil as well as reduce plasticity and improve gradation. The stabilizer must be capable of maintaining a high pH environment for a long period of time for pozzolanic bonding to become a significant factor in improving the strength and durability of the system. Without the formation of adequate networks of cementitious compounds through pozzolanic reaction (or through hydration as described above), the stabilized system may be susceptible to detrimental leaching of calcium from the system. If significant, leaching results in reduced pH, disruption of pozzolanic action, and reverting back of the soil toward its original unstabilized state.

Diffuse Cementation

Diffuse cementation is also referred to as lime migration or calcium migration. It is the hypothesis that describes the diffusion of calcium deep into clay soil lumps. As such, it should be equally applicable to any stabilizer that provides calcium ions; the source of this supply should be irrelevant. Both portland cement and lime, therefore, can provide the calcium necessary to accomplish diffuse cementation.

An extensive study by Stocker (*8–10*) on the physical and chemical changes occurring in coarsely pulverized soil stabilized with lime and portland cement provided evidence of the existence of diffuse cementation. Stocker described diffuse cementation as the form of cementation that takes place when soil is stabilized with either portland cement or lime. He also highlighted skeletal cementation, which can be produced with portland cement but not lime.

Stocker examined the physical and chemical properties of a heavy clay soil stabilized with hydrated lime or with Type I portland cement at 3 and 15 percent of dry soil. Stocker suggested that 0.5 percent calcium hydroxide was adequate to produce a unit layer of reaction product and eliminate swelling upon wetting. Reactions were postulated to occur initially at the edges of clay particles. After the initial reaction, the rate is quickly suppressed as the initial layer impedes further reaction. This results in a calcium concentration buildup in the pore fluid, increasing the chemical potential between the interior and exterior of the clay to cause a deeper diffusion. The calcium-clay reaction tends to produce uniform deposition of reaction products and, as a result, uniform cementation, or "diffuse cementation." He concluded that adsorption of reaction product along the edges and suppression of reaction rate are courses for diffuse cementation.

Stocker's diffusion cell studies monitored the modifications taking place within the lumps and near the interface. He found similar calcium profiles for both lime and portland cement. The calcium concentration for cement between $\frac{1}{16}$th in. (0.159 cm) and $\frac{1}{8}$th in. (0.318 cm) was 450 meq/100 g and is slightly below the comparable concentration of 510 meq/g for lime.

Figure 5 indicates the variation of acid-extracted calcium concentration with time over 1 year. Soils were stabilized with 3 percent cement and 3 percent lime. After 1 year, lime exhibited gains of approximately 1.4 and 1.5 percent at the exterior and interior of the lumps, respectively. Portland cement showed a gain of about 1 percent at both the interior and the exterior. At early ages, the lime sample exhibits a high concentration of calcium at the exterior of the lump and a low concentration at the interior. After about 8 days, this concentration difference decreased. This is indicative of a high chemical potential between the interior and exterior of the lumps initially, which evens out as the calcium migrates into the clay. The lag of calcium hydroxide content was much less pronounced in the case of portland cement. Initially, the calcium hydroxide concentrations increased at different rates, but the rates were similar after 4 days. After 10 days, the calcium hydroxide contents in the interior and exterior became virtually equal and they maintained this equality over the course of the study. Both lime and cement demonstrated a steady increase in calcium hydroxide content over the 1-year period. This indicates that a steady state has been reached between the supply of calcium at the interface and its consumption at the
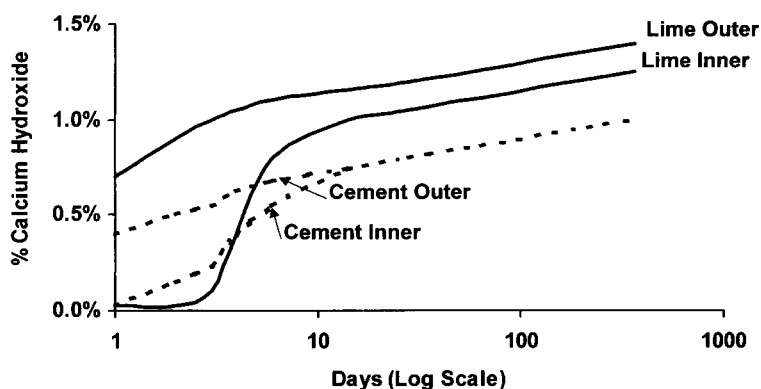
FIGURE 5 Gain of calcium by clay lumps stabilized with 3 percent portland cement and lime (*8*).

reaction front. It indicates the existence of a smooth continuum of cementation from interior to exterior for both portland cement and lime.

The slightly higher concentration of calcium hydroxide in the lime-stabilized lumps can be attributed to a higher concentration of calcium in the pore fluid. Cement generates calcium hydroxide at a rate of approximately 31 percent of its weight. Lime, depending on its purity and form, is 85 to 95 percent calcium hydroxide. This difference may appear to lead to the conclusion that more cement should be added than lime to maintain calcium equivalency. However, Stocker concluded that only 0.5 percent of calcium hydroxide eliminated swelling on wetting and that 2 percent increased the as-cured strength by a factor of 10. In the field, lime or cement additions of 3 to 8 percent are common, which indicates that the addition level normally used is higher than that necessary to achieve beneficial effects. Using higher amounts, of course, helps achieve a uniform mix. However, this is a physical and not a chemical necessity.

Stocker has conclusively shown that diffuse cementation is applicable to both lime and portland cement; they both supply the pore fluid with calcium ions capable of penetrating clay lumps. Although only 0.5 percent calcium hydroxide was enough to eliminate swelling upon wetting, the full benefit of stabilization will likely be achieved only with further penetration of calcium to the interior of the lumps. Stocker has shown this to occur effectively with both portland cement and lime at equivalent and relatively low amounts.

FACTORS AFFECTING STABILIZATION

Stabilizer Dosage

The stabilizer dosage determines to what extent the stabilizer will modify the properties of a soil. The addition of calcium ions is important and provides the most immediate effects in plasticity reduction and textural changes. In addition, a stabilizer may provide other beneficial characteristics to the soil. This is particularly true in the case of portland cement, which provides significant hydration products (C-S-H and C-A-H) to strengthen and "lock in" the calcium provided for ion exchange. Also, the cementitious materials resulting from the long-term pozzolanic reactions for both cement and lime improve soil properties and help ensure permanence of the stabilization.

The amount of stabilizer required is dictated by the ultimate objectives of the stabilization process:

- Soil modification: Enough stabilizer added to a soil to modify its properties enough to improve soil texture, bearing capacity, and compactibility. Strength and durability are normally not criteria at this dosage level. Constructing a stable work platform is the most common use for soil modification. "Cement-modified soil" and "lime-modified soil" are typical terms used to describe this modification level.

- Soil stabilization: A higher level of stabilizer is chosen to modify properties and to ensure permanence of these properties. Pavement subgrade construction, which assumes long-term permanence of the stabilized properties, is the most common use of this dosage level. Often the improvements in subgrade are quantitatively taken into account during the pavement design process. "Cement-treated soil/subgrade," "cement-stabilized soil/subgrade," and "lime-stabilized soil/subgrade" are all terms used to describe this dosage level.

- Stabilized base course: Generally the highest level of stabilizer added not only to achieve permanently modified properties but also to satisfy strength and durability criteria necessary for base course construction. Strength values are normally specified, and durability parameters that ensure wet-dry and freeze-thaw resistance must be met. This dosage level is referred to as "soil-cement," "cement-treated base," or "lime-treated base".

The first two levels of dosage mentioned above are the focus of this paper. Stabilized base course is a separate topic that is beyond the scope of this investigation.

The two primary factors in determining stabilizer content for soil are ensuring adequate calcium for cation exchange and flocculation and agglomeration (which accomplish immediate modification) and strength development (which is an indicator of long-term permanence). One or both of these factors may be required to determine the dosage required for a particular stabilizer. Tests that determine stabilizer dosage for modification objectives include pH measurement (Eades and Grim procedure, not applicable to cement as discussed below), PI reduction, California bearing ratio (CBR), and swell potential. Tests that determine stabilizer dosage for stabilization objectives include unconfined compressive strength (UCS), CBR, triaxial strength, and cohesiometer value.

Often inappropriate tests are specified that do not match the modification objectives. This is especially true for cement modification and stabilization, where often inappropriately high compressive strength values [2.0 to 5.5 MPa (300 to 800 psi)] or even freeze-thaw and wet-dry testing requirements are specified. These criteria may

be appropriate for base course construction with soil-cement but are too stringent for modification and stabilization. A summary of testing procedures is provided below.

Eades and Grim Procedure

Eades and Grim (*11*) developed a simple and inexpensive test to determine the amount of lime necessary to supply the calcium demand (ASTM C977 Appendix). This test is based on the fact that a saturated lime solution will result in a pH of approximately 12.5. The procedure specifies that enough lime must be added to a soil-water system to maintain a pH of 12.4 after 1 h. This ensures that adequate lime is provided to sustain the saturation during the 1-h period. Cation exchange will occur to some extent; however, not all the exchangeable sites are necessarily satisfied at this time.

A limitation of this procedure, recognized by Eades and Grim, is the fact that the test does not take into account any reaction that may result in a strength increase. They state, "Since strength gains are related to the formation of C-S-H, and as their formation varies with the mineralogical components of the soil, a strength test is necessary to show the percentage of strength increase" (*11*).

A further limitation of the procedure of Eades and Grim is that the test is applicable only to lime and not to portland cement. This is due to the more complex nature of the hydrating cement particles. Alkali ions (K^+ and Na^+), which occur as sulfates and chlorides in cement, are released quickly in the presence of water. The pH of the system rises rapidly as a result and can reach a value of 12 to 13 in just a few minutes, even before the system is saturated with respect to calcium hydroxide. Because of this, the Eades and Grim test is not appropriate for cement as it does not measure calcium saturation.

Inapplicability of the Eades and Grim test to cement-soil stabilization does not preclude cement from being used as a stabilizer; however, alternative tests must be used.

PI Reduction

Reduction of PI is a simple and inexpensive alternative to the Eades and Grim method for determining stabilizer content, and it is applicable to both lime and portland cement. PI is determined from the Atterberg limits test (ASTM D4318) and is the difference (expressed as a percent) between the liquid limit and the plastic limit. The raw soil is normally tested; then various percentages of stabilizer are added to determine the amount of PI reduction. A PI limit of less than 10 or less than 15 is often specified. The PI is an index test that, if sufficiently low, ensures that the subgrade will demonstrate minimal shrink-swell potential and will exhibit improvements in strength and texture.

UCS

UCS is probably the most prevalent test used for soil modification, if a strength test is specified. Cement and lime use different standards for UCS determination (ASTM D1633 and ASTM D5102). Notable differences in the standards include an allowance for a 1-h mellowing period for lime and a requirement in the soil-cement standard that the specimens be soaked for 4 h before testing. The soaking requirement is important because clays lose a significant proportion of their strength when wet. The cement standard takes this into account but the lime standard does not.

CBR

CBR (ASTM D1883) is another common strength-based test. It determines a bearing index instead of an actual strength, and it is based on a piston penetrating a predefined distance in a sample of soil (stabilized or unstabilized). The test also calculates swell potential, which can be useful for determining how a stabilizer decreases soil expansion upon wetting. The CBR allows for testing in a soaked condition. This is necessary because the strength of unstabilized dry clays can be extremely high, whereas almost all the strength is lost upon wetting. The advantage of stabilization is that the loss of strength upon wetting is significantly reduced.

Effect of Dosage on PI, Shrinkage, and Compressive Strength

Numerous researchers have studied the effects of lime and cement on the properties of clay soil. One study (*12*) determined the amount of both portland cement and lime in accordance with the Eades and Grim method, notwithstanding the limitations noted above. Dosages of 12 percent cement and 10 percent lime were selected to modify a soil with a PI of >60. Cement reduced the plasticity to 12, and lime reduced it to 17.

In another study, Christensen (*13*) examined 11 soils modified with 3 and 5 percent portland cement and lime. Atterberg limits were examined for all soils after curing for 24 h and for selected soils at 1- and 48-h delay. Comparable property changes were recorded for both cement and lime with regard to PI and shrinkage limit. UCSs were significantly greater at all ages for cement. Table 1 indicates the average percentage change of these properties for the clay soils tested.

Figure 6 indicates the PI reduction for selected individual soils. The PI, which is the difference between liquid and plastic limits, normally reduces with calcium-based stabilizers, because the plastic limit becomes higher, whereas the liquid limit varies just slightly.

TABLE 1 Average Percent Change in Properties for Clay Soils (*13*)

% Stabilizer	Plasticity Index[a]	Shrinkage Limit[a]	7-Day UCS[b]	28-Day UCS[b]
3% Cement	-52%	122%	468%	605%
3% Lime	-55%	123%	183%	348%
5% Cement	-64%	158%	775%	993%
5% Lime	-64%	151%	266%	481%

[a] 11 soils tested, absorption dish method
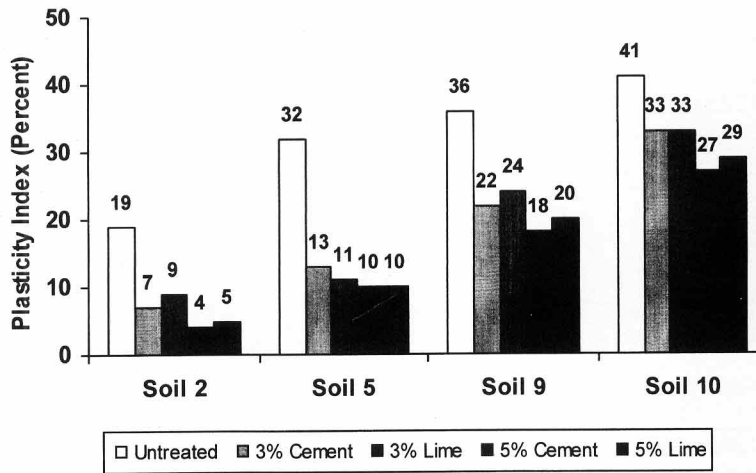[b] 9 soils tested

FIGURE 6 Effect of modification on PI (*13*).

Figure 7 indicates the shrinkage limit increases for those same soils. The shrinkage limit is the percentage moisture a soil can absorb without swelling. The higher the value, the less tendency the soil will have to expand and contract. One important aspect to the increase in shrinkage limit is that it is raised above the optimum moisture content for the soil (indicated in Figure 7). This dramatically reduces shrinkage potential in the most critical moisture states (at or below optimum moisture).

Table 1 and Figures 6 and 7 indicate that a small amount of stabilizer, whether portland cement or lime, changes the plasticity and shrinkage properties of a soil significantly. Additionally, the first few percent of stabilizer generally produce the most pronounced property changes, with additional amounts affecting the plasticity and shrinkage limit properties only marginally. This corresponds to Stocker's observation that a 0.5 percent uptake of calcium hydroxide occurs quickly, and further increase is controlled by diffused cementation. Both cement and lime resulted in similar modifications to plasticity and shrinkage limit.

Compressive strength also was affected significantly by stabilizer dosage. Cement generally produced significantly more strength increase than lime. Table 1 indicates that the average strength increase at 7 and 28 days for nine clay soils tested was much greater for cement than for lime. This is also indicated in Figure 8, where two soils, with untreated PI values of 41 and 25, have higher strengths at all ages with cement.

Petry and Wohlgemuth (Figure 9) (*12*) showed that, for lime, increasing dosage results in strength either remaining the same or decreasing slightly (although the conclusions state that strength increased with lime to an optimum and remained unchanged thereafter; this was not apparent from the figure). Cement, on the other hand, showed an increasing trend in all cases except for coarsely graded soil at the 15 percent dosage level, where strength decreased slightly.

Higher strengths for cement can be attributed to two factors. First, the calcium hydroxide crystals produced during cement hydration are pure and fine, and thus highly reactive, providing the calcium necessary for ion exchange. Second, a rigid network is formed by the cement reaction products, akin to that formed in concrete. At small dosages, the networks may be small and isolated; at larger dosages the reaction products may form large interconnected networks. These changes can allow different properties to be developed from the same soil, enabling one dosage level of cement to form "cement-modified soil" and a higher level to produce "soil-cement."
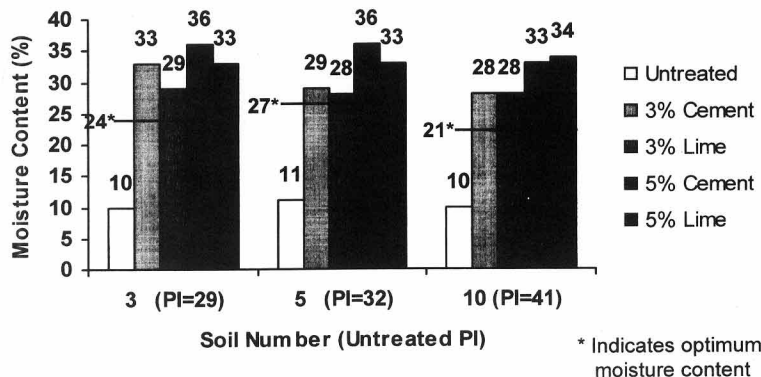

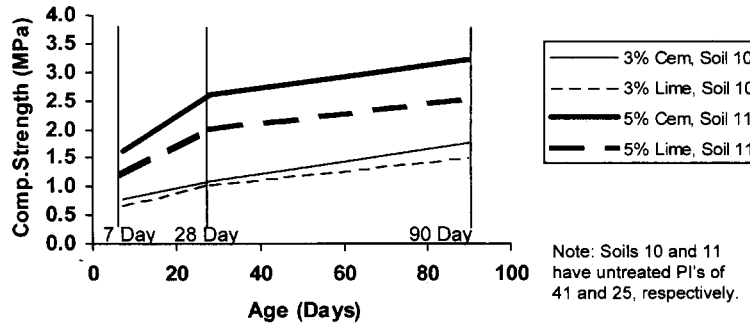**FIGURE 7 Effect of modification on shrinkage limit (*13*).**

FIGURE 8 Effect of stabilizer and curing age on compressive strength (*13*).

Mixing

The objective of the mixing process is to obtain an intimate blend of stabilizer and soil to produce the desired property changes. Field mixing procedures for cement and lime are different because of inherent differences in the stabilizer. Lime mixtures are normally cured for several days (the mellowing period) whereas cement mixtures are compacted immediately. Cement-treated mixtures achieve optimum results when compaction occurs soon after the mixing operation because of the development of cement hydration products.

Christensen (*13*) studied the effect of time delay on cement- and lime-stabilized mixes. Several soils were tested for Atterberg limits 1, 24, and 48 h after mixing. The study found that, for both lime and cement, the most significant plasticity and shrinkage limit changes occurred after only a 1-h curing period. Changes after 24 and 48 h were marginal. Results from two typical soils are presented in Figure 10.

Compaction

A given compactive effort at an optimum moisture content will allow soil-stabilizer particles to achieve their closest packing and maximum density. When optimum moisture and maximum density are achieved, the soil is generally at or near its highest strength for that compactive effort. Two compaction standards are generally practiced in the laboratory: standard and modified proctor. Standard proctor uses a 12,400-ft-lbf/ft³ (1937.5 kN/m³) compactive effort, whereas modified proctor uses 56,000 ft-lbf/ft³ (8750 kN/m³).

Christensen (*13*), in his study of 11 clay soils stabilized with 3 and 5 percent cement and lime, found that the maximum dry density decreased slightly [cement, 19.2 kg/m³ (1.2 lb/ft³); lime, 59.2 kg/m³ (3.7 lb/ft³) average] and average optimum moisture increased slightly (cement, 0.6 percent; lime, 2.1 percent) after treatment with either cement or lime from untreated soil. By delaying compaction for 24 h, dry density was further decreased [48 kg/m³ (3 lb/ ft³)] and optimum moisture increased (1.8 percent) for cement. The moisture-density relationship for lime treatment, however, was essentially unchanged upon delayed compaction.

Compressive strength decreased in nearly every case when cement-stabilized samples (nine soils at 3 and 5 percent) experienced 24 h of delayed compaction; 44 percent of the lime-stabilized samples showed strength decreases at 24 h of delayed compaction. Cement strength at no compaction delay was clearly superior for all samples and dosages when compared with the lime samples with 24-h compaction delay. However, even with the 24-h delay, 61 percent of the cement samples exhibited superior strength compared with the lime samples. Figure 11 indicates, for three typical soils tested, the effects of compaction delay on compressive strength.

Kennedy et al. (*14*) found that cement-stabilized specimens tended to be more accommodative to lower compactive efforts, and lime-stabilized specimens fared better at higher compactive efforts. This indicates that each stabilizer may have a specific compactive effort that achieves optimum engineering properties. However, it is difficult to correlate laboratory compaction standards with equipment and compactive effort in the field. Generally, the lower compactive effort standard proctor is specified in modification specifications.
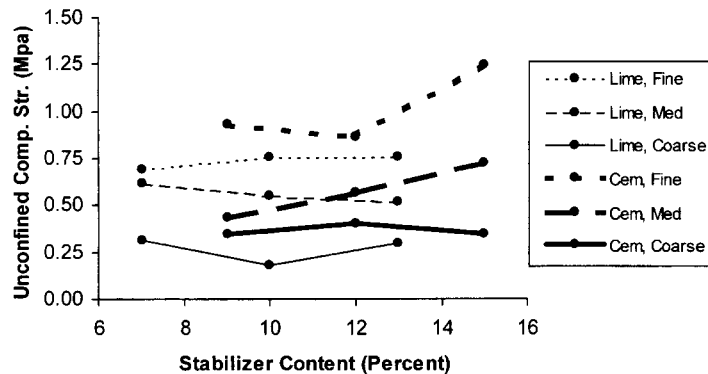

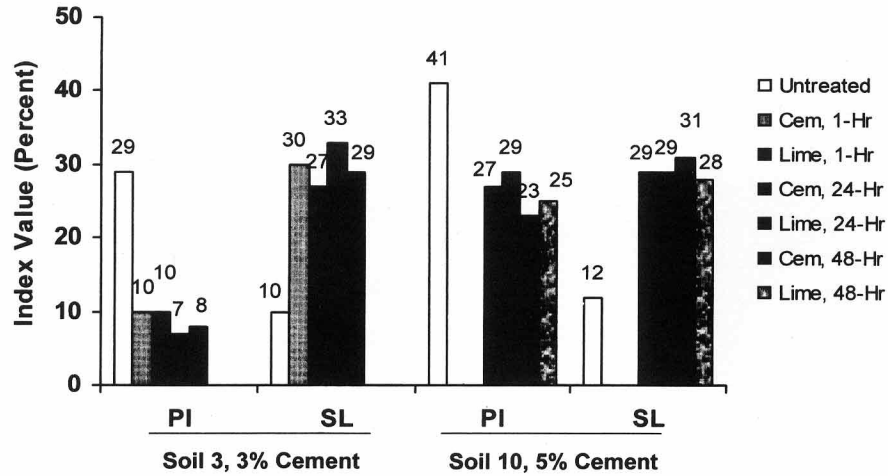**FIGURE 9** Compressive strength of pulverized soils treated with cement and lime (*12*).

FIGURE 10   Effect of curing time on PI and shrinkage limit (SL) (*13*).
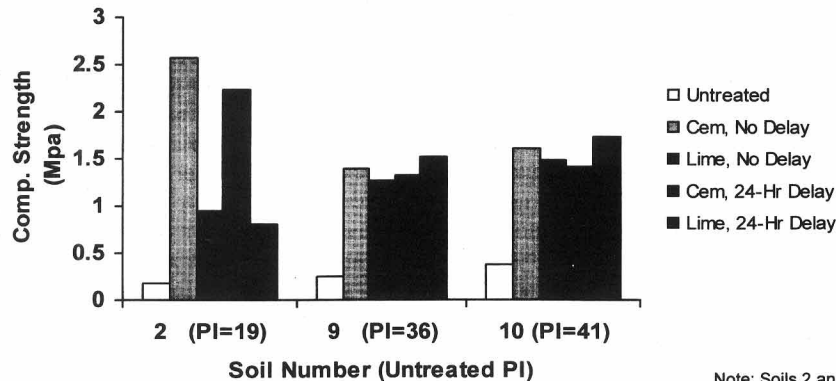
Gradation and Pulverization

The interaction between a stabilizer and the soil is influenced by the surface area available and adequate pulverization. Several studies have investigated the effects of pulverization. Field and lab studies in Oklahoma indicated that 95 percent passing the 25-mm (1-in.) sieve and 60 percent passing the 4.75-mm (No. 4) sieve were effective in soil modification over the long term (*15*). Grimer and Ross (*16*) found that increased pulverization improves compressive strength and that retained strength after immersion in water was greater in more highly pulverized soils. Davidson et al. (*17*) found that lime-stabilized soils with lumps exhibited a decrease in strength. However, after about 150 days of curing, the strength values were approximately the same as those with smaller numbers of lumps.

Felt (*18*) found that the percentage of lump soil (0 to 40 percent) did not appreciably affect the durability of a soil-cement (lime was not tested) in wet-dry or freeze-thaw tests as long as the lumps contained adequate moisture. Dry lumps were found to be detrimental to durability. He thus recommended prewetting clayey soils to ensure

adequate moisture of lumps. Although Felt's observations were specifically for soil-cement (not cement-modified soil), the logic of prewetting soils can likely be applied to cement-modified soil as well.

Petry and Wohlgemuth (*12*) showed that UCS for lime- and cement-stabilized clays improves with finer gradations. In contrast to Felt's findings, they reported failure of portland cement-modified soil in wet-dry and freeze-thaw tests. However, it should be noted that the soils tested by Petry and Wohlgemuth were of unusually high plasticity (PI 64 to 77), which are not indicative of most field conditions. In addition, freeze-thaw and wet-dry tests are not an appropriate design criteria for soil modification. Cement-modified soil (or lime-modified soil) is an improved soil that is unhardened or partially hardened. The true test of durability should be whether a soil is able to maintain improved material properties (such as lower PI, higher shrinkage limit, improved bearing strength) over the lifetime of a pavement. Figure 9 indicates the compressive strength of pulverized soils treated with various amounts of cement and lime; both cement and lime have improved compressive strength as pulverization is increased. Figure 12 indicates that both

Note: Soils 2 and 9 treated at 3% level, soil 10 at 5% level

FIGURE 11   Effect of stabilizer and compaction delay on 28-day compressive strength (*13*).
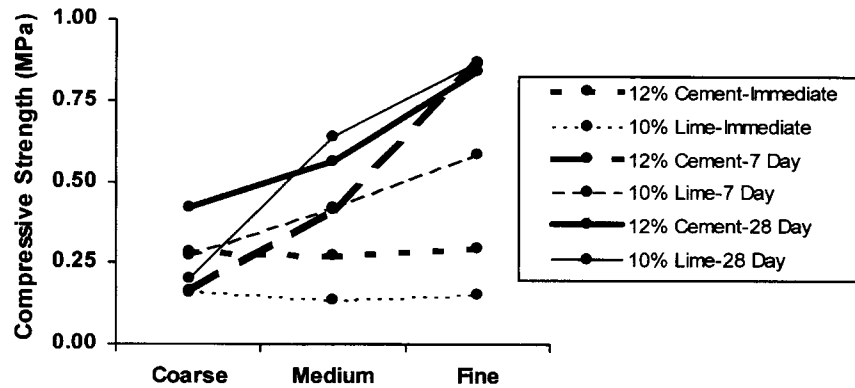
FIGURE 12 Variation in compressive strength with pulverization and time (*12*).

cement and lime behave in a similar manner at different ages after compaction.

Kennedy et al. (*14*) investigated pulverized and unpulverized specimens treated with cement and observed higher UCSs in both dry and wet conditions for the pulverized specimens. Unfortunately, the UCS of the unpulverized soil was not tested with lime. However, as observed by Petry and Wohlgemuth, the strength for both stabilizers should vary with gradation.

Road designers are sometimes concerned that, for cement, the pulverization achieved in the laboratory cannot be achieved in the field. This concern is unwarranted, however, because numerous documented examples of actual successful field application of cement to stabilize clay soils exist. These include studies between 1938 and 1983 in Oklahoma (*15*), Ruisseau Village Shopping Center in Plano, Texas (*19*), US-281 in Texas Department of Transportation's Corpus Christi District (*20*), a plant entrance road in San Antonio (*21*), and Denver's E-470 toll road (*22*).

DURABILITY

The ability of a stabilizer to maintain desired properties over the life of a pavement is important if that is one of the objectives of a stabilization effort.

Wetting-Drying and Freezing-Thawing

Soil samples subjected to wetting-drying or freezing-thawing provide an indication of how those samples will maintain strength properties in the field exposed to diverse environmental conditions. However, as previously mentioned, these tests are not necessarily indicative of a stabilizer's ability to achieve permanent changes in PI, shrinkage limit and bearing values, which are the ultimate objectives.

Kennedy et al. (*14*) concluded that based on dry and wet strengths portland cement is an inferior stabilizer compared with lime. However, the data do not appear to support such a broadly stated conclusion. Three soils of PI 39, 36, and 11 were stabilized with 4 and 7 percent lime and cement. The soil with a PI of 39 exhibited higher dry and wet strengths with lime. However, the soil with a PI of 36 at 7 percent cement and compacted with a modified proctor showed higher dry strength and lower wet strength than soil with an equal amount of lime. That same soil, when compacted at standard proctor, demonstrated higher wet and dry strengths with cement at 4 and 7 percent levels. The soil with a PI of 11 showed significantly higher dry and wet strength when stabilized with cement. In addition, the method of mixing was different for cement and lime. Lime was mixed into the soil as a slurry, whereas cement was mixed dry and then combined with water. The lime-modified soil will likely produce quicker and more complete interaction with the soil than the cement-modified soil because of the slurry mixing. Both cement and lime can be mixed dry or as a slurry, so the difference in stabilizer addition methods produced results that are not directly comparable.

Petry and Wohlgemuth (*12*) subjected highly plastic soils stabilized with lime and cement (PI 64 to 77) to modified wet-dry testing. They subjected samples to 12 wet-dry cycles as specified in ASTM D559 after 7 days of curing in a wet room. However, the wire brushing called for in the specification was not performed. Also, the specimen size was larger than standard. The results indicated that the lime-stabilized specimens retained their integrity better than the portland cement specimens at each gradation level. They attributed the performance differences between cement and lime to the theory of "water proofing." Lime achieved superior water proofing through formation of a coating but with little gain in strength. With cement, the soil lumps were held together by a cement coating that was inadequate to provide the required water proofing. The superior compressive strength of cement was ascribed to the cement coating at lump interfaces and the shear strength of clay clods.

An alternative explanation not considered by Petry and Wohlgemuth relates to capillary pore pressure. The capillary force exerted on a pore wall depends on the pore size: the smaller the pore, the higher the suction force. As water enters and exits the pores, it can generate considerable pressure and degrade the surrounding material. The achievement of higher maximum densities and lower optimum moisture contents with cement indicates that porosity is lower and the pore structure is finer than lime. Therefore, the poorer performance of cement-stabilized specimens in wetting-drying tests may be at least partly attributed to the phenomenon of pore pressure. If lime-stabilized clay does, in fact, demonstrate increased porosity, this could lead to higher amounts of highly soluble calcium hydroxide being leached from the soil-lime system.

In contrast, Felt (*18*), in his research on soils with PI values ranging from nonplastic to a PI of 33, found that portland cement was highly effective in resisting wet-dry and freeze-thaw stresses. Although soil-cement, instead of cement-modified soil, was the focus

of much of this research, Felt reported some data for cement-modified clay soils. He showed that cement modification was very effective in reducing the PI and increasing the bearing strength of cement-modified clay soils. In addition, one clay soil with a PI of 31 was stabilized with cement from 2 to 10 percent and subjected to 60 freeze-thaw cycles with little detrimental effect on PI or shrinkage limit. Felt concluded that "(t)he small differences between the test constants [plasticity index and shrinkage limit] indicate that the effectiveness of the cement is not readily destroyed." These same soils showed that the percentage of fine-grained clay and silt-sized particles was reduced by cement stabilization (Figure 13). Felt finally concluded that up to 30 percent unpulverized soil was not significantly harmful to soil-cement (which is judged by a higher durability standard) as long as the clay lumps were damp before stabilization. Stocker's research (*8–10*), as previously discussed, confirms the fact that with both lime and cement the calcium diffuses into clay lumps and effectively stabilizes the soil. It is difficult, therefore, to see how waterproofing of lime would be more effective than cement.

Leaching

Leaching of a stabilized soil is due to the percolation of ground water through the pore structure of the soil: the more permeable the soil, the greater the potential for leaching. As calcium hydroxide is a soluble, and therefore leachable, compound, the concern with leaching is the breakdown of the soil-stabilizer system. Only limited information is available on leaching of cement-modified soil specimens. However, extensive leaching investigations by McAllister (*23*) and McAllister and Petry (*24–26*) were performed on lime-stabilized samples. Lime addition levels in soils were defined at two levels: lime modification optimum (LMO) as determined by the Eades and Grim pH test and lime stabilization optimum (LSO) as determined by the lime addition percentage, which provides the maximum UCS. For the soils tested, the lime levels for LMO were 3 to 4 percent and for LSO they were 7 to 8 percent. Figure 14 indicates the calcium concentration in the leachate over 90 days of leaching.

Leaching tests showed that leaching was detrimental to the engineering properties of postleached specimens. PI, shrinkage limit, and compressive strength all deteriorated toward initial values as leaching occurred, and not enough lime was available to counteract the effects of leaching. The researchers hypothesize that, to minimize detrimental property changes, sufficient pozzolanic reactions must occur, which close off flow channels and improve interparticle
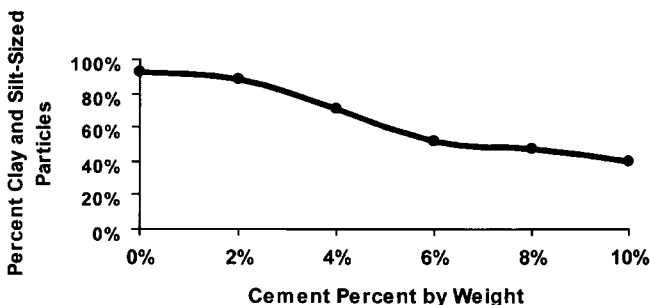

FIGURE 13 Effect of cement modification on gradation of a clay soil (*18*).

bonding. This will, after a time, tend to partially minimize the loss of calcium due to leaching. The dissolution of C-S-H formed during pozzolanic reactions is significantly slower. The researchers state that the amount of lime prescribed by the LMO is not sufficient to permanently stabilize a soil and that a lime level of at least 1 percent above LSO is necessary. This would result in lime contents 4 to 5 percent above the amount determined by the Eades and Grim method. Such an addition is necessary to maintain high pH, to enable pozzolanic reactions, and thus to prevent washout.

Correlation of field with laboratory data was limited and inconclusive. However, the field data indicated that substantial deterioration, most likely due to leaching, occurred, resulting in the PI and swelling of the soils to revert toward that of the natural soil.

Although a comparable study with cement has not been performed, the results and conclusions from this investigation indicate that portland cement would likely produce a stabilized soil much more resistant to leaching. Portland cement hydration forms primarily C-S-H, which is similar to the pozzolanic product. Calcium hydroxide is formed as a by-product of this reaction and is available for cation exchange and development of additional C-S-H through pozzolanic activity. Permeability of the soil would be low, thus minimizing percolation and washout. This will help retain the engineering properties for a longer time. Clearly, research to confirm this hypothesis needs to be undertaken.

Long-Term Performance

Controlled long-term field performance investigations are limited with both cement and lime. The principal concern about long-term performance is whether the ion-exchange process can be reversed, thus causing beneficial engineering property gains to revert to their unmodified values.

The state of Oklahoma has performed studies with both cement and lime to determine long-term performance. Although each stabilizer has been shown to be effective in retaining engineering properties, the time scales involved are much different: 45 years for cement and 5 to 12 years for lime.

In 1938, an 11-km (7-mi) test section containing expansive clay (original PI values from 18 to 51) was stabilized with 11 different cement contents from 4 to 16 percent. In 1983, 45 years later, a lab study reexamined these sections. In 1938, the PI values of the original soils were reduced to between 7 and 18. In 1983, these PI values were further reduced to between nonplastic and 13. The shrinkage limit, however, has decreased slightly from an average of 2.1 times the untreated soil to 1.6 times—still a significant improvement. Figure 15 indicates the PI and shrinkage limit for four of the soils tested. These data indicate that cement was highly effective in maintaining engineering properties over a very long-term period (*15*).

Another Oklahoma study (*27*) for lime-treated soils was conducted in 1980 on soils that had been in service for 5 to 12 years. One significant difference in this study was that the untreated properties of the lime-stabilized soils were assumed to be the same as the untreated subgrade layer beneath the lime-treated layer. At some of the locations, the characteristics of the stabilized and unstabilized layers appeared to be reversed. That is, treated soil had the properties of untreated soil and vice versa. This difference was attributed to material heterogeneity, although leaching of calcium as a probable cause could also be a factor. For the lime-treated soils, the average PI was reduced from 22 to 15, and the shrinkage limit of 12 increased to 17 (a factor of 1.4). In contrast, for cement over
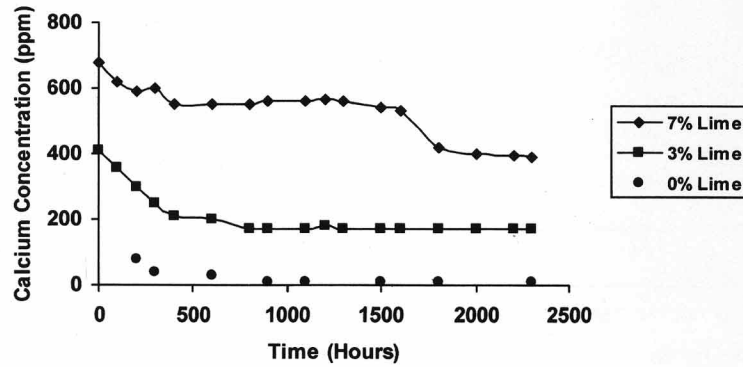
FIGURE 14   Calcium concentration in leachate during 90 days leaching (Site 2 soil) (20).

45 years, the original average PI of 29 was reduced to 6, and the shrinkage limit of 13 was increased to 21 (a factor of 1.6).

CONCLUSIONS

Improvement of inferior clay soils through stabilization with a calcium-based stabilizer allows the soils to be used as a subgrade material, in lieu of excavation and replacement or thickening of the base course layer. Stabilization conserves resources, reduces cost, and improves road performance. Both portland cement and lime can effectively modify and stabilize inferior clay soils. The arbitrary assumption that cement cannot effectively stabilize soils with PI values greater than 10 or 20 is invalid. Thus engineers and constructors have two principal alternatives to evaluate when stabilization is considered. The road designer's choice of stabilizer for plastic clays should be based on a comparison of soil property enhancements, permanence of stabilization, relative cost, and material availability. Detailed conclusions from a review of relevant research and literature include the following:

1. Calcium is the most important ingredient in stabilization of clays. Cement provides lime initially through dissolution of the major oxide phases (C_3S and C_2S primarily) and later through the formation of calcium hydroxide as a by-product of the hydration reactions. Lime provides calcium through the dissolution of calcium hydroxide in the presence of water.

2. Both cement and lime change the properties of clay through a series of physiochemical modifications including cation exchange, flocculation and agglomeration, and pozzolanic reaction.

3. Only cement produces strength and durability-enhancing cementitious material at relatively early ages through cementitious hydration.

4. Diffuse cementation, the process of calcium ions migrating into lumps of clay, occurs in both cement and lime.

5. The Eades and Grim procedure (through pH measurement) is effective in determining an amount of lime necessary to initially modify a soil. This procedure, however, is not applicable to cement because of the presence of alkali ions (K^+ and Na^+). PI reduction measurements by performing the Atterberg limits tests are effective for both cement and lime in determining dosage requirements.
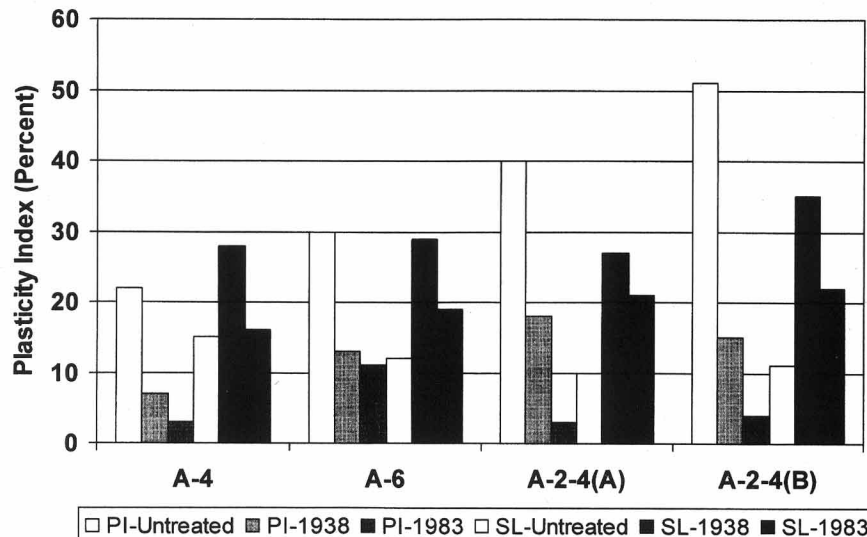

FIGURE 15   PI and shrinkage limit (SL) of cement-modified Oklahoma soils (20).

6. Cement and lime accomplish similar reductions in PI and shrinkage limit at similar dosage levels. Cement generally produces much higher strengths at all ages.

7. Delayed compaction with cement tends to be detrimental to compressive strength and maximum dry density, although plasticity and shrinkage limit values are not appreciably affected. Modified properties of lime are not affected appreciably with delayed compaction.

8. The modification of properties with both cement and lime is improved with finer pulverization. However, unpulverized clay lumps will, with time, tend to be stabilized through diffuse cementation.

9. Both cement and lime can produce property changes that are durable over the life of a pavement as long as the stabilizer is proportioned and applied properly. Leaching of calcium is a concern with lime. A lime dosage 4 to 5 percent higher than that determined by the Eades and Grim procedure is normally necessary to develop long-term pozzolanic formation of cementitious material, which inhibits detrimental leaching of lime. Cement forms significant amounts of cementitious material (due to hydration) within several hours after mixing, which reduces permeability and inhibits leaching.

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