Stabilization of Clay Soils by Portland Cement or Lime— A Critical Review of Literature

by Sankar Bhattacharja, Javed I. Bhatty, and H. Alan Todres

KEYWORDS

Calcium migration, cation exchange, clay, consolidation, diffuse cementation, durability, flocculation, leaching, lime, portland cement, pozzolanic effects, pulverization, soil, stabilization, stabilizing agents, stabilization mechanism, stabilizing factors, sulfate.

ABSTRACT

Stabilization in clay soils results from two distinct chemical processes caused by the stabilizing agent. These are: the cation exchange and flocculation effects which are immediate, and the pozzolanic and hydration effects which are time-dependent. To stabilize clay soils within the time constraints usual in the field, the fast reaction provided by cation exchange and flocculation processes plays a vital role. In all practical cases, the primary ingredient necessary for stabilizing soils is calcium. While both portland cement and lime, the most commonly used stabilizing agents for clay soils, are capable of providing calcium, they differ in their chemical nature. Thus, their mode of reaction and the reaction-products that eventually form may differ. In addition to plasticity reduction, portland cement, by its inherent nature of producing strength-developing hydration products, provides improved strength as an added benefit. This review presents a critical comparative account of the published work on clay soil stabilization as achieved by portland cement or lime. The mechanisms involved in stabilization, the methodologies applied, the evaluation criteria, and the resulting data have been appraised and interpreted. The differences in the methodologies and the testing criteria for lime and cement stabilization have been identified and their implications on performance evaluation have been discussed. Critical factors affecting stabilization, such as dosage, material processing, curing conditions, etc., have been reviewed and recommendations have been made to attain a meaningful comparison between cement and lime usage. The needs for additional research have also been identified and specific recommendations made.

REFERENCE

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INTRODUCTION

The modification of clay soils to improve their engineering properties is well recognized and widely practiced. Among the various stabilizing agents investigated by numerous researchers, the most prominent is lime, followed by portland cement. 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 results of a number of chemical processes that take place in the presence of a stabilizer. These processes can be divided into two discernible types. The effect of cation exchange and flocculation is generally within a few hours. The effects of other processes, such as pozzolanic reactions, development of structure due to cement hydration, carbonation, and the formation of new materials, are time-dependent and may continue over a long period. Two parameters primarily associated with the effective stabilization of clay soils within the time constraints typical in the field are cation exchange and flocculation. While the contributions from other processes add benefits to the stabilization process, their effects on clay soils are secondary. However, the time-dependent additional benefits should be welcome and may even be included in the design.

While both portland cement and lime are capable of providing calcium, the primary ingredient necessary for stabilizing soil, they differ in their chemical nature, their mode of reaction in the presence of water, and their resulting reaction products. Based upon the technical aspects, questions can be raised about the ultimate superiority of one over the other. This has been an issue for investigation to many researchers, who have produced a number of technical articles. The lack of a serious and unbiased attempt to review this issue in the literature prompted this report which presents a critical review of the clay soil stabilization process as achieved by portland cement and lime. The focus is, however, on a comparative evaluation of these two stabilizing agents with respect to the mechanisms involved, test methods used for their evaluation and, thereby, the influence and interpretation of the results.

MECHANISM OF STABILIZATION

As the primary requirement is to stabilize a clay soil within a reasonable time, the cation exchange and flocculation processes, because of their rapid action, become the most dominant among other processes involved in the stabilization. This requirement is true regardless of the type and amount of stabilizer used in modifying the engineering properties of a soil. This

universal necessity leads us to provide a brief description of this mechanism, as it is equally applicable to both portland cement and lime.

Cation Exchange and Flocculation

Higher plasticity is primarily caused by the presence of montmorillonite in the soil. Owing to the charge deficiency within the crystal structure of montmorillonite, cations are attracted to the cleavage surfaces to neutralize the negative charge. In a dry clay, cations are either adsorbed to the surface or reside as a precipitate. In the presence of water, the cations are hydrated and in conjunction with water molecules are attracted to the clay surface, thereby forming a diffuse double layer. The thickness of the double layer determines the plasticity of the clay. The attractive potential is such that anions are virtually excluded from the clay surface. When the cation responsible for the neutralization is monovalent, such as sodium, the clay becomes plastic. In order to reduce the plasticity of the clay, the monovalent cations present in the montmorillonite cleavage surface must be exchanged so that the thickness of the double layer is reduced.

Fortunately, the adsorbed monovalent cations within the double layer may readily be exchanged for other cations. All other factors being equal, adsorption of trivalent cations are preferred over divalent cations, and divalent cations are preferred over monovalent cations. A typical exchange series in ascending order of exchange preference is as follows: $Na^+ < K^+ < Ca^{2+} < Mg^{2+} < Al^{3+}$ (Grim, 1962). 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 are replaced. This phenomenon is illustrated in Figure 1.

The process of flocculation-agglomeration of clay soil particles changes the texture from that of a plastic, fine-grained material to that of a more granular soil. An increase in electrolyte content of the pore water and adsorption of Ca^{2+} ions in the exchange process have been attributed as causing this phenomenon (Herzog and Mitchell, 1963). In a high pH environment, the solubility of silica and alumina is greatly enhanced. Therefore, depending upon the availability of calcium, calcium-silicate-hydrate (C-S-H), and calcium-aluminate-hydrate (C-A-H) may form. This process is often termed "pozzolanic reaction" and occurs over many months or even years. In lime-stabilized soils, formation of C-A-H having cementitious properties is reported to be significant in the development of agglomerates (Diamond and Kinter, 1965). On the other hand, portland cement, as a multimineralic compound, forms primarily C-S-H and also C-A-H immediately upon hydration, and a flocculation process similar to lime-stabilized soil is expected to take place.

Source of Calcium in Stabilization of Soil with Lime

Lime, as a stabilizing agent, is used in various forms and purity. The most commonly used types are hydrated high-calcium lime, hydrated dolomitic lime, quicklime, and dolomitic quicklime. The availability of calcium from these stabilizers varies due to their composition and solubility. In order to properly stabilize a soil, they should be able to offer an adequate supply of calcium. In the presence of magnesium (dolomitic lime), the calcium availability for unit weight is reduced and, thereby, should be compensated by a higher dosage. As magnesium in high pH conditions forms $Mg(OH)_2$, the likelihood of magnesium participating in soil stabilization process is low. Therefore, regardless of the source of calcium used, ideally an equivalent amount

of calcium should be available from the stabilizing agent. This can be achieved by varying the amount of addition, unless the solubility of the stabilizer is sufficiently low. Because of the low solubility of $CaCO_3$ in water, it is not recommended as a stabilizer. Unfortunately, there is often confusion due to the indiscriminate use of the word "lime" to refer to CaO, $Ca(OH)_2$, Ca^{2+}, limestone, dolomitic limestone, etc.

Eades and Grim Method to Determine Stabilizer Requirement

As the inherent characteristics of a soil to be stabilized are virtually fixed, the amount of stabilizer necessary to achieve a desired level of stabilization becomes the primary parameter. In order to determine the amount of lime that can adequately supply the required amount of calcium, Eades and Grim (1966) developed a method, since named after them, based on the pH of soil, lime, and water mixtures. In this test, a fixed weight of soil (20 g oven dried) and quantity of water (150 ml) are used, to which variable amounts of lime ranging between 2% and 6% in increments of 1% are added. After an hour, the pH of these soil-lime mixtures is measured, and the minimum amount of lime that provides a pH reading of 12.4 is considered adequate to stabilize the soil under investigation. (When the required pH cannot be reached, an additional lime dosage is also allowed in this test.) The Eades and Grim method is widely practiced as it is simple, convenient, quick, and inexpensive. While providing the dosage necessary for reduction of plasticity, it does not address questions of long-term strength modification or durability. The procedure is detailed in the Appendix to ASTM C 977-90, "Standard Specification for Quicklime and Hydrated Lime for Soil Stabilization."

The basis of the Eades and Grim method lies in the relationship between the solubility of hydrated lime and the resulting pH of the solution. According to Figure 2 (Boynton, 1980), the solubility limit of $Ca(OH)_2$ at 25°C is 1.2 g per liter of water, and the resulting pH is 12.5. A small amount of $Ca(OH)_2$ increases the pH sharply from 7 to about 11. The concentration at which saturation is reached varies inversely with temperature. A soil-lime mixture with a pH of 12.4 ensures that the amount of calcium available in the system is adequate to sustain full saturation an hour into the test when the pH is measured. In this period, cation exchange will take place to a certain extent. However, the cation exchange sites satisfied may not represent all the available exchangeable sites.

The pH method suffers from a few limitations. It takes no account of any interaction between lime and soil that may result in a strength increase. In fact, recognizing this limitation, Eades and Grim (1996) stated explicitly:

"The 1 hr pH or 'Quick Test' can be used only to determine the lime requirements of a soil for stabilization. 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."

Another limitation is that the stabilizer amount determined in this method is only applicable to lime, and it may lead to a wrong estimate if the stabilizer (such as portland cement) contains compounds such as alkali sulfates or chlorides that are highly soluble in water.

Usually, alkali cations (Na^+ and K^+) are present at less than 1% of the total weight in all portland cements. These alkali cations normally occur as sulfates and chlorides. They may also be incorporated in the major phases of clinker (a pyroprocessed material prior to intergrinding with gypsum to make cement). In the presence of water, the alkali compounds dissociate into

their respective cations (Na^+ and K^+) and anions (SO_4^{2-} and Cl^-). Electrical neutrality of the system is maintained by equality of numbers of opposite charges. However, a certain fraction of these anions gets consumed through the formation of lower solubility products and by the hydration products. In order to maintain the electrical neutrality of the system, equivalent numbers of OH^- ions are released, and the pH of the system accordingly increases rather rapidly. In fact, the pH of a fresh cement paste reaches values of 12 to 13 within a few minutes and before the system becomes saturated with respect to calcium hydroxide. Thus, when used to determine the amount of portland cement required for soil stabilization, the Eades and Grim method can be misleading.

The Eades and Grim method does not exclude portland cement from being a potential stabilizer. Portland cement does generate calcium hydroxide as a result of hydration and the pore solutions of portland cement systems (such as concrete, mortar, etc.) generally remain saturated with respect to calcium hydroxide. Therefore, the determination of the dosage of portland cement necessary for stabilizing a soil should be based on the demand for, and supply of, calcium. The demand for calcium is dictated by the nature of the soil and the amount and rate of supply of calcium is determined by the stabilizer. If a stabilizer is unable to supply the amount of calcium necessary for an immediate stabilizing effect, a simple increase of dosage can readily remedy the situation. Thus, we need to know the reactions that take place when portland cement comes in contact with water and the products produced due to the hydration reactions.

Portland Cement Hydration and Its Interaction with Clayey Soil

Portland cement is manufactured by intergrinding clinker, a pyroprocessed hydraulic material, made from raw materials in a cement kiln with calcium sulfate (usually gypsum rock at approximately 5% by weight). Clinker is comprised of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). According to the standard notation used in cement chemistry, $C = CaO$, $S = SiO_2$, $A = Al_2O_3$, and $F = Fe_2O_3$. The clinker is ground to a sufficiently fine powder to increase the rate of hydration. In the context of soil stabilization through the cation exchange and flocculation-agglomeration, which requires a supply of calcium, the two calcium silicate phases, C_3S and C_2S, are the most important. The room temperature hydration reactions of these two phases are:

$$2C_3S + 6H \longrightarrow C\text{-}S\text{-}H + 3Ca(OH)_2 \qquad \qquad \text{Equation 1}$$
$$2C_2S + 4H \longrightarrow C\text{-}S\text{-}H + Ca(OH)_2 \qquad \qquad \text{Equation 2}$$

where,

$H = H_2O$ and C-S-H = calcium silicate hydrate ($C_3S_2H_3$).
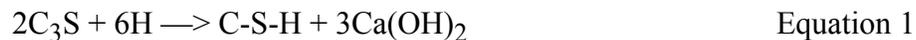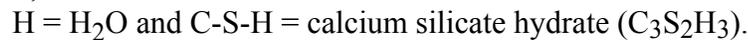
Figure 3 (Lawrence, 1966) shows the rate of concentration build-up in the early stages of hydration of portland cement. It is obvious from the graph that calcium concentration builds up quite rapidly (within minutes). For most cements, according to Gartner et al. (1985), the solution is saturated with $Ca(OH)_2$ within 12 minutes of the time water and portland cement first come in contact. Gypsum in cement has a solubility (2 g per liter of water at 25°C) similar to that of $Ca(OH)_2$ and the solution reaches saturation with respect to gypsum within approximately 6

minutes. Dissolution of gypsum generates Ca^{2+} and SO_4^{2-} ions as shown in Figure 3. The drop of Ca^{2+} concentration at 12 hours is related to the setting of cement when a substantial amount of calcium is consumed from the solution to produce C-S-H and $Ca(OH)_2$. In this process, a substantial amount of water is also consumed.

Typically, Type I and II cements contain a combined amount of C_3S and C_2S of approximately 75% of the total weight of cement. Depending upon the fineness, the hydration of cement grains may continue for years and, consequently, $Ca(OH)_2$ is produced over the same period. Because of this, mortar and concrete containing portland cement maintain a pH of approximately 12.5, which is approximately the pH of a saturated lime solution that is specified in the Eades and Grim method.

The formation of calcium hydroxide as a by-product of the hydration reaction of the calcium silicate phases in portland cement is a through-solution process. As Ca^{2+} ions are released into the pore fluid, they are available for stabilizing the surrounding clay soil. Upon initial absorption of Ca^{2+} ions by clay, the absorption rate slows down as it becomes increasingly diffusion dependent. When such conditions prevail, depending on the rate of supply of Ca^{2+} by the hydrating cement particles, Ca^{2+} ion concentration may rise locally to a level high enough to cause precipitation of $Ca(OH)_2$. Cement particles in cement modified soil are so highly dispersed that the opportunity of $Ca(OH)_2$ crystals to grow is very low. As a result, they remain in the form of very fine particles of pure hydrated lime. Although $Ca(OH)_2$ is chemically known as hydrated lime, the word "lime" in soil stabilization is often wrongly referred to and is assumed as a direct addition of lime to soil. Such a reference excludes or misrepresents the potential for stabilization of other materials that can efficiently supply $Ca(OH)_2$.

The formation of calcium-silicate-hydrate (C-S-H), upon hydration of portland cement, is attributed to the development of its strength. Therefore, the formation of C-S-H may further strengthen a soil that is stabilized with the $Ca(OH)_2$ produced as the by-product of cement hydration. The formation of C-S-H upon hydration is an inherent characteristic of portland cement, but not of lime. Additional C-S-H can form in both the portland cement-soil and lime-soil systems due to the reaction between $Ca(OH)_2$ supplied by either cement or lime and the silica supplied by soil. This process is known as a pozzolanic reaction. Calcium may also react with alumina and produce C-A-H that is cementitious in nature. The reactions are as follows:

$$Ca(OH)_2 + SiO_2 \longrightarrow \text{C-S-H} \qquad\qquad\qquad \text{Equation 3}$$
$$Ca(OH)_2 + Al_2O_3 \longrightarrow \text{C-A-H} \qquad\qquad\qquad \text{Equation 4}$$

The formation of these additional cementing materials (C-S-H and C-A-H) may require the solubilization of silica and alumina from the soil components (Herzog and Mitchell, 1963). In a typical soil, the possible sources of silica and alumina are clay minerals, quartz, feldspars, and micas; other silicates and alumino-silicates, either crystalline or amorphous, may also be present (State of the Art Reports, 1976, 1987).

The solubilities of silica and alumina are increased in the elevated pH conditions that prevail in portland cement- and lime-soil systems (Harty, 1970). High pH environments also increase the reactivity of surface silica and alumina (Herzog and Mitchell, 1963). It has been speculated that silica from the clay lattice dissolves in the presence of high pH and then combines with Ca^{2+} ions to form C-S-H (Eades, 1962). It has also been speculated that the

calcium adsorbed on the clay surfaces reacts with adjacent clay surfaces and the reaction products are formed as precipitates (Diamond et al., 1964), which explains the agglomeration process. While these studies hypothesized the occurrence of a clay-calcium reaction exclusively through a solution process, a direct reaction of $Ca(OH)_2$ at the clay surface has also been considered a possibility (State of Art Report, 1976, 1987). In a study of lime and portland cement stabilization of heavy montmorillonite clay soil, Stocker (1975) proposed a diffused-cementation theory based upon evidence that montmorillonite is the exclusive reactant with calcium and the concept that the bulk of the reaction takes place at the montmorillonite crystal edges. Indications of reactions taking place at the clay surfaces and formation of new phases thereupon have also been reported in studies on lime-kaolinite and -montmorillonite (Diamond and Kinter, 1966), and lime-clay-water systems (Ormbsy and Bolz, 1966; Ford et al., 1982). According to a study by Cabrera and Nwakanma (1979) on the stabilization of red tropical soil with lime, an increase in strength beyond the initial 7 days of curing is a result of hydration and increase in crystallinity of the hydration products, and not from the continued formation of cementitious products due to pozzolanic reactions.

Based upon the results of the analytical and mechanical characterizations, the following hypothesis for clay-portland cement interactions was reported by Herzog and Mitchell in their 1963 report:

"Primary and secondary processes may be distinguished during the hardening of a clay-cement mixture. Hydrolysis and hydration of cement could be regarded as primary reactions. These processes would initially form usual cement hydration products and increase the pH of pore water. The fresh calcium hydroxide formed during this period would be more reactive than ordinary lime.

"Clay may participate in the secondary processes. The calcium ions produced by cement hydration first convert the clay to the calcium form and tend to intensify the flocculation initiated by the increase in total electrolyte content accompanying the addition of cement. The calcium hydroxide initiates attack of the clay particles and amorphous constituents. Dissolved silica and alumina combine with calcium ions and precipitate additional cementitious material.

"Calcium hydroxide used up in the secondary processes could be replenished to some extent by the release of lime from the hydrating cement. Thus, products of the primary reaction provide a reactant necessary for the continuation of the secondary processes. "Since the secondary cementitious matter would be mainly formed on or near the surface of clay particles, the flocculated particles would be *glued* together at points of contact by the secondary cementitious materials. Even stronger bonds may be expected to develop between the hydrating cement paste and clay particles coating cement grains. The structural similarity between some cement hydration products and clay minerals even suggests possibly epitaxy; i.e., a direct propagation of a similar structure from clay crystal to cement particles.

"The overall effect of the postulated cement-clay interaction would be the formation of primary and secondary cementitious matter. The primary products harden into a high strength *aggregate* and differ from normally hydrated cement in that their calcium content is lower. The secondary processes enhance the strength and stability of soil-

cement by producing additional cementitious matter which increases interparticle bond strength."

Tests performed by Herzog and Mitchell (1963) support their hypothesis on the portland cement-soil system. There is also a hypothesis that as a stabilizer, lime has the capability of migrating deep into the soil lumps to cause stabilization, often referred to as lime migration. But in this case it is difficult to see this as other than the migration of Ca^{2+} ion in which case the source of supply would surely be irrelevant.

HYPOTHESIS OF LIME MIGRATION

The term "lime migration" is primarily used in the context of diffusion and "diffuse cementation" of soil in the presence of stabilizers. Conceptually, the parameters that control this phenomenon should be those (such as concentration gradient, temperature, activation energy, etc.) associated with the diffusion process. As lime migration or diffused cementation refer primarily to the migration of Ca^{2+} into the layer structure of clay, it will be equally applicable to any stabilizer that supplies calcium. The extent to which this takes place depends, primarily, on the chemical potential (concentration gradient of calcium) between the core (reaction front) and the outer surface (pore). Therefore "lime migration", in principle, will not be associated solely with the addition of lime as stabilizer.

Stocker (1972, 1974, 1975) published a series of papers on the physical and chemical changes that occur in coarsely pulverized clayey soil stabilized with lime or portland cement. The 1975 paper was the last of this series in which the chemical aspects of the concept of diffusion and diffuse cementation associated with both the stabilizers have been discussed at length. A number of recent publications have repeatedly hypothesized the existence of this phenomenon with regard to the diffusivity of lime into lumps of coarsely pulverized soil. In this context, Stocker's work has been grossly misinterpreted. According to Stocker, "diffuse cementation" is the form of cementation that takes place when soil is stabilized with both portland cement and lime. However, additional cementation, called "skeletal cementation" can be produced with portland cement but not with lime.

Stocker's work compared the characterization of the physical and chemical properties of a heavy clay soil stabilized either with calcitic hydrated lime or with Type I portland cement, at dosages of 3% and 15% by dry weight of soil. From the concentration profile of calcium, silica, and alumina from the surface to core of clay lumps, he proposed that the $Ca(OH)_2$-clay reaction product contains SiO_2 and Al_2O_3 molar ratio of 4.5:1. The estimated volume of the calcium silicate and aluminate hydrates formed prompted him to suggest that the reaction occurs exclusively at the montmorillonite edges and approximately 0.5% $Ca(OH)_2$ was adequate to produce a unit layer of reaction product and eliminate swelling on wetting. He suggested that after the initiation of reaction, the rate is rapidly suppressed as the first layer of reaction products significantly impedes further reaction between montmorillonite and $Ca(OH)_2$. For further reaction, $Ca(OH)_2$ must diffuse through the reaction product and, as a result, the reaction rate is further reduced. This results in a concentration build-up in the adjacent pore fluid, which sufficiently increases the chemical potential between the interior and exterior of the clay lump to cause a deeper diffusion. The initial adsorption of 0.5% $Ca(OH)_2$ occurs rapidly and the $Ca(OH)_2$ concentration remains high throughout the system. Further, the $Ca(OH)_2$-clay reaction shows a tendency to produce uniform deposition of similar reaction products and, thereby, a

tendency of uniform cementation, also called "diffuse cementation," throughout the system. He proposed that the adsorption of reaction product on the crystal edges and suppression of reaction rate are essential for diffuse cementation.

In his diffusion cell studies, Stocker used artificially prepared clay lumps and monitored the modifications taking place both within the lumps and in the matrices near the interface. These lumps were then removed at various ages and dissected at different depths. The concentrations of calcium in soil samples stabilized either with 15% lime or with 15% portland cement at the diffusion edge were measured following the acid extraction and are shown in Figures 4 and 5. The calcium concentration at 1-day at a depth between 1.6 mm (0.063 in.) and 3.2 mm (0.13 in.) for soil stabilized with portland cement was 450 meq/100 g and is close to that for soil specimens stabilized with 15% lime (510 meq/100 g). Apart from the slightly lower maxima, the calcium profiles in either case are similar in all respects.

The stabilizer dosage selections of 15% by Stocker above is not representative of the addition level typically used in the soil-stabilization practice. Illustrated in Figure 6 is the variation of acid-extracted calcium concentration (not contributed by gypsum) with time in natural soil lumps stabilized separately with 3% each of lime and portland cement. At the age of one year, the percentages of $Ca(OH)_2$ by weight of soil in lumps stabilized with 3% lime exhibit a gain of approximately 1.5% at the outer edges of the lumps (0 to 5 mm depth) and approximately 1.4% at the interior of the lumps (5 to 10 mm depth). A similar value (approximately 1% $Ca(OH)_2$) was also observed at the exterior and interior of lumps of soil stabilized with 3% portland cement at the age of one year. Initially, in both cases, the level of $Ca(OH)_2$ in the interior of the lump was lower than that at the exterior. While this lag is not so drastic in the case of portland cement, it is substantial in the presence of lime. The depressed value of $Ca(OH)_2$ content in the interior is most likely attributable to the formation of reaction products and retardation of the reaction mentioned earlier. After three days, because of the higher concentration of lime at the outer surface of the lump, the chemical potential between interior and exterior became high enough to cause a significant rise in the $Ca(OH)_2$ content. At approximately eight days, the inner concentration in the lime-stabilized soil lumps caught up with the outer concentrations and rose in a similar fashion, thereafter maintaining a stable difference in concentration. The initial depression, an abrupt rise (a few days later) in $Ca(OH)_2$ content, and the time period at which the $Ca(OH)_2$ content of the interior and the exterior of lumps converged are indications of the differences in concentration between the front of the reaction and the pore solution.

This lag of $Ca(OH)_2$ content between interior and exterior of lump was virtually absent in the case of portland cement-stabilized soil lumps. Initially, the $Ca(OH)_2$ concentration at the inner and outer sections increased at different rates, and after four days the rates were quite similar. At approximately 10 days the $Ca(OH)_2$ content in the inner and outer lumps became equal and maintained the equality over the investigation period of one year (see logarithmic scale of Figure 6). This equality, however, is absent in the case of lime-stabilized soil, where the $Ca(OH)_2$ content exhibited a rise while maintaining approximately a constant difference. In both cases, the similarity in the rate of rise in $Ca(OH)_2$ content between the interior and exterior of the lump indicates that a steady state has been reached between the supply of calcium at the interface and its consumption at the reaction front. The prevalence of a steady state may likely be linked to the existence of smooth continuity (lack of abruptness in soil modification across the reaction front) of cementation across the interface between lump interior and exterior.

Based upon the work by Stocker (1972, 1974, 1975), 0.5% $Ca(OH)_2$ was sufficient to cause cementation that was only a layer thick and retarded the rate of further reaction. It was also mentioned that the first 0.5% $Ca(OH)_2$ was rapidly gained uniformly by all the systems, and further advancement of the reaction front depended upon the chemical potential between the reaction front and the pore solution. However, the diffusion of $Ca(OH)_2$ continued, although at a reduced rate that was determined by the concentration of calcium in the pore fluid. A higher concentration in pore fluid will generate higher chemical potential and, thereby, will result in deeper and faster penetration.

Retardation after 0.5% uptake and subsequent diffusion dependence may be attributed to the small difference (slightly less than 1% for portland cement and slightly more than 1% for lime) in the overall gain in $Ca(OH)_2$ content in a year between soil stabilized with 3% portland cement or lime (see logarithmic scale of Figure 6 at 365 days).

In soil stabilization, lime is added as hydrated lime (essentially $Ca(OH)_2$), and the $Ca(OH)_2$ generated by hydration of cement is typically 31% of the weight of cement. This may mislead some to believe that, in order to maintain the $Ca(OH)_2$ equivalency, one has to add more portland cement. However, according to Stocker, 0.5% of diffused $Ca(OH)_2$ was adequate to eliminate swelling upon wetting from the as-cured state and 2% of diffused $Ca(OH)_2$ increased the as-cured strength by 10-fold. A lime addition in the field of 4% to 5 % is common. Therefore, the addition level practiced and the level needed for beneficial effect are not the same. One reason for using a higher than required amount is, of course, to achieve a uniform mixture. However, this is a physical and not a chemical requirement.

This phenomenon of diffused cementation (or lime migration as described by some researchers) is applicable to any stabilizer that provides pore fluid with Ca^{2+} ions, the essential component necessary for stabilizing heavy clay. From the practical point of view and from Stocker's (1972, 1974, 1975) results, however, the use of a higher amount of portland cement may not be necessary as only a 0.5% uptake of $Ca(OH)_2$ was enough to eliminate swelling upon wetting. But, it is not clear from the reference whether this is a short- or long-term effect; it seems probable that the full benefit will only be achieved upon further penetration of Ca^{2+} to the interior with more complete ion exchange as Stocker has shown to occur with both portland cement and lime. Furthermore, the formation of networks such as C-S-H will also be beneficial in strength development, leaching characteristics (McCallister, 1990; McCallister and Petry, 1990) and, thereby, long-term performance.

FACTORS AFFECTING THE STABILIZED PROPERTIES

In general, most clay soils can be successfully stabilized with portland cement or lime. However, the achieved engineering properties of a stabilized soil are dependent upon a number of parameters as discussed in the following sections. Besides all the engineering properties, the clay mineral composition of a soil is one of the most dominant factors determining the chemical and physical properties of a soil. The presence of a small amount of montmorillonite, with the highest cation exchange capacity, can greatly influence the physical properties of soils. Christensen (1969) investigated a total of 11 soils and observed a linear relationship (see Figure 7) between the clay content of soils and cation exchange capacity. The characteristics of these soils are shown in Table 1. A linear relationship (see Figure 8) was also observed between the clay content and the plasticity indices. A combination of these two linearities indicates that there

should be a linear relationship between cation exchange capacity and the plasticity index (PI). The particle size and shape also influence the properties of soils. As the ion exchange in illite and kaolinite takes place primarily at the interface and edges, the cation exchange capacity of soils in their presence may be different as particle size and shape are changed.

Only limited information is available regarding how various factors influence the engineering properties of a stabilized soil. While the contributory parameters are many (Felt, 1955), some of the more important ones are listed below.

1. Stabilizer dosage
2. Mixing conditions
3. Compaction method and effort
4. Gradation and pulverization
5. Curing period and conditions
6. Delayed compaction
7. Climatic conditions

Table 1. Characteristics of Soils Investigated by Christensen (1969)

Soil No.	1	2	3	4	5	6	7	8	9	10	11
CEC* (meq/100 g)	45.8	13.1	31.2	13.3	46.0	16.0	30.7	19.1	27.6	25.8	20.0
Particle size distribution (%)											
Gravel (76.2-2.0 mm)	0	7	1	4	0	2	0	0	9	1	0
Coarse sand (2.0-0.42 mm)	2	14	2	6	3	4	1	3	6	2	0
Fine sand (0.42-0.074 mm)	4	18	16	29	4	38	27	32	5	1	20
Silt (0.074-0.005 mm)	40	31	41	32	34	29	25	32	33	23	52
Clay (< 0.005 mm)	54	30	40	29	59	27	47	33	47	73	28
Maximum dry density at optimum moisture											
MDD[†] kg/m^3 (lb/ft^3)	1474 (92)	1826 (114)	1537 (96)	1778 (111)	1394 (87)	1714 (107)	1554 (97)	1714 (107)	1602 (100)	1634 (102)	1602 (100)
OMC**, %	25	14	24	15	27	18	24	16	22	21	21

*CEC = cation exchange capacity [†]MDD = maximum dry density **OMC = optimum moisture content

Stabilizer Dosage

The amount of stabilizer determines the supply of calcium, the most necessary component for clay soil stabilization, and calcium may be supplied from various sources. The presence of a stabilizer may not only supply calcium to the system, but its other characteristics may also contribute to the overall properties of a stabilized soil. This is true particularly in the case of portland cement or lime stabilization of clayey soils. In the case of time-dependent effects, some of the improvement may occur too late to be of interest or to be applied in design considerations. In addition to the supply potential, there is also a lower limit of the stabilizer dosage below which the necessary mixing uniformity cannot be achieved in normal construction operations in the field as opposed to the laboratory.

The two primary factors, plasticity index (PI) reduction and strength development, either individually or in combination, are generally specified. Often, minimum strength requirements are specified at a particular time period, usually 7 days, after treatment with a stabilizer. All these factors need to be considered in selecting the type of stabilizer and dosage levels necessary.

When lime is added to soil for modification of soil properties, it is termed a stabilizer and the resultant soil is called lime-modified soil. However, when portland cement is used for the same purpose, it is generally termed differently depending on the dosage level. This is primarily due to the fact that the dosage level determines the properties to be achieved. As an example, simple modification of soil properties with portland cement, as with lime, is termed a cement-modified soil. This resulting modified soil is an improved soil in unhardened or semi-hardened state. This is achieved by using the least amount of cement. When the cement content is increased, the resulting material is referred to as hardened soil-cement. In this case, the criterion is based upon durability and the compressive strength. Soil-cement provides a hardened and durable pavement base with sufficient strength to help support traffic loads.

It is, therefore, imperative not to mix the range of dosages of portland cement necessary to achieve different properties with the dosage used for lime-modification. While the range of properties achievable by varying the dosage levels of portland cement is advantageous in many situations, the tests used for soil-cement (a much harder material) should not be used to evaluate the performance of a cement-modified soil that is much weaker. *Often, lime-modified soils are evaluated using appropriate tests, while cement-modified soils are inappropriately tested using those tests designed for evaluating hardened soil-cement.*

Procedures for Designing Soil-Lime Mixes. In order to determine the necessary lime dosage, a number of mixture design procedures are available for lime. These procedures, listed in the State of the Art Report on Lime Stabilization (State of Art Report, 1976, 1987), are given below with the properties these tests are based upon. California Procedure: Optimum moisture content and unconfined compressive strength of lime-soil mixes with various lime content.

Eades and Grim Procedure: This measures pH to determine the design lime dosage. The amount of lime necessary to achieve a pH of 12.4, the saturation pH of $Ca(OH)_2$, is considered to be adequate.

Illinois Procedure: This procedure is designed for two stabilization objectives: base or subbase stabilization, and subgrade modification. The criterion used for the former is based upon the unconfined compressive strength and that for the latter is based upon the reduction in Plasticity Index (PI).

Oklahoma Procedure: This is based upon the Eades and Grim procedure. However, a PI reduction criterion is also used as an alternative.

South Dakota Procedure: Initial lime requirements are determined using the pH procedure of Eades and Grim. Supplemental strength data are generated through California Bearing Ratio (CBR) and unconfined strength measurements.

Texas Procedure: Unconfined compressive strength is used as the criterion (AASHTO T-220).

Thompson Procedure: This procedure is more elaborate than the others and separate criteria are used for subgrade modification and for base and subbase materials. It combines a number of properties, such as maximum dry density, unconfined compressive strength, PI reduction, etc.

Virginia Procedure: This is based upon the compressive strength measurements of cured mixtures of soil and various dosages of lime.

It will be noted that strength is usually a secondary criterion, and that durability criteria are notably absent. Where CBR is used as a strength criterion, clearly the advantage of stabilized clay soils resides in their lesser loss of bearing strength after saturation, as the CBR in "dry" conditions can be extremely high for clays but is almost entirely lost upon soaking.

Procedures for Designing Soil-Portland Cement Mixes. For cement-modified soils, PI reduction and compressive strength measurements are typically used for mixture design determination It has been reported (Pendola et al., 1969) that while the strength of sands, and silty and clayey soils was improved with the incremental addition of cement, the strength developed in these materials was different, and the sandy soil exhibited the greatest strength. The effect of cement content on strength development with age had also been reported (Cierco et al., 1962). The rate of strength development was higher with higher cement content. Increasing cement content also was reported to improve the durability (Abrams, 1959) and load-bearing capacity (Nussbaum and Larsen, 1965). This behavior corresponds well to the discussion above regarding the enhancement of properties when the resulting material is changed from a cement-modified soil to a soil-cement by increasing the cement content.

Comparative Discussion On The Dosage Of Portland Cement And Lime. When comparative studies are conducted to evaluate the effectiveness of stabilizers, and an equal amount of stabilizer is used, the sample preparation and the testing procedures may not be universally applicable to all stabilizers. In a comparative study, Petry and Wohlgemuth (1988) determined the amount of lime (10%) and portland cement (12%) required by using the Eades and Grim method and also measured the resulting Atterberg limits. In the case of lime, the pH was 12.4 and the plasticity of the soil was reduced from over 60 to 16.8. In the case of portland cement, however, no pH value has been mentioned and a 12% addition reduced the plasticity of the soil to 12. The portland cement dosage selection in this method may be misleading due to the limitations mentioned in Section 2.3. The 10% to 12% dosage levels are somewhat higher than what is practiced in the field for soil-modification.

Christensen (1969) measured the liquid, plastic, and shrinkage limits of 11 different soils modified with 3% and 5% portland cement and lime. Prior to measuring these limits, all modified soils were also cured for 24 hours and some selected ones were cured for 1 hour and 48 hours. Two kinds of drying methods, oven dry and absorption dish, were used for comparison purposes. In the oven dry method, the samples were dried at 60°C (140°F) and subsequently the soil was ground and that passing the No. 40 sieve was collected to measure PI. In the absorption dish method, the wet mixture was placed and kept on an absorption dish made of plaster of paris until the excess water was absorbed. The absorption dish method has been mentioned as providing a more representative field performance. Cement- and lime-modified soil samples, cured for 24 hours, when dried by the absorption dish method, exhibited a small decrease in liquid limit but a large increase in plastic limit. The reduction in liquid limit was higher when the modified soils were dried in an oven. As a result, the PIs of oven-dry modified soils were lower than those dried in an absorption dish. Regardless of the drying method and the stabilizer (portland cement and lime) used, the reduction in PI was quite comparable for both the modifiers. In addition, when a major reduction in PI of 11 clayey soils was achieved by using only 3% modifier and by increasing the dosage to 5%, there was little further reduction in PI.

This observation is in line with that of Stocker (1975) mentioned earlier, that a 0.5% uptake of $Ca(OH)_2$ is very rapid and subsequent increase is controlled by the diffused cementation.

Shrinkage limit, measured by Christensen (1969), 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 assures 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, and likewise, a loss of moisture will not cause any shrinkage. The effects of addition of portland cement and lime to soil on the shrinkage is shown in Figure 9. The addition of either stabilizer increased the shrinkage limit of 10 for the untreated soil to above 30 for the treated ones. Apparently, the higher dosage level (5%) increased the shrinkage limit in all cases. However, out of 11 soils evaluated with 5% lime or portland cement, the shrinkage limit of eight soils was higher when portland cement was used. This suggests that portland cement-modified soils are dimensionally more stable over a wider moisture range than the lime-stabilized soils.

Similar to the shrinkage limit, the cohesiometer test values also increased as the stabilizer content was increased from 3% to 5%. The cohesiometer value is determined (Test Method Tex-122-E, 1962) by measuring the force required to bend or break the soil specimen supported as a cantilever beam. The cohesiometer value is defined as the weight in grams required to break a test specimen with dimensions equivalent to 3 in. in height and 1 in. wide. With respect to the compactive effort and curing conditions (discussed later), this test method discriminates between the soil stabilized with portland cement and lime. The formation of a rigid network in the case of portland cement-modified soil may be attributable to higher cohesiometer values.

Petry and Wohlgemuth (1988) mostly observed a decreasing trend in the 1- and 7-day unconfined compressive strengths of the stabilized soils as the lime content was increased. At 28 days, they claim that the strength increased with lime content to the optimum and remained unchanged thereafter. However, from Figure 10 such a trend is not apparent. Rather, the strength had either remained unchanged or decreased by varying the lime content from 7% to 13% (error limits in these data were not mentioned). The trend with the portland cement stabilized soil at 7 and 28 days, however, is that the strengths increased with the amount (9% to 15%) of portland cement. In general, the unconfined compressive strength values of portland cement-modified soils were higher than the lime modified-soils at all curing days. Therefore, when enhancement in strength is necessary, the use of portland cement is appropriate, as beyond a certain dosage level, increasing lime does not enhance the strength of the resulting material.

The achievement of higher strength with portland cement may be attributed to two factors. Firstly, the $Ca(OH)_2$ crystals generated as a by-product of the hydration of calcium silicates are pure and fine; thereby, they are much more reactive. This provides the calcium necessary for ion exchange. Secondly, there is the formation of a rigid network by the hydration of portland cement, as occurs in mortar or concrete. The extent to which a network may form in soil should depend on the amount of portland cement used. At smaller dosages the networks may be small and isolated. However, with increasing amounts of portland cement, a three-dimensional network may form where the soil particles are either isolated or may form their own three-dimensional network. This versatility may be of significant use when different properties are required from the same soil.

Mixing Conditions

The purpose of mixing is to disperse the stabilizer efficiently and uniformly. As the pavement bases are most frequently constructed by in-place mixing, the laboratory mixing conditions should, in the optimum case, approximate the field conditions. Often the mixing sequence, duration, and time period between mixing and compaction for soil stabilized with either portland cement or with lime are different. Soil-lime mixtures are generally cured for a few days (known as the mellowing period) while the portland cement-stabilized soil mixtures are compacted immediately after the mixing. Even if a particular soil is mixed with portland cement or lime, often the mixing procedures, compaction time, curing conditions, preparation of the test specimens, etc. are different. Furthermore, the stabilizing mechanisms are not quite the same. Therefore, these two products may differ in their engineering properties. In fact, allowing no time between the end of mixing and compaction of cement-treated soil makes the mixing procedure even more critical compared to that for lime-stabilized soil where a few days of mellowing is generally permitted. It is rather important that mixing procedures for the cement-treated soil and the time of compaction be optimized prior to drawing any meaningful conclusions on the relative effectiveness of the stabilizer.

In order to monitor the effect of delay period after mixing, Christensen (1969) measured the Atterberg limits of clayey soils (with and without portland cement or lime as modifier) at 1 hour (four soils with 3% modifier), 24 hours (11 soils with 3% and 5% modifiers), and 48 hours (four soils with 5% modifier) after mixing. The soil and modifiers were first mixed with a spatula. Following water addition, the mixture was further mixed. Although it is possible that mixing with the spatula did not produce a homogeneous mix, the results do not indicate any significant gain or loss in PI compared to those delayed for 24 hours. This is applicable to both portland cement- and lime-stabilized soils and at both 3% and 5% dosage levels. However, as discussed later, the moisture-density relationship in portland cement modified soil was altered (in reference to compaction immediately after mixing) when the compaction was delayed by 24 hours. In contrast, the moisture-density relationship remained unchanged when the soils were modified with lime.

Effect of Compaction Method and Compactive Effort

Soil is essentially a mixture of solid minerals, water, and air, and for specific compactive effort at a certain moisture content the solid particles will achieve their closest packing or highest density. A number of factors, such as surface tension of the liquid, surface charges, and polarity of the mineral structures determine the interparticle distances. During compaction, entrapped air is expelled rapidly to produce a compact mass, in contradiction to the long-term expulsion of water under load, which constitutes consolidation. Thus, both the moisture content and compactive effort are critical in determining the density of a soil. Compacted soil specimens always contain an interconnected pore structure filled with air and free (not chemically bound) water. Therefore, a higher compactibility is strongly related to the porosity and the pore structure of the specimen.

The density of cement (3.15 g/cm^3) is 40% higher than that of lime (2.25 g/cm^3). Furthermore, hydrated lime, as opposed to quicklime, has no affinity for water, whereas unhydrated cements are made of calcium silicates and aluminates and have a high affinity for water. When portland cement hydrates, it generates a number of hydration products having

different numbers of bound water molecules. It also generates $Ca(OH)_2$ as a byproduct of the hydration reaction of the calcium silicates. The formation of all these phases containing water and $Ca(OH)_2$ obtain the requisite water from the soil specimen. This reduces the amount of free water in the mixture as a whole. In this context it is important to know that in the reaction $CaO + H_2O = Ca(OH)_2$, every mole of CaO requires one mole of water, and this corresponds to 3.2 g of H_2O for 10 g of CaO. Clearly the situation is complex, as sufficient water must be present for lubrication to achieve high dry density (as seen by the concept of optimum moisture content). However, any moisture beyond the optimum moisture content (OMC) "gets in the way" of further densification.

Standard Laboratory Compaction Methods. Primarily there are two standard laboratory compaction methods, commonly known as standard Proctor (ASTM D 698 and AASHTO T 99) and modified Proctor (ASTM D 1557 and AASHTO T 180). Compaction is performed at varying moisture contents in steel molds using a drop hammer to provide a consistent effort. Standard and modified Proctors differ by the number of lifts and the compactive effort; 600 kN-m/m^3 (12,400 ft-lbf/ft^3) for standard Proctor and 27,000 kN-m/m^3 (56,000 ft-lbf/ft^3) for modified Proctor. Dry density and moisture content are determined and plotted. Usually a curve with a well-defined maximum is obtained. The peak defines the maximum dry density (MDD) and the optimum moisture content (OMC), which are used in specifications, e.g. "field compaction shall be at a moisture content of OMC ±2%, and achieve a minimum of 95% of MDD."

Effect of Gradation. Petry and Wohlgemuth (1988) measured the moisture content for the maximum dry density of soils with three gradations. These gradations were coarse: 100% passing 44 mm (1.75 in.) sieve and 60% passing No. 4 sieve; medium: 100% passing 25 mm (1 in.) sieve and 80% passing No. 4 sieve; and fine: 100% passing No. 4 sieve. The compaction curve or the moisture-density curve for each gradation was determined separately for each stabilizer: lime and portland cement. The compaction of the stabilized soil was performed following a modified compaction method based upon Test Method Tex-113-E (Texas Department of Transportation standard). A compaction energy of 331 kN-m/m^3 (6,912 ft-lb/ft^3) was achieved by using a 150 mm (6 in.) diameter and 100 mm (4 in.) high mold and a 2.5 kg (5.5 lb) hammer that was dropped from a height of 300 mm (12 in.). The compaction effort used in the standard methods, however, is higher than that used by the investigators by a factor of 1.8 for standard Proctor and 8 for modified Proctor. However, it should be noted that the effects of compaction effort on density are far from linear; as an example, the difference between standard and modified MDD for soil is usually only about 5% even though the ratio of efforts is almost 5:1.

It has also been reported that upon lime addition and compaction after 24 hours, the maximum dry density and optimum moisture content values remained virtually invariant. Furthermore, no influence of soil gradation was observed (Petry and Wohlgemuth, 1988). On the other hand, portland cement acted as a compaction aid, and at lower optimum moisture content, higher maximum dry densities (compacted immediately after mixing) were achieved in all three gradations. Like lime-treated soil, no trend in moisture-density behavior was observed with gradation of the portland cement-modified soils. While the probable reason(s) can be derived from the consideration of the physico-chemical nature of cement and lime, no explanation for these observations was given.

Immediate vs. Delayed Compaction. The above observed behaviors have some similarity and dissimilarity with those reported by Christensen (1969). Christensen investigated a total of 11 soils with Type I portland cement or hydrated lime, and the moisture density relationship was established by using the standard Proctor procedure (ASTM D 698). All clay soil specimens used passed the No. 4 mesh and the amounts of lime or portland cement used to stabilize these soils were 3% and 5%. Upon treatment with portland cement or lime, the maximum dry density decreased (portland cement by 19.2 kg/m^3 (1.2 lb/ft^3), lime by 52.3 kg/m^3 (3.7 lb/ft^3); and the optimum moisture content increased (portland cement by 0.6%, lime by 2.1%) in both cases. However, the decrease in maximum dry density and increase in optimum moisture content of lime-treated soils were more than those stabilized with portland cement. Upon delaying the compaction by 24 hours after mixing with the portland cement, the maximum dry density was further reduced (approximately 48.1 kg/m^3 or 3 lb/ft^3) and the optimum moisture content was increased (approximately 1.8%) compared to those compacted immediately after mixing. On the other hand, no particular change was observed between the lime treated specimens compacted immediately after mixing and those compacted 24 hours later. The observation of such differences may be related to the nature of the clay soil, stabilizer dosage, stabilizing mechanism associated, and the compaction methods used.

From Christensen's (1969) work it is apparent that compaction of portland cement-modified soil immediately after mixing provides higher maximum dry density at lower moisture than those compacted 24 hours after mixing, whereas nothing can be gained or lost in the moisture-density relationship when lime is used. This is an indication that the reaction mechanisms are somewhat different for these two stabilizers and, therefore, appropriate caution should be taken when undertaking a comparative investigation.

Effect on Unconfined Compressive Strength. The unconfined compressive strength measurements were performed by Christensen (1969) on clayey soils with lime or portland cement (3% and 5% dosage levels in both cases) that were machine-mixed and compacted using standard Proctor either immediately after mixing or after a 24-hour delay. These specimens were cured at room temperature in polyethylene bags until tested at 7 and 28 days. It is assumed that care must have been taken so that no moisture was lost from the specimens.

Figures 11 and 12 illustrate the effect of clay content of untreated soil and the delay of compaction by 24 hours on the 28-day unconfined compressive strength of soils treated with 5% portland cement or lime. It is evident that the unconfined strength of all cement-modified specimens is higher when the compaction was immediate. In the case of lime-modified soils, the unconfined compressive strengths varied when the compaction was delayed by 24 hours. The following four conclusions can be drawn from Figures 11 and 12:

- Portland cement modification exhibits higher strength than lime modification for all soils when the compaction was performed immediately.
- The difference in strength between portland cement and lime diminishes at higher clay content of soil.
- The difference in strength between portland cement and lime also diminishes as the compaction was delayed by 24 hours and in a few cases lime-modified samples had higher strength than cement-modified ones.

- While all the cement-modified soil samples exhibited diminished strength when the compaction was delayed, approximately half of the lime-modified samples also exhibited reductions in strength.

The observation of lower unconfined compressive strength of portland cement-modified soil when compaction was delayed may have been taken by some researchers as the rationale for immediate compaction for cement-treated specimens and a mellowing period for lime-treated ones.

In addition to the above observations, further trends in the unconfined compressive strength can be established by critically analyzing the data presented by Christensen (1969) on the effect of 3% and 5% dosage levels over a period of 4 weeks. All specimens were cured in polyethylene bags at room temperature. Both the portland cement- and lime-stabilized soils gained strength between 7-and 28 days and, as discussed above, portland cement-stabilized soils generally exhibited higher strengths. However, the percent gain in strength in this 3-week period was higher (average 60%) for lime-stabilized soil than that (average 30%) for cement stabilized soil. On the other hand, the increase in strength attained by increasing the dosage level from 3% to 5% was higher for cement-stabilized soil. The dosage-dependent gain in 7- and 28-day strengths was approximately 60% for the cement-stabilized soils and approximately 35% for the lime-stabilized soils. This indicates that with portland cement, the strength development begins early on and the contribution to strength of a stabilized soil is superior to that achieved through lime stabilization.

In a comparative study by Kennedy et al. (1987) between the standard and modified Proctor for clayey soil with a PI of 36, it has been demonstrated that the higher compactive effort substantially increased (approximately by a factor of 4) the dry unconfined compressive strength of soil stabilized with either portland cement or lime. One clay with a PI of 39 stabilized with lime and compacted with modified Proctor exhibited higher strength than that stabilized with portland cement. Another clay with a PI of 36 reported to have comparable or higher compressive strength when stabilized with portland cement and compacted using either standard or modified Proctor. The sandy clay with a PI of 11 and modified with portland cement had much superior strength values.

For soils with PIs as high as 70 and stabilized with portland cement, Petry and Wohlgemuth (1988) reported consistent superiority over lime in unconfined compressive strength with both curing period and dosage level (7% to 13% for lime and 9% to 15% for portland cement) at all three gradations. They found that most cement stabilized soils exhibited higher loss of wet strength between 28 and 126 days. However, for two soils (PI of 36 and compacted at standard Proctor and PI of 11 and compacted at modified Proctor) the wet strengths were higher than those stabilized with lime of similar amount. Nevertheless, the stabilization with portland cement was concluded to be inferior (Kennedy et al., 1987).

The clays used by Christensen (1969) had PIs ranging from 18 to 41 and the lime and portland cement dosages used were 3% and 5% based on the dry weight of the soil. The clays used by Kennedy et al. (1987) had PIs of 11, 36, and 39; and 4% and 7% lime or portland cements were used as stabilizers. Apparently, these two investigations have some similarities, but the results obtained are quite different. Christensen (1969) demonstrated the superiority of portland cement over lime through an extensive experimental program measuring a number of relevant properties. On the other hand, Kennedy et al. (1987) do not refer to Christensen's work and indicate the inferiority of portland cement based upon the performance of one soil with a PI of 39 and compacted using modified effort, while ignoring the results obtained with two other

soils with PIs of 36 and 11 and the superior performance of portland cement when compacted using standard effort. These conflicting observations indicate that even after years of research the true phenomena are far from being understood, and conscious efforts with truth-finding missions are warranted.

Although Kennedy et al. (1987) attributed the loss of unconfined strength upon wetting of the cement-modified specimens to the generation of increased swelling pressure, it may equally be true for the lime-modified specimens. According to Christensen (1969), the swelling of portland cement-stabilized soil with higher shrinkage limit is expected to be less than for lime stabilization. As no information was reported regarding the shrinkage limit, dry density, and optimum moisture content of these specimens, it is difficult to conclude that such a phenomenon was applicable only to the cement-modified soil specimens.

Effect of Compactive Effort. An increase in compaction brings the particles closer together and removes more air from the system, which may make the system less accommodative to any volume change. According to the data presented by Kennedy et al. (1987), it appears that while the lime-modified specimens accommodate relatively well at higher compaction, the cement-modified specimens perform better at lower compaction levels. This may be an indication that the compactive effort may need to be varied over a range to achieve the optimum characteristics from soil specimens stabilized with either portland cement or lime. In other words, the moisture-density curve may need to be supplemented by strength or other engineering data of relevance to the proposed need, and possibly more than one moisture-density curve developed in order to define the best all-around mix design. However, the problem with this approach is that compaction in the field is performed with equipment that does not relate directly to the laboratory equipment, and it may be necessary to define project needs based on such laboratory studies and leave it to the contractor to find equipment and procedures to attain the desired properties of the stabilized soil.

The cohesiometer values are related to the tensile properties of the stabilized soil. Cementitious systems, such as mortar and concrete, are known to have high compressive strength but low tensile strength due to size and concentration of defects. However, an increase in compressive strength generally improves the tensile strength (maybe at a different rate). Therefore, the unconfined compressive strength and cohesiometer values of soils modified with either portland cement or lime should exhibit a similar trend. The validity of this rationale can be drawn when the cohesiometer results (discussed below) of Christensen (1969) and unconfined compressive strength results (discussed above) of Kennedy et al. (1987) are combined.

Christensen (1969) performed the cohesiometer test on soils stabilized with 3%and 5% portland cement or lime and compacted at two compactive efforts, 570 kN-m/m^3 (13.26 ft-lb/in.^{3}) and half of that, 280 kN-m/m^3 (6.63 ft-lb/in.^{3}). The Test Method Tex-122-E (1962), however, calls for a compactive effort of 570 kN-m/m^3 (13.26 ft-lb/in.^{3}) for lime-stabilized soil and of 280 kN-m/m^3 (6.63 ft-lb/in.^{3}) for portland cement-stabilized soil. The cohesiometer values for both portland cement- and lime-stabilized soils increased when the compactive effort was doubled, and in general, all cement stabilized soil, both at 3% and 5% dosage levels, exhibited higher cohesiometer values. Furthermore, the degree by which the cohesiometer values was greater in soil stabilized with 5% portland cement compared to that in soil stabilized with 5% lime depended on the clay content of the soil. For a clay content between 40% and 73%, the average cohesiometer value was higher by 31%, whereas at 27% to 33% clay content the value was higher by approximately 200%. A cross comparison by Christensen (1969)

indicates that cohesiometer values are a function of compactive effort. Therefore, when the tests are performed on portland cement and lime-stabilized soils following the Test Method Tex-122E (1962), attempts to compare the test data may not be appropriate.

Effect of Soil Gradation and Pulverization

Any physico-chemical phenomenon is affected by the surface area available and the size distribution of the reacting particles. While the chemical portion of the reaction is facilitated as more surface area is exposed for further reaction, an appropriate gradation provides the mechanical interlocking and a better packing to achieve higher density of the compacted mass.

For soils that are sandy, silty, and clayey, Felt (1955) reported that for the same amount of cement and at all ages of curing the sandy soil exhibited higher compressive strength. The reaction of cement with different soils was different. With sandy soil, the reaction with the sandy fraction is expected to be similar to that in portland cement mortar. With clay, on the other hand, the reaction will be first cation exchange and subsequently C-S-H or C-A-H formation. It is, therefore, obvious that depending on the exposed surface, the reactivity of the system varies.

Presence of organic matter also influences the stabilization characteristics of a soil. Low molecular weight organic compounds such as nucleic acid, dextrose, etc., generally act as retarders and in their presence the strength gain is usually poor (Winterkorn, 1942). Likewise, the shape (angular vs. rounded) of the soil particles is also important in providing higher interparticle friction and better packing. Mechanically, a well-graded denser soil system, when stabilized with either portland cement or lime, is expected to provide improved shear and compressive strength.

A majority of the soil stabilization research was performed on finely pulverized (100% passing No. 4 sieve) soil samples. What can be expected in the field depends then on the ability of construction equipment to pulverize to this fineness, and the extent to which the presence of larger particles may affect short- or long-term reactions. Petry and Wohlgemuth (1988) investigated the effect of pulverization on the strength and durability of highly plastic clay soils that have been stabilized with lime and portland cement. They give various references that portland cement and lime react differently with the soil depending on the gradation. As a result, construction specifications normally ask for finer gradations for portland cement stabilization. According to Petry and Wohlgemuth, the United States Department of Transportation and Texas DOT ask for 100% passing the 25 mm (1 in.) sieve and a minimum of 80% passing the No. 4 sieve. Although the reference provided performed an investigation on soils with such gradation, it does not indicate any such requirement from U.S. DOT or Texas DOT. They also state, with no reference, that the Portland Cement Association (PCA) asks for 100% passing the 44 mm (1.75 in.) sieve and a minimum of 75% passing the 19 mm (0.75 in.) sieve. The authors find that these numbers are misleading as the literature indicates different size requirements.

Test Method Tex-120-E (1995), Soil-Cement Testing, and Test Method Tex-121-E (1995), Soil-Lime Testing, have requirements that the material retained by the No. 4 sieve should be processed according to the Test Method Tex-101-E (1995) and particles larger than 44 mm (1.75 in.) should not be used. Although Test Method Tex-120-E (1995) is for soil-cement, the requirements are similar to those for lime. The requirements for cement-modified soil, according to the Cement Stabilization Manual (1995), state that the plus No. 4 materials to be minimum 100% passing 38 mm (1.5 in.) sieve and a minimum 85% passing 19 mm (0.75 in.) sieve. The City of San Antonio Standard Specifications for Construction (1994) specifies the plus No. 4

sieve materials to be minimum 100% passing 44 mm (1.75 in.) sieve and a minimum of 85% passing 19 mm (0.75 in.) sieve.

Unfortunately, Felt's (1955) conclusions on soil-cement have been misrepresented as cement-modified soil, although Felt repeatedly mentioned in his article that soil-cement is different from cement-modified soil. The unavailability of specifications for cement-modified soils prompted some investigators to use specifications established for soil-cement. Technically, this is inappropriate as these two materials are not the same with respect to their engineering, chemical, and durability requirements, and the ultimate use.

Influence of Pulverization on the Physical Properties. The work by Grimer and Ross (1957) on the effect of pulverization on the unconfined compressive strength indicates that pulverization improves the strength properties. Also, the strength retained after immersion in water (for 7 or 28 days) following 7 days of curing was more for specimens with pulverized soil. From a physicochemical (exposed surface area, packing, etc.) viewpoint, this observation is quite appropriate and is equally applicable to both portland cement- and lime-soil systems. In fact, Petry and Wohlgemuth (1988) observed a similar behavior for soils stabilized with either lime or portland cement (see Figure 13). It is obvious from the figure that portland cement-modified soil specimens at all gradations and curing periods exhibited superior or equal strength behaviors compared to those stabilized with lime.

Davidson et al. (1965) reported that soil specimens containing lumps and stabilized with lime exhibited a decrease in strength. However, after approximately 150 days of curing, the strength values were comparable to those with smaller amounts of lumps. This observation may be equally applicable to soils modified with portland cement. Furthermore, if these soil specimens were tested in a manner similar to that of Grimer and Ross (1957), the likelihood of obtaining similar results are highly probable. This implies that the curing and the testing times are rather important regardless of the stabilizer used, and, therefore, undertaking the proper testing scheme is necessary to realize the beneficial effects of stabilizers.

Referring to the soil stabilization process with lime as a physicochemical phenomenon and that with portland cement as a mechanical one by Petry and Wohlgemuth (1988) contradicts a number of prior observations. In this context, the chemistry of cement hydration has been ignored. Furthermore, the discussion on waterproofing that soil-lime reaction product provides a complete coating of soil particles and that from soil-portland cement reaction does not is not convincing and ignores the chemistry of cement hydration.

Felt's (1955) results indicate that the amount of lump (0%, 20%, and 40%) plays little role in determining the loss of weight due to wetting and drying, and freezing and thawing. The primary factor controlling the loss was the state of the lump when added. When air-dried lumps were added to air-dry mixture, and water was added to bring up the moisture content to the optimum level and compacted immediately, these specimens exhibited the most resistance to wetting and drying, and freezing and thawing. Most of the materials investigated by Felt had a PI of approximately 30 and below, with an exception of one with a PI of 83. The failure of portland cement-modified soil in wetting-drying tests depicted by Petry and Wohlgemuth (1988) is rather opposite to what has been reported by Christensen (1969) for modified soil and by Felt (1955) on soil-cement and cement modified-soil. The PI of the soils used by Petry and Wohlgemuth (1988), were unusually high (between 64 and 77) and contained 40% montmorillonite (primary contributor to plasticity).

The effect of pulverization on the unconfined compressive strength was also investigated by Kennedy et al. (1987). The pulverized specimens were 100% passing the No. 4 sieve and unpulverized soil specimens were 85% passing the No. 4 sieve, and the remaining 15% passing the 38 mm (1.5 in.) sieve and retained on the 19 mm (0.75 in.) sieve. In order to verify whether a high degree of soil pulverization is necessary prior to portland cement addition, they measured the unconfined compressive strength of the unpulverized soil treated only with portland cement and not with lime. Therefore, the effect of pulverization on the dry and wet properties of the three Texas clays stabilized with lime is not available. Also not available is the effect of compaction methods (standard and modified Proctor) on the dry and wet strength of the unpulverized clays. The observation of higher unconfined compressive strength both in dry and wet conditions in pulverized soil specimens modified with portland cement is logical. However, this does not imply that strength of lime-modified soils remains invariant to pulverization, and Petry and Wohlgemuth (1988) demonstrated the existence of such variation.

It is apparent that a better understanding of the exact need for pulverization of the soil when stabilized with portland cement or lime is needed. The $Ca(OH)_2$ concentration profile (from the surface to the core) in soil lumps, and the rapid and uniform uptake of $Ca(OH)_2$ throughout the system as reported by Stocker (1975) does not indicate that pulverization to any different degree than with lime should be needed for soil stabilization with portland cement. In future work it is recommended that the effects of the degree of pulverization be determined both for short-term effects on such parameters as plasticity, as well as long-term effects on strength. Another area needing exploration is the effect of allowing cement longer contact times (analogous to lime mellowing periods) on both short-term and long-term performance. In such cases, some loss of ultimate achieved strength may be expected due to disturbance, but this may be of minimal consequence in many potential applications.

Curing Conditions and Curing Period

The immediate benefit with respect to engineering properties achieved upon addition of a stabilizer to a soil is due to cation exchange, flocculation, and agglomeration. The long-term strength development, however, mainly depends upon the conditions of exposure. In the case of lime-stabilized soil, this is due to pozzolanic reactions, mentioned earlier. In the case of cement, the time-dependent strength development is attributable to two factors, cement hydration and pozzolanic reaction.

The discrepancy between the curing methods used for soil stabilized with lime and portland cement is apparent in the unconfined compressive strength test method as prescribed by the Texas DOT (Test method Tex-120-E, 1995; Test method Tex-121-E, 1995). In the case of portland cement, it is referred to as "soil-cement" and for lime "soil-lime." However, it is known that soil-lime is a soil that is modified with lime but soil-cement is not soil modified with cement. The curing requirement for "soil-cement" is 7 days in a moist room. After removing the specimen from the moist room, an unconfirmed compressive strength test is performed after wiping off the free water from the surface. On the other hand, soil-lime is cured at room temperature for 7 days in a triaxial cell. Upon removing from the cell, the specimen is dried for 6 hours at (140^oF) until one-third to one-half of the molding moisture has been removed. Following this, the specimen is allowed to cool to room temperature and then placed in a triaxial cell and subjected to capillarity under pressure for 10 days. Following this, the soil-lime

specimen is tested under triaxial compression. In order to make a reasonable comparison between the performance of these two stabilizers, the test requirements should be similar.

Strengths typically increase with increased curing temperatures. A faster strength development with increase in temperature has been reported for soil treated with portland cement (Clare and Pollard, 1959; Dumbleton and Ross, 1960). Studying the strength development characteristics of heavy clay, silty clay, and sand treated with lime and portland cement cured at temperatures between 32°F and 113°F, Dumbleton and Ross (1960) reported that for the cohesive soil, the increase in strength per degree increase in curing temperature was higher at higher curing temperatures. For the treated sand, the strength increase with an increase in curing temperature was uniform in the range covered. Evaluating the effect of curing temperature on the strength development of soil mixed with 10% portland cement at ages up to 90 days, Clare and Pollard (1959) made the following conclusions: (i) the strength in the first three months of cement-treated base constructed in the spring will be 50% to 100% higher than if it were constructed in the fall, (ii) cement-treated materials will harden in cold weather, provided the temperature is above 0°C, and (iii) the 7-day strength increased directly with the temperature at a rate of 2%-2.5% per degree Celsius in the curing temperature.

The increase in strength of lime-stabilized soil is also an observed phenomenon. Curing at 22.8°C (73°F) often improved the strength of many lime-stabilized soils and there is indication that the strength of some soil-lime mixtures continues to improve over a period in excess of a decade (State of the Art Report, 1976, 1987). Temperature facilitates the reaction and, thereby, the rate of strength development. From the 96-hour soaking experiment performed on the lime-treated soils, it has been reported that a 48-hour curing period at 48.9°C (120°F) was approximately equivalent to 30 days of curing at 21.1°C (70°F) (Thompson, 1969). However, the reaction mechanism and the products formed may be altered (discussed below) if cured at higher temperatures, and drawing such an equivalency can be misleading. While certain properties may seem to correspond well between the accelerated and nonaccelerated curing, other properties may not. A good example is the counter effect of temperature on the time of set and compressive strength of cementitious systems.

When the temperature is increased, any activated process (such as diffusion, some chemical reactions, etc.) is accelerated. As a result, it is expected that cement hydration and pozzolanic reactions will be accelerated, and the rate of strength development will be higher as the curing temperature is increased. This, however, does not assure an improved ultimate strength, and usually the ultimate strength of mortar or concrete cured at elevated temperatures becomes less in comparison to nonaccelerated curing. The reduction in ultimate strength, generally, comes from the alteration of the reaction products and their topology.

It should also be recognized that the solubility of $Ca(OH)_2$ decreases as the temperature increases. This, in addition to chemical and topological alteration, will reduce the supply of calcium. The hydration behavior of cement, on the other hand, is not as straightforward. At lower temperatures, the solubility of gypsum is higher but the reactivities of the hydraulic phases of cement are less. At higher temperatures, the opposite is true, and in a concentrated suspension of cement paste this may cause rapid loss of workability. However, in a cement-modified soil, the amount of cement is low and the particles are much farther apart compared to that in a cement paste, and workability problems may never be encountered. As a result, accelerated strength gain with temperature will be equally applicable in the case of portland cement-modified soil.

Durability

The durability of stabilized soil is primarily evaluated from the degree to which the engineering properties are retained. The durability concern may arise from the exposure to wetting and drying, freezing and thawing, sulfate attack, etc. Although dominating exposure condition(s) may vary geographically, such exposures are common and, therefore, should be considered as a part of the design procedure. For lime-modified soils no standard test is available to evaluate their durability. On the other hand, for soil-cement, a number of tests are available (ASTM D 559-93 test "Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures," ASTM D 560-93 test "Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures") to evaluate their durability. *However, soil-cement is different from the soil modified with portland cement with respect to composition and property requirements*.

The ASTM D 559 test is designed to test the wetting and drying characteristics for soil-cement. *Soil-cement is different from cement-modified soil*. The amount of cement used in cement-modified soil is less than that used in soil-cement. In addition, soil-cement is generally a hardened erosion-resistant material with considerable bearing strength. On the other hand, cement-modified soil is an improved soil, usually unhardened nor partially hardened. The use of the ASTM D 559 wet-dry test is clearly too severe for cement-modified soil. Indeed, the test is not used for lime-stabilized materials, and appears to be used for cement-treated materials by confusion of the purposes of soil-cement and cement-stabilized clay soil. In this regard, the common term "cement" is taken to imply equivalence, but this is clearly not correct. If a comparison of durability of a particular soil stabilized with either lime or portland cement is warranted, it is crucial that the same test is performed in either case, and that the selected test be appropriate to the intended design purpose, field conditions, etc.

Depending on the time period, the exposure to wetting conditions generally reduces the unconfined compressive strength values compared to that in the unsoaked conditions. The deterioration introduced by repeated wetting and drying is generally cumulative. Upon exposure to repeated wetting and drying, the compressive strength of a stabilized soil is gradually reduced (the rate of reduction may vary) before total disintegration. The freezing and thawing generally results in volume increase and strength reduction. Therefore, it is important to consider durability in the selection of mix design in regard to the ultimate achieved properties when exposed to the field conditions. However, caution must be used in the interpretation of results because test conditions may substantially deviate from the actual field conditions. This stems from the fact that stabilized soil primarily lies under a pavement or a cover of similar nature, and the swing of moisture content may never be between saturated to totally dry condition. Similarly, the stabilized soil may never freeze when saturated.

Effect of Wetting-Drying and Freezing-Thawing on Strength. Felt (1955) evaluated the wet-dry and freeze-thaw characteristics of a number of soils that ranged from nonplastic to a PI of 83. These evaluations were performed following the standard ASTM procedures. His results indicated that the wet-dry and freeze-thaw loss percentages were about the same for soils (with PIs of 1, 14, and 28 and containing 8%, 56%, and 12% portland cement by volume, respectively) compacted with standard and modified Proctor. However, the compressive strength values were improved for specimens compacted with higher effort. The performance of soil with a PI of 28 and stabilized with 12% cement was inferior to those with lower PI that exhibited excellent durability. Considering that ASTM D 559 and D 560 tests require wire brushing, the weight loss

percentage of these soil-cement specimens compacted at modified effort after 24 freezing-thawing cycles was only approximately 6% and after 12 wetting and drying cycles was 28% for the soil with a PI of 28 and only 3% for those with PIs of 1 and 14.

The interpretation of the results by Kennedy et al. (1987) and the conclusion that portland cement is an inferior stabilizer do not appear to be logical when the following scenarios are considered. They investigated three soils with PIs of 11, 36, and 39, and most of them were stabilized with 4% and 7% lime or portland cement. The wet strengths were measured after exposing the compacted specimens to water for 7 days following various curing periods. The soil with a PI of 39 stabilized with lime and compacted with modified Proctor exhibited higher dry and wet strengths than those obtained with cement. The soil with a PI of 36 modified with 7% portland cement and compacted with modified Proctor exhibited higher dry strength and lower wet strength relative to that stabilized with an equal amount of lime. In contrast, the same soil when compacted at standard Proctor gave higher dry and wet strengths with portland cement both at 4% and 7% additions. The sandy soil with a PI of 11 and compacted with modified Proctor exhibited significantly higher dry and wet strength when stabilized with portland cement. Therefore, drawing the conclusion that portland cement as a soil stabilizer is inferior to lime is not obvious from the observations described above. Furthermore, the mixing technique used for portland cement and the representativeness of the data, particularly for portland cement (out of two replicate specimens, some were broken prior to testing), make their conclusions rather ambiguous.

Petry and Wohlgemuth (1988) used a wet-dry test that is a modified version of ASTM D 559. The major differences stated between the modified and the standard tests are in the procedure from which the step of scarification of the surface by wire scratch brush was dropped. In addition, the sample preparation and the dimensions of the mold used for compaction were different. These specimens were cured for 7 days in a moist room and the wet-dry test was performed for 12 cycles or until failure.

The results indicate that the lime-stabilized soil specimens at each gradation level retained their integrity distinctly better than that of the portland cement stabilized-soil specimens. However, increasing the volume of the test specimen over the usual standard, but keeping the soaking time the same, the achieved saturation level of these specimens would have been modified. As the specimen volume for both stabilizers and duration of soak are the same, specimens with higher suction power will take up more water than the other. For the larger specimens used, the observed effect will thus be more severe than in the smaller standard specimens. This is a good example of the danger of changing test methods without giving any consideration to the possible nonlinear effects of changes of scale. Although the amount of water uptake has not been stated in the report, it is expected that the difference in optimum dry density of soil specimens stabilized with lime and portland cement is an indicator of the fact that they will achieve a different saturation level.

Felt (1955) showed the excellent wet-dry and freeze-thaw performance of soils, ranging from nonplastic to a PI of 28, stabilized with portland cement of approximately 8% to 12% by volume. Furthermore, these tests were performed following ASTM D 559 and 560, where the specimens were scarified by wire brushing. The discussion below is intended to put forward the role of different parameters in determining the wet-dry and freeze-thaw properties of stabilized soil.

Deterioration Mechanism in Wetting-Drying Cycles. It was mentioned earlier that compactibility is related to the pore structure of a specimen. When a stabilized soil specimen is placed in water or dried in an oven, water penetrates into or leaves the specimen through the interconnected pore structure. It is also known that the surface tension of water is high enough to generate substantial capillary pressure to cause cracking of the surrounding matrix, especially for stabilized soils with very little tensile strength. The capillary force exerted on the pore wall depends on the pore size; the smaller the pore, the higher the water suction force. As water moves in and out through the pore network during the wetting and drying cycle, the tensile force generated can cause irreversible damage to the integrity of the material. Due to the cumulative nature of this effect, the specimen eventually collapses.

The results reported by Petry and Wohlgemuth (1988) indicate a gradual increase in wetting and drying durability of lime-stabilized soil with finer gradation. However, soil stabilized with various amounts of portland cement does not follow such a trend in a definite way. The achievement of higher MDD at lower OMC in soil stabilized with portland cement (which itself has a relatively higher water demand than hydrated lime) indicates that porosity in cement-treated specimens is lower and the pore structure is finer than that of lime-stabilized specimens. The observation of poor performance of portland cement-stabilized soil specimens in wetting-drying tests by Petry and Wohlgemuth (1988), may be attributed partly to the phenomena described above. This warrants further research relating the compaction level with the wetting and drying cycles.

This clearly indicates that a number of other parameters may also contribute to this phenomenon of gradual disintegration of soil specimens in repeated wetting and drying. These parameters could be attributed to mechanical properties such as strength and interparticle friction (direct function of shape, roughness, and surface area), cohesion (chemical in nature), and moisture content of the specimen.

While explanations relating to pore structure and capillary forces were not given any considerations, Petry and Wohlgemuth (1988) rationalized the difference in the performance in wetting and drying test results of the soil specimens, especially with coarse gradations, stabilized with lime and portland cement by invoking a phenomenon of water proofing (validity is discussed below). It was also reported that a superior water proofing with lime was achieved through the formation of a coating but with little gain in strength. With portland cement, the soil lumps were held together by a cement coating that was inadequate to provide the required water proofing. While the ineffective water proofing resulted in poor performance in the wetting and drying test, higher unconfined strength was attributed to the cement coating at lump interfaces and shear strength of the clay clods. This hypothesis was prompted by the observations made upon inspection of the specimens following unconfined compressive strength testing. While the inspection appears to be visual, the phenomenon of water proofing derived from such observation may logically exist at a scale too fine for a naked eye to detect.

Stocker (1975) observed the adsorption of unreacted lime at early ages in soil containing approximately 15% lime. However, he emphasized that it was a transient phenomenon associated with unsuually high lime content, and is not a prerequisite for lime-clay reaction. For soils stabilized with lower lime content (3%) and after one year, approximately 1.5% lime was absorbed by unpulverized lumps. At the same dosage level and time period, uniform distribution of lime generated by hydration of cement was also observed.

In diffusion cell analysis, Stocker reported that there was no abrupt change in Ca^{2+} concentration between the surface and the core of stabilized soil lumps. The first 0.5% Ca^{2+} was

adsorbed very rapidly throughout the system and further reaction was impeded by the reaction products formed. Subsequent modifications deep inside the lumps took place as Ca^{2+} migrated through the clay that had a large capacity for further adsorption of calcium. This phenomenon apparently is dependent on the concentration of Ca^{2+} ions in the adjacent pore fluid and independent of the Ca^{2+} supply potential of the stabilizer. With higher Ca^{2+} concentration in the adjacent pore fluid, the chemical potential between the supply end and the reaction front will be higher and diffusion will be deeper. The hypothesis of water proofing, however, is rather difficult to explain based upon Stocker's observations (1975).

The phenomenon of gradual disintegration of soil specimens in repeated wetting and drying is primarily attributed to changes in parameters such as interparticle friction (mechanical in nature and a function of shape, roughness, surface area, and compaction) and cohesion (chemical in nature), the tensile force exerted on the pore wall by the capillary pressure generated by movement of water, pore size and porosity, the moisture content of the specimen, etc. Therefore, the observation of improvement of wetting and drying test results with finer gradation of soil stabilized with either portland cement or lime may be logical and is equally valid for both the stabilizers.

LONG-TERM PERFORMANCE

Investigations evaluating the long-term field performance of stabilized soil are few. The evaluation of stabilized soils in the laboratory to predict the long-term performance in field conditions requires proper designing of experiments. While the short-term performance may be evaluated through appropriate existing test methods, the concern over long-term performance stems from questions about whether the ion-exchange process (resulting in stabilization) may be reversed, either fully or partially, and whether some of the engineering properties achieved through stabilization would be lost.

Long-Term Field Performance of Soil Stabilized with Portland Cement or Lime

Two studies performed in the State of Oklahoma indicate that both portland cement and lime are effective in retaining the engineering properties of stabilized soils. However, the time-scales involved in these two studies are quite different; 45 years for portland cement stabilized soils and between five and twelve years for the lime stabilized soils.

In the portland cement stabilization study by Roberts (1986), a 7-mile test section containing expansive clay was stabilized using portland cement in 1938. The project consisted of 38 different sections. These sections were stabilized using 11 different cement contents ranging from 4% to 16% by volume with an average cement content of 6%. Forty-five years later, in 1983, a follow-up laboratory study was undertaken to characterize each of the 11 cement-modified test sections. Upon coring out the asphalt concrete patches and concrete pavement, three representative samples of cement-modified subgrade were collected from each of the 11 sections using thin-walled sampling tubes. The laboratory test results of a few representative cement-modified soils (CMS), both from 1938 and 1983, and original soils are shown in Table 2.

Table 2. Long-Term Performance of Portland Cement-Modified Soils (CMS)

Soil description & classification	Cement content used (volume %)	Test specimen	Plasticity index	Shrinkage limit	Shrinkage ratio
Brown silty clay A-6	9.0	Original soil	29.6	12.1	2.01
		1938 CMS	12.7	28.9	1.50
		1983 CMS	11.0	19.3	1.57
Brown silty sand A-2-4	9.5	Original soil	40.8	10.2	2.12
		1938 CMS	18.0	27.4	1.55
		1983 CMS	3.0	21.1	1.4
Reddish brown clay A-4	6.0	Original soil	21.5	15.0	1.9
		1938 CMS	6.6	28.2	1.5
		1983 CMS	3.0	15.9	1.61
Brown sandy silty clay A-2-4	16.0	Original soil	50.5	10.5	2.1
		1938 CMS	15.0	34.7	1.42
		1983 CMS	4.0	22.3	1.42

In 1938, the PIs of the untreated soils varied between 18 and 51, and upon cement modification in 1938, the PI range was reduced to between 7 and 18. After 45 years in service, the PI range was further reduced to between nonplastic and 13. In 1938, the average shrinkage limit of the treated soils was 2.1 times higher than the untreated soil. After 45 years in 1983, although the shrinkage limit has reduced slightly, it is still 1.6 times higher than that of the original soils. Shrinkage ratio (shown in the last column of Table 2) is defined as the ratio of a given volume change, expressed as a percentage of the dry volume, to the corresponding change in water content above the shrinkage limit, expressed as the percentage of the mass of oven-dried soil. The reduction in the shrinkage ratio after treatment in 1938 was approximately 25%. After 45 years of service, more than half of the specimens exhibited either a decrease or no change in the shrinkage ratio. These performance results indicate that the effectiveness of stabilization of soil with portland cement is unquestionably long-lasting.

The evaluation of the effectiveness of lime-treated soils performed by the Oklahoma Department of Transportation (1980) was performed on subgrade soil in service for five to twelve years. Originally, the top 150 mm (6 in). of the existing soil was mixed with lime and water and compacted in place. A total of 11 such projects were chosen in this study. The sampled subgrade soil was considered to have two layers; the top layer is the soil treated with lime, and the lower layer represents the untreated soil. The criticism associated with this investigation is the assumption that the soil in the second layer has the same characteristics as the original soil that was treated with lime and placed immediately above it. On several projects, a great deal of variation was noted between specimens sampled from the same layer but from different areas of the pavement.

In some projects, the results were opposite what was expected; treated soil had properties of untreated soil and vice versa. In one project, virtually all the characteristics of the untreated and treated soils were reversed. Although material heterogeneity was attributed to such observations, leaching out of calcium as a probable cause of this was not mentioned. However, the report concluded that hydrated lime is an effective stabilizer in modifying the engineering characteristics of clay soils.

When the properties of these lime-treated soils are compared with those given in Table 2 for portland cement-modified soils (CMS), it is obvious that even after 45 years of service, the latter exhibited superior properties. After lime stabilization and five to twelve years of service, the average PI of 21.6 of the original soil became 14.8. In contrast, the average PI of 29 was reduced to 6 after cement modification and 45 years of service. Similarly, for the lime-stabilized soil, the average shrinkage limit of 11.6 of the original soil increased to 16.5 after five to twelve years of service. On the other hand, the average shrinkage limit of 12.9 of the original soil was found to be 20.7 following portland cement modification and 45 years of service. The average shrinkage ratio also followed the same trend. In retrospect, the long-term evaluation of the lime-stabilized soil is only limited between five and twelve years, and that of cement-modified ones is 45 years. Although these studies are different, considering the time-scale of these projects and the results obtained, the cement-modified soils, in general, exhibited properties that are superior to those achieved from the lime-modified ones.

Leaching of Soil Stabilized with Lime

Leaching is related to the percolation of ground water through the interconnected pore structure of soil. The effects of leaching may be both chemical and physical in nature. Soils with higher water retention capacity and poor drainage are less affected by leaching. When leaching results in chemical breakdown of a soil-stabilizer system, the electrolyte concentration in the pore water is altered and the engineering properties of the soil are affected. The information available in the investigations of leaching behavior of soils stabilized with a combination of lime and portland cement by Barenberg (1970) and with 40% portland cement by Plaster and Noble (1970) is limited and does not clearly indicate any particular trend in the context of this report.

An extensive investigation on the long-term effects of continuous leaching of lime-treated soils from North Central Texas was performed by McCallister (1990) and McCallister and Petry (1990, 1991, 1992); some selected results are shown in Table 3.

Table 3. Characteristics of Soil (McCallister and Petry, 1992)

Characteristics	Soil data		
	Site 1	Site 2	Site 3
Silt and clay, <0.07 mm (%)	85	90	98
Clay fraction, <0.002 mm (%)	34	12	60
Maximum dry density, kg/m^3 (lb/ft^3)	1658 (103.5)	1618 (101.0)	1602 (100.0)
Optimum moisture, %	22.5	22.5	24.5
Liquid limit, %	63	60	76
Plastic limit, %	33	27	31
Plasticity index, %	30	33	45

The specimens prepared in the laboratory were continuously leached and the changes in physicochemical properties of the soil and the chemistry of leachate over a period were monitored. The parameters kept invariant are the compactive effort (standard Proctor), curing conditions (48 hours at 48.9°C [120°F]), and a leaching flow pressure of 1450 MPa (10 psi). However, the lime content (0% to 9% by dry weight of soil), moisture content (± 3% of the optimum, –3% to –8% of the optimum, and +3% to +8% of the optimum), and leaching duration (45 days for all specimens and 90 days for selected ones) were varied. The work is extensive

and requires close attention to follow the variations of properties with leaching time, lime content, and moisture content. A few relevant points are discussed below.

McCallister (1990) and McCallister and Petry (1991) classified the lime addition level based upon two physical properties. The lime modification optimum (LMO) is between 3% and 4% and was determined by the pH test. The lime stabilization optimum (LSO) is between 6% and 7% and was determined by maximum unconfined compressive strength. Consequently, the results obtained were also classified based upon the lime content, as designated by LMO and LSO.

Prior to mixing, the soil samples were air-dried at 48.9°C (120°F) for 5 days and all of it was passed through the No. 4 sieve. Upon mixing with lime and water, the mixture was wrapped with plastic sheets and mellowed for 24 hours. An accelerated curing was performed by placing the lime-treated soil specimens in a 48.9°C (120°F) oven for 48 hours. As mentioned earlier, such accelerated curing may produce materials that are different in some characteristics from those not heat-cured. Samples were compacted using standard Proctor at three different moisture contents. The leaching tests were performed using a flexible wall permeameter and applying a 1450 MPa (10 psi) flow pressure. A number of physical properties such as Atterberg limits, linear shrinkage, swelling pressure, free swell, and unconfined compressive strength were measured on specimens before and after the leaching. In addition, during the leaching experiment, the effluents were collected and analyzed for their pH, and the concentrations of calcium, potassium, sodium, and magnesium.

Effect of Leaching on the Chemical Properties. The leachate analysis indicates that although the leachate pH was increased with lime content, it decreased linearly with leaching time. While the pH of all leachates at lime content above LMO (approximately 4%) were close to that obtained in the Eades and Grim test, the increase in leachate pH was small compared to that below LMO. Figure 14 illustrates this behavior for soil (from Site 1) and compacted at ±3% of the optimum moisture content. Leaching time does not seem to affect the pH of leachate from untreated specimens. Since the pH of a soil-lime system may be taken as an indirect indication of the calcium content, the decrease in pH with leaching time gives a strong indication of diminishing calcium and, as a result, gradual loss of engineering properties achieved through stabilization.

The concentration of calcium in leachate increased significantly when lime content was above LMO. Sodium and potassium concentrations in leachates were also minimum for samples containing 3% lime. The maximum concentrations of all these cations in leachate occurred for specimens containing the maximum amount of lime. Also, the concentrations of calcium, sodium, and potassium ions declined with leaching time at a rate that was the highest for samples containing higher lime contents or containing only 1% lime.

Although the phenomenon of washout was invoked to justify this observation, this decline also may be attributable to diffusion and dissolution. The concentrations of calcium in leachates of the three soils investigated are shown in Figures 15 (a, b, and c). The calcium content of untreated soils from Site 1 and 3 was higher than that from Site 2. Although the data have been fitted with linearity, a smooth but step-wise decrease (not recognized by the investigators) is quite obvious in all three figures. This step-wise decrease may indicate that a different calcium leaching phenomenon is operative at different leaching periods.

The calcium concentration in leachates from Site 2 and Site 3 soils still remains high. The higher calcium concentration in leachate from Site 2 soil stabilized with 7% lime indicates

that with additional leaching time more and more calcium will be removed from the system. As the amount of calcium available in the system is fixed (as determined by the initial lime content), the presence of a higher concentration in the leachate indicates that less calcium is retained in the specimen.

The amount of lime retained in specimens after leaching was estimated from the calcium concentration measured by titration with 0.1M EDTA (ethylenedinitrilo tetraacetate) after extraction with ammonium chloride. However, such an attempt was made only for the soil from Site 1, and unfortunately, the results obtained are not conclusive. The titration data shown in Figure 16 indicate that the amount of lime retained after leaching is significantly less than that in unleached specimens. The investigators considered the titration data in Figure 16 as nonlinear and do not pass through the origin because at higher lime content the degree of pozzolanic reaction is substantially higher and, thereby, the dissolution was incomplete. Based upon this observation, further extraction was performed.

However, the authors of this report find that the nonlinearity is not totally valid over the range of lime content investigated. The data points for 4%, 6%, 8%, and 10% lime contents (shown in Figure 16) do show a linear behavior and a line drawn by the authors goes through the origin. Therefore, the deviation from linearity is primarily from soil specimens containing 1%, 2%, and 3% lime where the degree of pozzolanic reaction is relatively less. This may be an indication that at lower lime content the removal of exchanged calcium in the titration process was minimal. However, at higher lime contents, a significant part of the lime may have remained in the system in the form of lime and was removed during continuous leaching.

Effect of Leaching on the Physical Properties. The permeabilities of the lime-treated specimens were substantially higher than that of the natural clay. Figure 17 illustrates the effect of lime content and leaching time on the soil permeability. Although the permeability decreased for up to 300 hours (12.5 days), specimens containing 3% lime were always the most permeable. Continuous leaching was detrimental to the engineering properties of the post-leached lime-treated soil specimens. Linear shrinkage, plasticity index, and swelling pressure increased with leaching time, while the unconfined compressive strength decreased. Specimens containing 1% to 4% lime suffered the most in leaching. The deterioration of these properties due to leaching was minimal at different lime contents. For the Atterberg limits, the optimum lime content was between 5% and 6%; for swelling, between 6% and 8%; and for unconfined compressive strength, between 7% and 8%.

The above phenomena of property-selective optimum have been rationalized by hypothesizing that at lime contents below the optimum for maximum pozzolanic reaction, bonding due to flocculation is weak, and during leaching could possibly be washed out. However, as the amount of pozzolanic reaction products formed depends upon the supply of calcium (silica and alumina supplied by the soil), defining the optimum lime content for maximum pozzolanic reaction could be difficult. According to McCallister and Petry (1990, 1991), at higher lime contents the pozzolanic reaction offsets the leaching effect by closing off (in actuality, it may be less than what is claimed) the flow channels and improved interparticle bonding. It was also suggested that, in order to minimize the deterioration due to leaching, it was necessary to increase the lime content by 1% above LSO, which is 7% to 8%. The intention was to increase the pozzolanic reaction products and inhibit the flow path, thereby offseting the disruption.

Discussion on the Leaching Investigation. It is important to remember that the difference between pre- and post-leached specimens is not only the leaching process, but also the effect of the time period (45 to 90 days) over which the leaching is performed. Although comparison of calcium retained was made between the beginning and the end of the 45- and 90-day leaching, a significant amount of electrolyte from the specimen was removed during continuous leaching, while that in the unleached specimen was retained.

The soils investigated, especially from Site 1 and Site 3, had naturally high concentrations of calcium. In general, all cation concentrations in the pore-water of both untreated and treated soil specimens declined with leaching time. The calcium concentrations in the pore-water of post-leached specimens were less than that in the pre-leached specimen, but steadily increased with the increase of lime content. When the lime content was greater than 4% to 5%, the difference in calcium concentrations between pre- and post-leached specimens was negligible. This indicates that the calcium concentration in the pore-water of pre-leached specimens (containing more than 4% to 5% lime) was the same as in the post-leached specimens. This is only possible when the amount of calcium in the stabilized soil is more than enough to compensate for the continuous leaching of calcium from the specimen. McCallister (1990) and McCallister and Petry (1990, 1991) claim that this amount is 2% to 3% lower than the lime content necessary to minimize the changes in physical properties.

The changes in pH and calcium concentration in the pore-water of post-leached specimens do not seem to correlate. The solubility of hydrated lime is approximately 0.2 g. per liter of water at room temperature, and a saturated solution of $Ca(OH)_2$ has a pH of approximately 12.5. When some of the calcium ions are lost due to ion exchange, more calcium ions (depending on their availability) come into solution through dissolution and the pH of 12.5 is maintained. The soils investigated by McCallister (1990) and McCallister and Petry (1990, 1991) required 4% to 5% lime to maintain the pH at 12.5. A pH of 12.5 of the pore-water in pre-leached specimens is from the saturation of hydrated lime. When the lime content was between 5% and 7%, the pH of pore-water of post-leached specimens was less than 12.5. On the other hand, calcium concentrations in pore-water from pre- and post-leached specimens containing 4% to 5% lime were about the same. As the calcium concentration in the pore-water was maintained by the dissolution of hydrated lime, the pH should also have been maintained – which was not the case. In actuality, both pH and calcium concentration should be correlated, provided that the solution is not interfered with by the presence of alkali ions. Nevertheless, it has been emphasized that all the detrimental effects of the continuous leaching can be taken care of if the lime content in the soil is above the LSO. The phenomena observed and the conclusions drawn, however, can be rationalized somewhat differently, and are discussed below.

Under high pH conditions, the aluminosilicates from soil are slowly dissolved and, in the presence of calcium, pozzolanic reactions occur. The pozzolanic products consist primarily of calcium silicate hydrate (C-S-H). McCallister (1990) and McCallister and Petry (1990, 1991, 1992) emphasize that the lime content should be high enough so that pozzolanic reaction products will be more prevalent and, as a result, the flow channels will be closed off, although a total close-off of pores in the soil system is not possible. In a continuous leaching process, the dissolution of $Ca(OH)_2$ is much greater than that of C-S-H. While upon prolonged leaching the $Ca(OH)_2$ will totally disappear from the system, C-S-H will gradually (at a much slower rate) change the C/S ratio and eventually will remain as silica and alumina gel. It is anticipated that the calcium ions attached electrostatically to crystal lattices due to ion exchange will not be dislodged as easily. It is prescribed by the investigators that the amount of lime necessary to

counteract the leaching effect should be at or above the LSO, which is 7% to 9%. However, considering the chemistry of the system, a prescription of this amount of lime is essentially based upon 45 to 90 days of continuous leaching. If the leaching was continued further, the lime requirement would go even higher because the concentration of calcium in pore-water declines with leaching time.

An attempt to identify an equivalency between the accelerated leaching process and time period in the field conditions was not successful. The field data collected were limited and the correlation with laboratory results was poor. Furthermore, the field data indicted that substantial deterioration, apparently due to leaching, occurred and the swelling and PI of soils reverted almost to those of natural untreated soil.

The importance of the formation of pozzolanic reaction products in promoting interparticle bonding and, as a result, blocking flow of water has been emphasized by McCallister (1990) and McCallister and Petry (1990, 1991). They also suggested, based upon a 45- and 90-day leaching test, that in order to minimize the effect of leaching on strength, the lime content should be increased at least by a percent over the LSO. This would result in lime contents 3% to 5% above the amount of lime determined by the Eades and Grim method. Such an addition is necessary to compensate for the so called "washout," although components of diffusion and dissolution are also associated with it. This indirectly implies that the formation of enough pozzolanic material is probably the most important parameter in minimizing the adverse effect of leaching on the engineering properties of soil.

Based upon the results obtained from the investigation of leaching of lime-treated soil, it appears that the use of portland cement as stabilizer would produce a material with superior resistance to leaching. As discussed earlier, hydration of portland cement produces primarily C-S-H (similar to primary pozzolanic product), and $Ca(OH)_2$ is formed as a by-product of this hydration reaction. As a result, the C-S-H network that forms in soil containing portland cement is expected to be more extensive and, thereby, may provide a superior interparticle bond. The formation of $Ca(OH)_2$ is a through-solution process, and it is anticipated that calcium ions will be exchanged first. When the concentration builds sufficiently, $Ca(OH)_2$ will crystallize out. The $Ca(OH)_2$ generated in this process is highly reactive because of finer size. The calcium ions will also be used up in pozzolanic reactions, but it is expected that ion exchange will precede the pozzolanic reaction. As a result, there will be a significant reduction in the calcium leaching out from the soil specimen. This will help retain the engineering properties of soil over a period longer than can be achieved when lime is used at a comparable concentration.

EFFECT OF SULFATES ON STABILIZED SOIL

Sulfate-induced problems are generally exhibited through cracking and heaving caused by reactions that produce expansive products such as ettringite ($C_3A \cdot 3CaSO_4 \cdot 32H_2O$) and thaumasite ($CaSiO_3 \cdot CaSO_4 \cdot CaCO_3 \cdot 15H_2O$). A reaction is termed expansive when the volume of product formed is more than the combined volume of the ingredients. The sources of sulfate ions are either soil or groundwater or both. The silica and alumina from clay become solubilized in high pH during the course of stabilization, and the calcium ions are supplied by the stabilizer used. In the presence of water, these ions then can react to form ettringite. The extent to which ettringite may form, therefore, depends upon the availability of these ions. The crystalline nature of ettringite, formed synthetically, is mostly lost when heated or subjected to a high vacuum. At

approximately 50°C (120°F) and at ordinary relative humidities, the water of crystallization of ettringite is rapidly lost, and this dehydration of water causes lattice shrinkage (Taylor, 1990).

Thaumasite, on the other hand, forms through the combination of sulfate attack and carbonation. Citing the work by Mehta and Klein (1966), Petry and Little (1992) reported that ettringite transforms into thaumasite when there is an adequate supply of carbonate (CO_3^{2-}) and dissolved silica, and the temperature is between 4°C (40°F) and 15°C (59°F). However, according to Taylor (1990), a prerequisite is the prior formation of ettringite which probably acts as a nucleating agent, and the rationale for the need of a continuing source of alumina. The compositional formula of thaumasite given by Petry and Little (1992) is, however, incorrect. In another study, Crammond (1985) described that the conditions conducive to the formation of thaumasite are a high relative humidity, a temperature of approximately 4°C (40°F), an adequate supply of sulfate (SO_4^{2-}) and carbonate (CO_3^{2-}) ions, and the presence of reactive alumina.

Ettringite is also known as tricalcium-alumino-trisulfate hydrate (AFt phase). A lower sulfate nonexpansive form, known as tricalcium-alumino-monosulfate hydrate ($C_3A \cdot CaSO_4 \cdot 12H_2O$) also forms in circumstances similar to that required for ettringite formation (AFm phase). However, which of these forms will be favored depends on the availability of sulfate and reactive alumina, or the sulfate-to-alumina ratio. For a limited supply of sulfate, when the amount of reactive alumina is high, the monosulfate phase will be formed by the decomposition of ettringite. When the supply of alumina is limited, ettringite will be favored. These phases can form back and forth depending on the prevailing ionic conditions, but ettringite is the most insoluble and thermodynamically stable phase. However, the remarks by Petry and Little (1992), "researchers further explain that monosulfate hydrate is only stable in moist conditions, whereas ettringite is stable in both wet and dry conditions" are not true. Ettringite is unstable in dry conditions (Taylor, 1990). Carbonation also plays an important role in disintegration of some of the phases formed in stabilized soil. Carbon dioxide dissolves in the pore water of stabilized soil producing carbonate (CO_3^{2-}) ions. Depending on the carbonate availability, disintegration may set forth through the (i) formation of $CaCO_3$, (ii) conversion of monosulfate and ettringite to $CaCO_3$, (iii) conversion of $Ca(OH)_2$ to $CaCO_3$, (iv) formation of hydrous alumina and gypsum, and (v) decalcification of C-S-H, initially by lowering the Ca to Si ratio, and eventually conversion to the hydrous form of silica.

It is the soluble sulfates that promote these expansive reactions. Therefore, the techniques used to determine the sulfate level are important. Furthermore, the level of sulfate detrimental to the performance of stabilized soil is also an unsettled issue. In fact, the degree of sulfate-related deterioration depends not only upon the level of soluble sulfate, but the availability of other ionic species, pH, degree of carbonation, moisture content, temperature, etc. all playing a role. The effect of moisture conditions in the specimen surroundings has been reported by Sherwood in 1958. In a later study, Sherwood (1962), and recently Huntington et al. (1995), reported that the principal reaction causing the sulfate-related deterioration is between clay and sulfate in the presence of cement. This investigation was performed on cement-treated soil only, and the cement was the source of calcium. Lime is also a source of calcium, and under similar circumstances it will also participate in similar expansive reactions.

Although there are no standard tests available to evaluate the effect of sulfate content in the soil, in recent years durability problems associated with the presence of high levels of sulfates in untreated soil have been reported. Determination of sulfate-induced durability problems in laboratory conditions requires control of many parameters. The test results may differ depending on the procedure and the conditions under which the tests are performed, and

they may not accurately simulate field conditions. It is rather important that some meaningful tests be performed in order to evaluate the type and quantity of stabilizer necessary to alleviate sulfate-related problems.

CONCLUSIONS AND RECOMMENDATIONS

Both portland cement and lime are capable of providing calcium, the primary ingredient necessary for stabilizing soil and improving its engineering properties. Lime as a stabilizing agent is used in various forms and purity, and as a result, the availability of calcium varies. There is often a confusion due to the indiscriminate use of the word "lime" to refer to CaO, $Ca(OH)_2$, Ca^{2+}, limestone, dolomitic limestone, etc. While lime may have some advantage in reducing the plasticity index (PI) of highly plastic soils, portland cement has the advantage of improving strength in addition to PI reduction. Portland cement upon hydration forms C-S-H and in the process generates $Ca(OH)_2$. C-S-H is also the pozzolanic reaction product, found to be important in improving strength and retaining the engineering properties of soil.

In general, lime-modified soil refers to an unhardened or semihardened soil. However, in the case of portland cement, different terms are applied depending on the dosage level and the properties achieved. An unhardened or semihardened soil state achieved with the least amount of cement is called cement-modified soil. When the cement content is increased, the resulting material is referred to as soil-cement which is a hardened material with considerable strength, bearing capacity, and resistance to deterioration due to wetting-drying and freezing-thawing. *As a result, lime-modified soils are often evaluated using appropriate tests, while cement-modified soils are inappropriately tested using methods designed for evaluating soil-cements*.

The term "lime migration" is primarily used in the context of "diffuse cementation" of soil as it refers primarily to the migration of Ca^{2+} into the layer structure of clay, and it is equally applicable to any stabilizer that supplies calcium, and should not be associated solely with the addition of lime.

A number of factors influence the stabilization process and the ultimate engineering properties achieved. The widely practiced Eades and Grim method is only applicable to lime, and may lead to a wrong estimate when portland cement is used as a stabilizer. The dosage may also depend on what is to be achieved. Generally, PI reduction and strength development are specified either individually or in combination and are used as a guide in selecting the type and dosage of stabilizer. For effective stabilization homogeneous mixing is necessary, and to achieve this the amount of stabilizer used in the field is often more than that found to be adequate in laboratory conditions.

In order to determine the necessary lime dosage, various states in the U.S. apply their own specifications. Surprisingly, strength is usually a secondary criterion, and durability is not even considered. For portland cement-modified soils compressive strength is typically used as the acceptance criteria with PI reduction as a secondary consideration. In general, the unconfined compressive strength values of portland cement-modified soils are higher than lime-modified soils at all curing ages. When the enhancement in strength is specified, use of portland cement is most appropriate.

The maximum dry density (MDD) of portland cement-stabilized soil compacted immediately after mixing is generally higher than soil stabilized with lime and compacted either immediately or after 24 hours of mellowing. This was also found to be true for different soil gradations. While portland cement was found to be very effective in increasing the unconfined

compressive strength of soil low in clay content, at higher clay contents (47% to 73%), its effectiveness is somewhat diminished but remains higher than that stabilized with lime. The unconfined compressive strength is also sensitive to the time of compaction, and a 24-hour delay as opposed to immediate compaction of soils stabilized with portland cement usually results in a reduction of compressive strength.

Many physico-chemical phenomena and engineering properties are affected by the size distribution and the available surface area of soil particles. As early-stage reactions between soil and stabilizer are usually confined to the particle surface, depending on the exposed surface and the nature of soil, the reactivity of a system may vary. However, no unambiguous conclusions can be drawn with respect to the gradation requirements for portland cement or lime.

Generally, the rate of strength development of soil stabilized with portland cement or lime is enhanced as the curing temperature is increased. Often equivalency is drawn between accelerated elevated temperature curing and long-term room temperature curing. However, the reaction mechanism and the products formed in these two conditions may differ. While certain properties may seem to correspond well between accelerated and nonaccelerated curing, other properties may not, and do not assure an improved ultimate product. When comparing stabilizers, the use of higher curing temperatures is not recommended.

At a higher compactive effort, higher dry density and unconfined compressive strength may be achieved, and this may change the degree to which any change in volume is accommodated. As a result, the strength retained after wet-dry cycles may vary depending on the stabilizer and the compactive effort used. While for lime-modified soils no standard test is available to evaluate their durability, a number of tests (ASTM D 559 and ASTM D 560) designed for soil-cement are often mistakenly used to evaluate the durability of portland cement-modified soil. No standard test is available to evaluate sulfate-related durability problems. The existence of conflicting wet-dry performance characteristics between soils, stabilized either with portland cement or lime, indicate that no systematic pattern exists and superiority of one over the other is yet to be established.

Whether the engineering properties achieved through stabilization are adversely affected in the long run is still a matter of concern. Two studies performed over a vastly different time scale (45 years for portland cement and five to twelve years for lime) in Oklahoma indicate that both portland cement and lime adequately preserve the engineering properties of stabilized soils. However, a comparison between the initial and the retained properties clearly indicates that the cement-modified soils exhibited superior properties.

Leaching due to the movement of groundwater also determines the extent to which original properties are retained. The amount of lime necessary to counteract leaching effects was found to be 4% to 5% above that determined by the Eades and Grim method. While such a prescription was arrived at based upon 45 to 90 days of continuous leaching, it is anticipated that the lime requirement would go even higher if the leaching was continued further. The formation of pozzolanic reaction products was found to be critical in promoting interparticle bonding and reducing the influence of leaching. As C-S-H is produced upon hydration of portland cement, cement-stabilized soil is expected to retain its engineering properties longer than can be achieved when lime is used. Furthermore, the optimum lime content for leaching was found to be different from that for other physical properties.

Sulfate-related deterioration depends on the level of soluble sulfate, the availability of other ionic species, pH, degree of carbonation, moisture content, and temperature. The level that is detrimental to the performance of a stabilized soil is an unsettled issue. While the tests

determining the extent of sulfate-related problems may give different results depending upon the methodology used, they may not accurately simulate field conditions. So, cautious effort and meaningful interpretation of results are critical.

In this review, a number of contradictions among the results reported by researchers have been pointed out. Furthermore, the design of a testing program and interpretation of results, in many cases, is dependent on the orientation of the researchers. As a result, the ambiguity of the outcomes often does not draw the true picture. With different testing methods and acceptance criteria for each stabilizer, there is a need for a unified testing program to efficiently demonstrate the performance of Portland cement or line as a soil stabilizing reagent.

ACKNOWLEDGEMENTS

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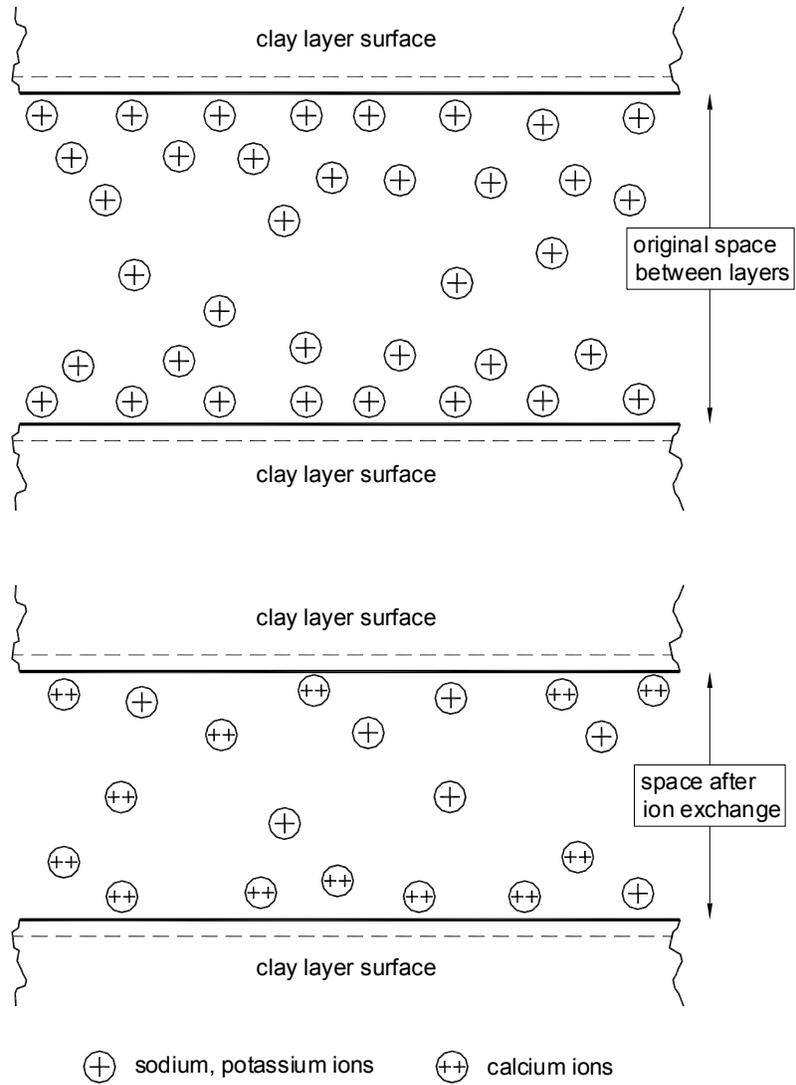
Figure 1. Schematic explanation of clay stabilization by ion-exchange mechanism.
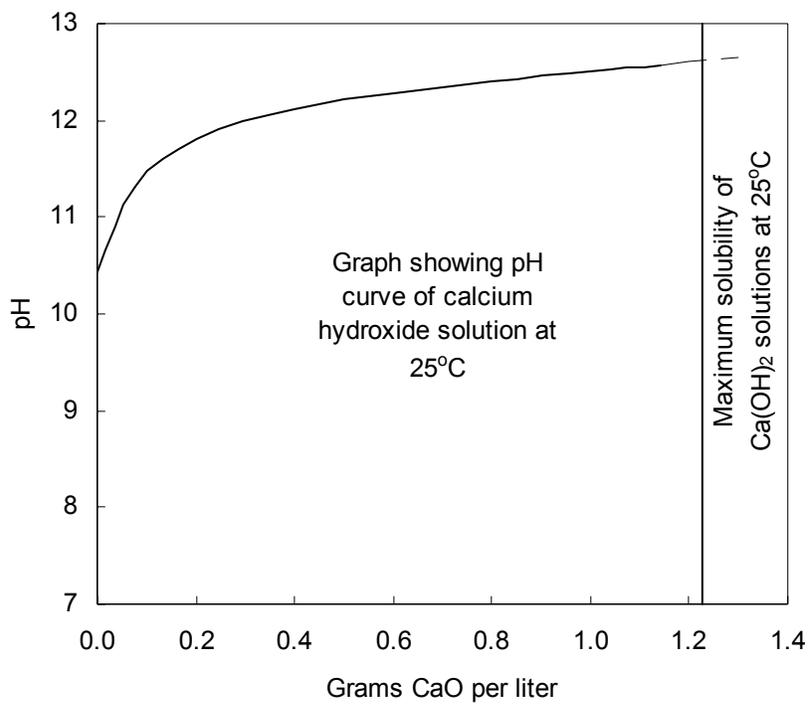
Figure 2. Solubility of Ca(OH)$_2$ in water at 25°C and the resulting pH of the solution. Adapted from Boynton, 1980.
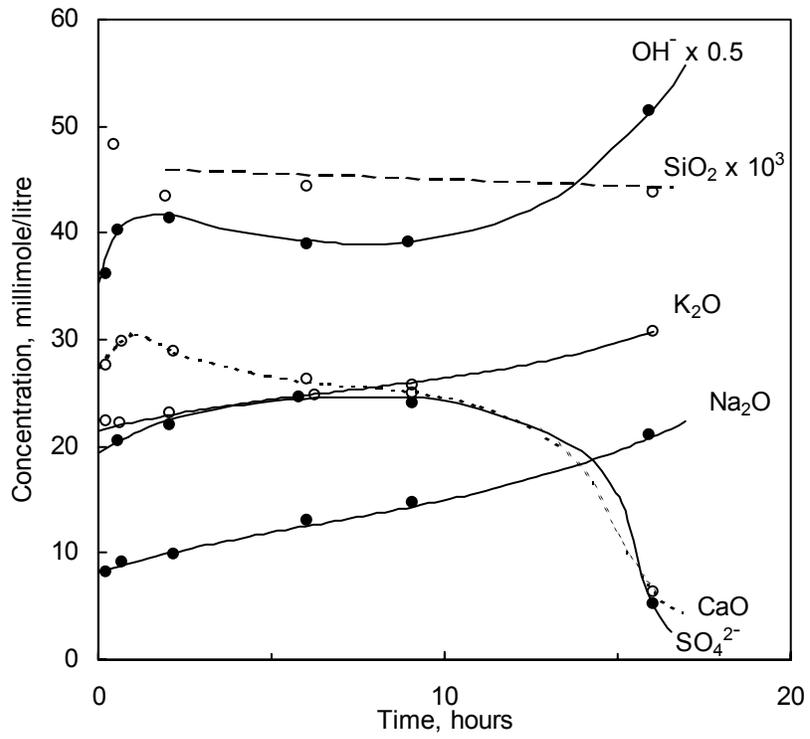
Figure 3. Concentrations of various species in pore solution of cement paste at w/c of 0.5. Adapted from Lawrence, 1966.
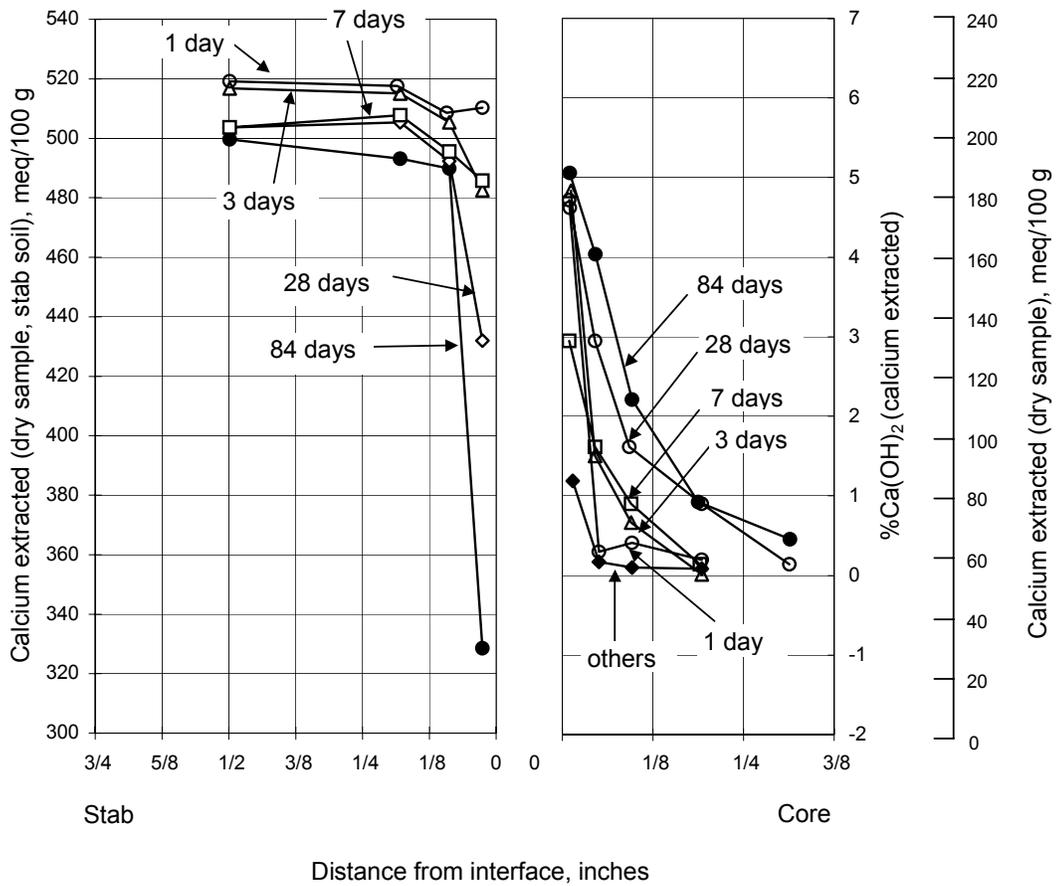
Figure 4. Diffusion of calcium into soils stabilized with 15% lime. Adapted from Stocker, 1975.
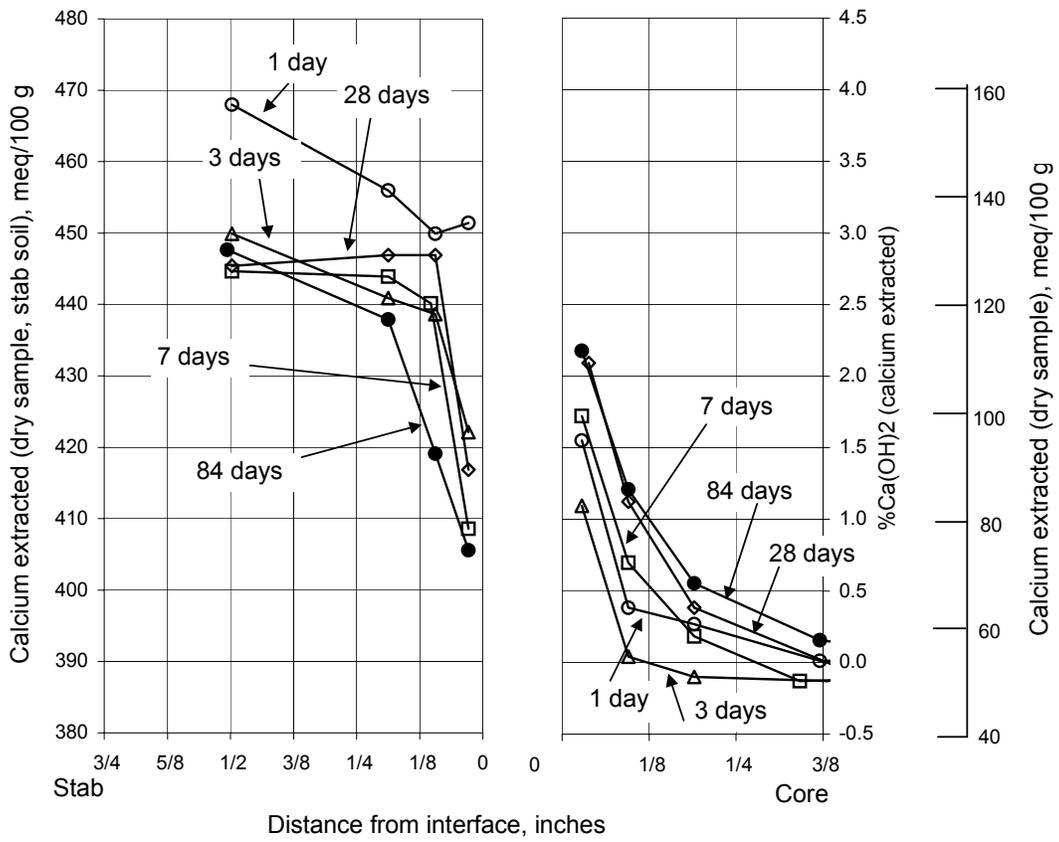
Figure 5. Diffusion of calcium into soils stabilized with 15% portland cement. Adapted from Stocker, 1975.
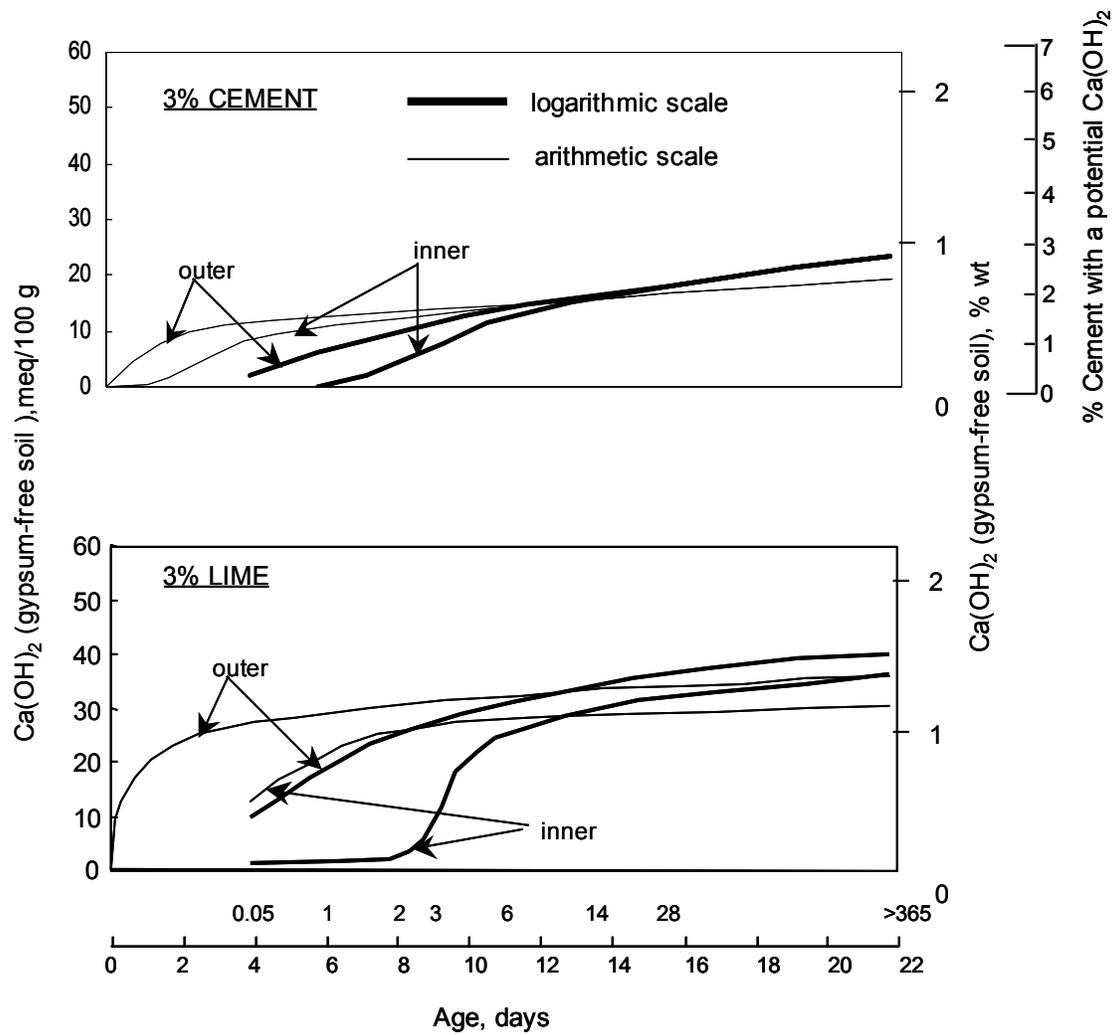
Figure 6. Gain of calcium by soil lumps stabilized separately with 3% lime and portland cement. Adapted from Stocker, 1975.
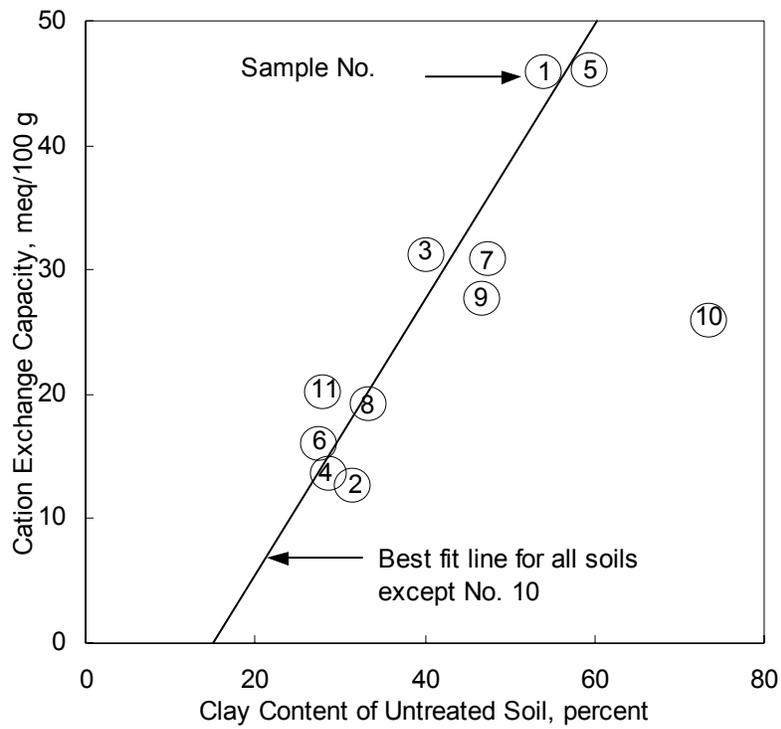
Figure 7. Linear relationship between cation exchange capacity and clay content of untreated soil. The deviation of soil No. 10 with 75% clay content was attributed to the presence of calcite and quartz. See Table 1 for soil characteristics. Adapted from Christensen, 1969.
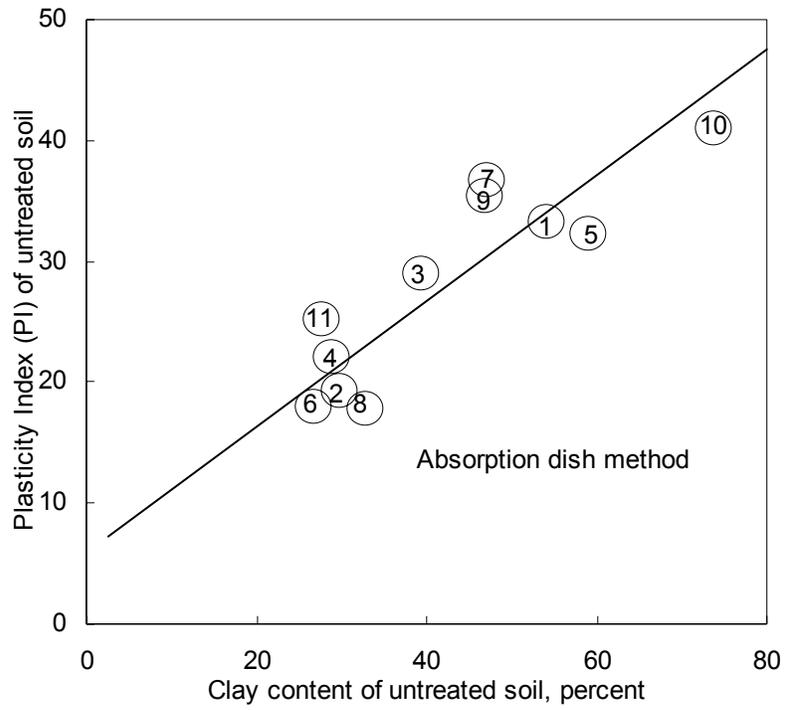
Figure 8. Linear relationship between plasticity index and clay content of untreated soil. See Table 1 for soil characteristics. Adapted from Christensen, 1969.
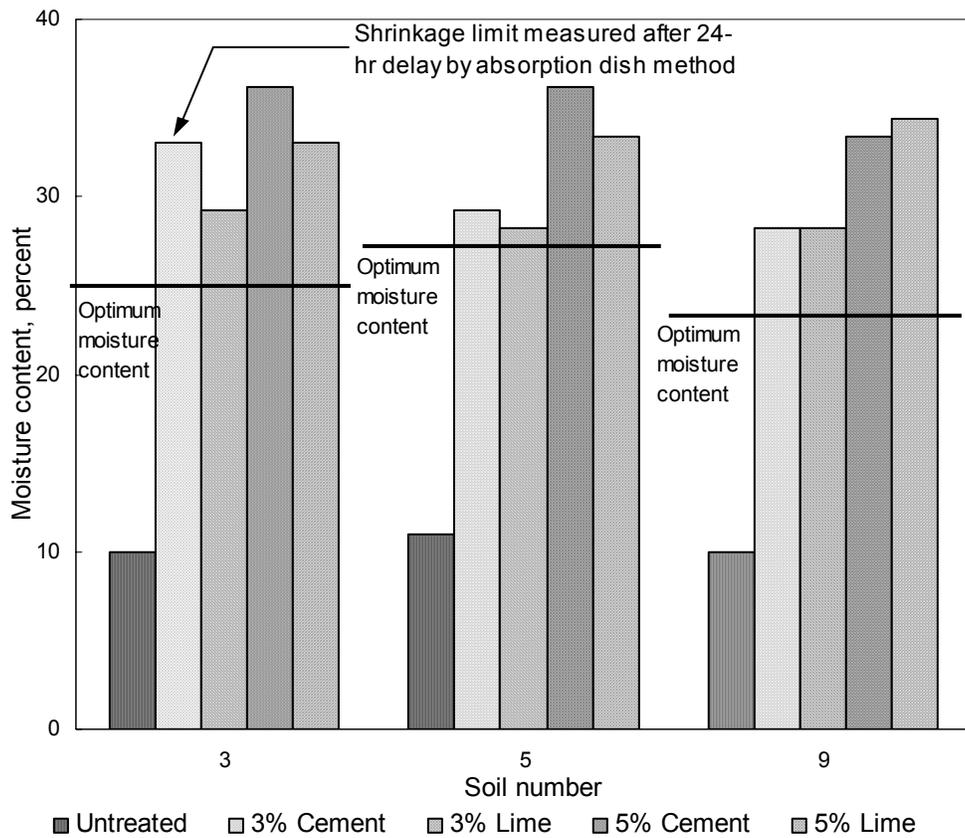
Figure 9. A comparative presentation between shrinkage limits and optimum moisture contents of untreated soils and soils treated with 3 and 5% portland cement and lime. See Table 1 for soil characteristics. Adopted from Christensen, 1969.
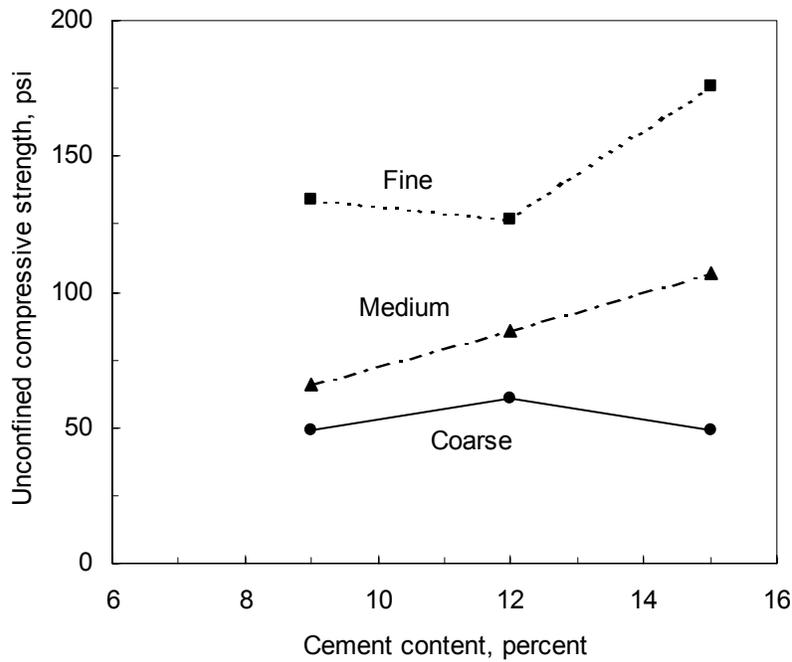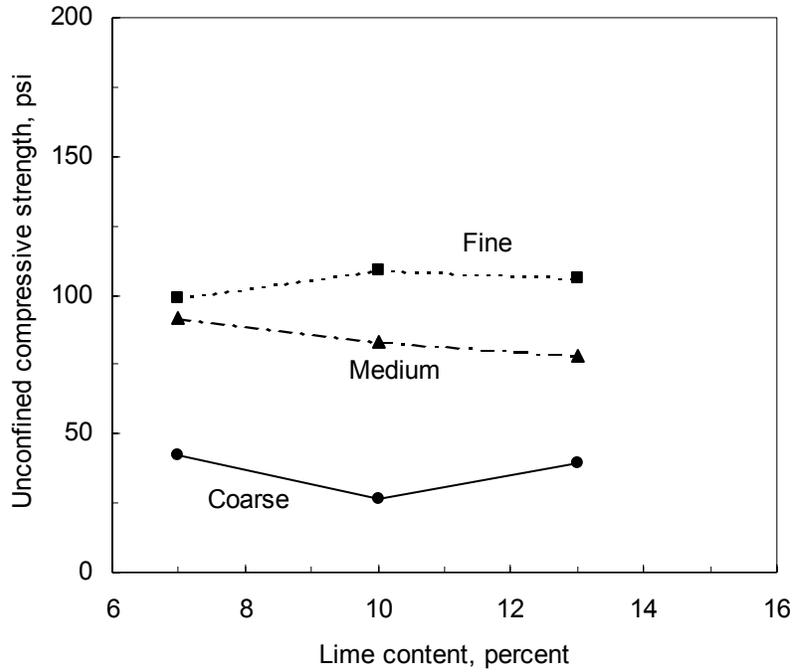
Figure 10. 28-day unconfined compressive strength of pulverized soils treated with various amounts of portland cement and lime. Size designations: Fine-100% passing No. 4 sieve; Medium-80% passing No. 4 and 100% passing 1 in. sieve; Coarse-60% passing No. 4 and 100% passing 1¾ in. sieve. Adapted from Petry and Wohlgemuth, 1988.
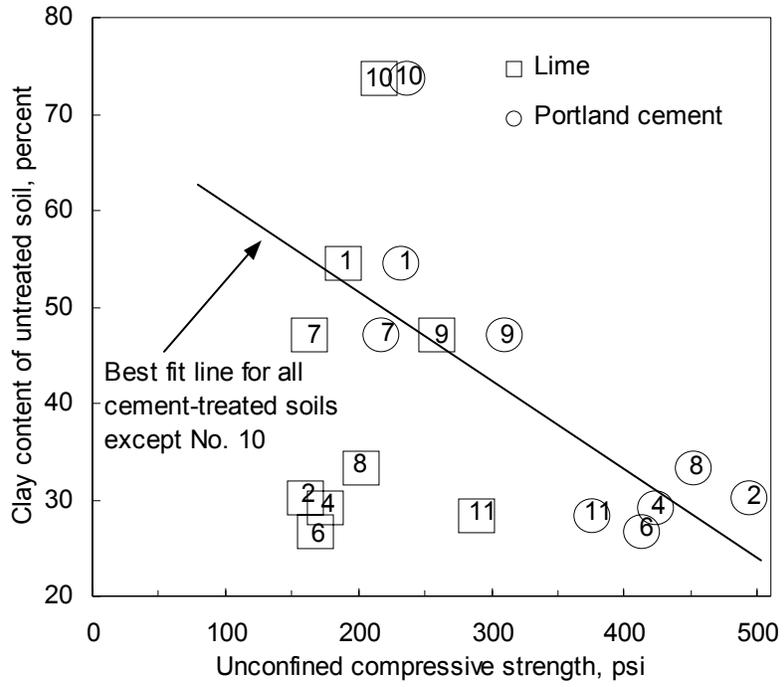
Figure 11. Relationship between clay content of soils and 28-day unconfined compressive strength of soils treated with 5% portland cement or 5% lime, and compacted immediately. See Table 1 for soil characteristics. Adapted from Christensen, 1969.
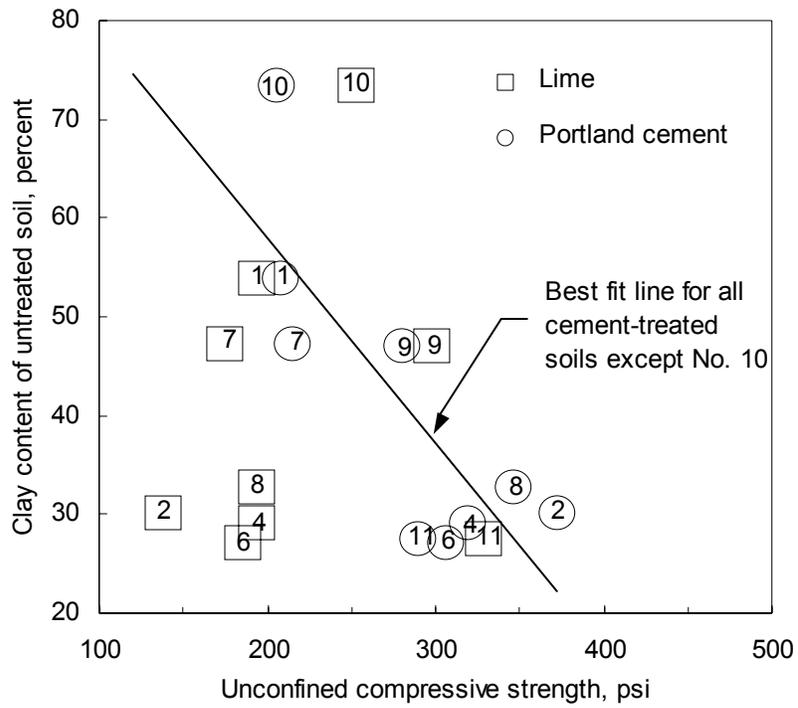
Figure 12. Relationship between clay content of soils and 28-day unconfined compressive strength of soils treated with 5% portland cement or 5% lime, and compacted after a 24-hour delay. See Table 1 for soil characteristics. Adapted from Christensen, 1969.
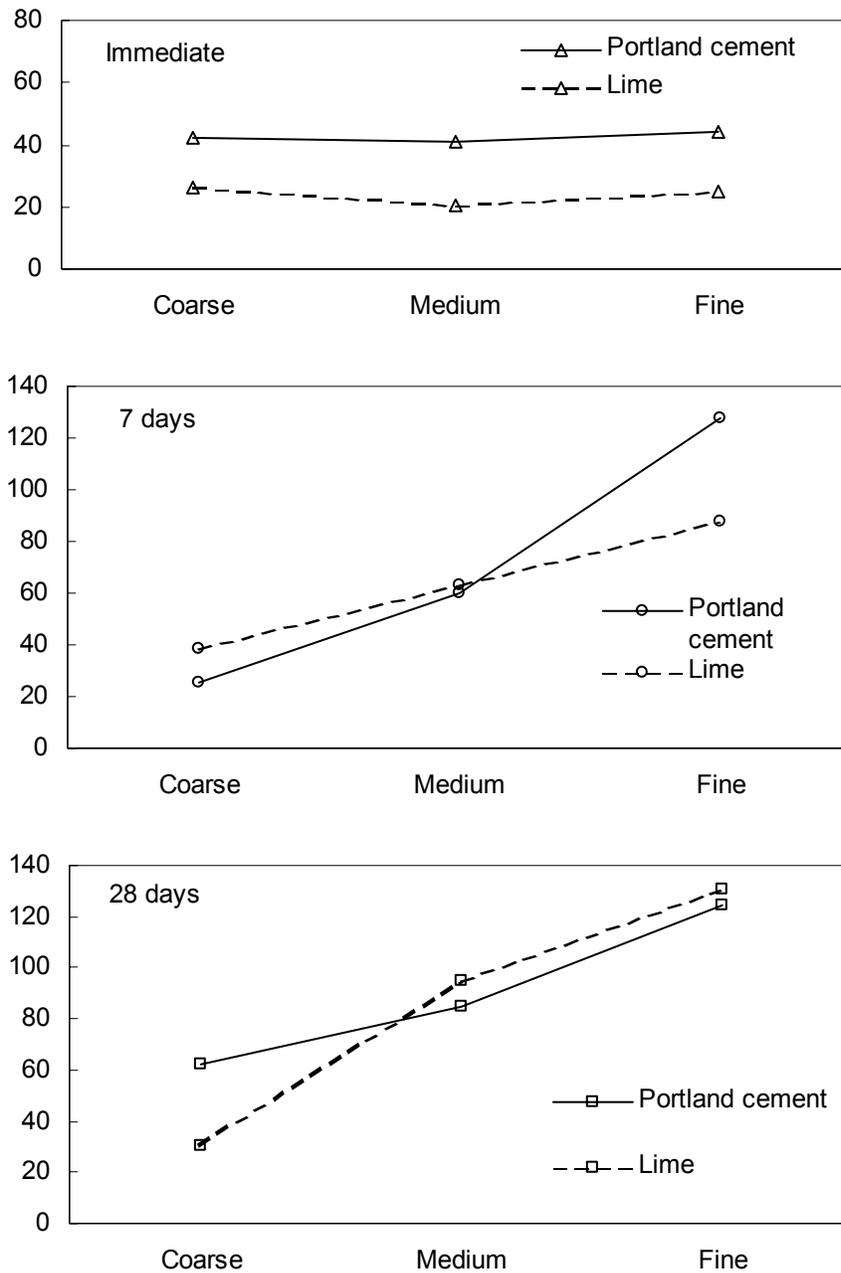
Figure 13. Variation of unconfined compressive strength, normalized by the differences in dry unit weights, with gradation of soil stabilized with either 10% lime or 12% portland cement. Adapted from Petry and Wohlgemuth, 1988.
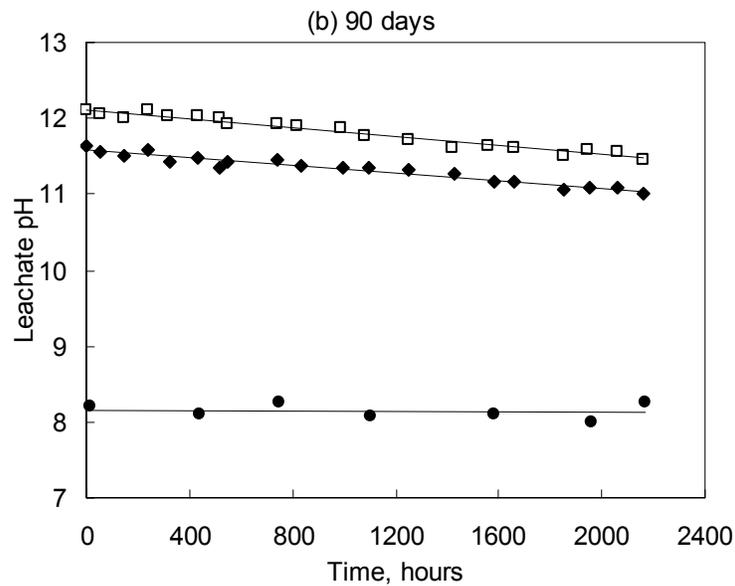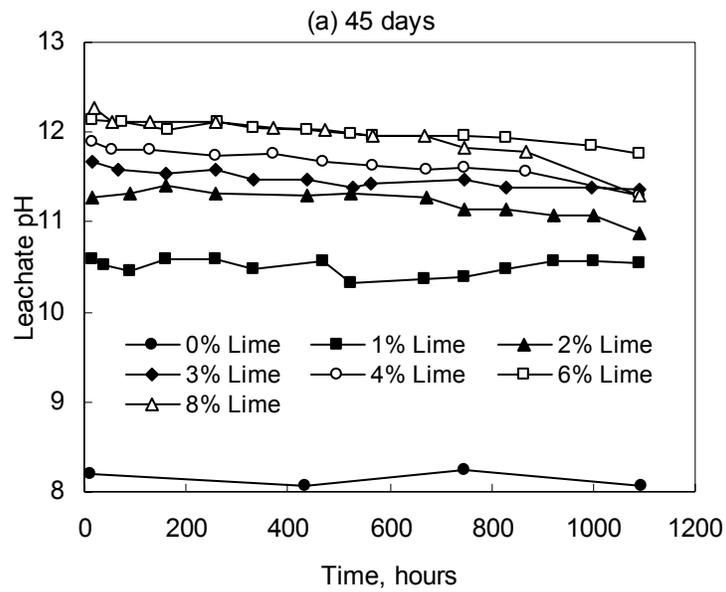
Figure 14. Change in leachate pH with duration of leaching from Site 1 soil compacted ±3% of OMC. (a) 45 days leaching, (b) 90 days leaching data fitted to straight lines. For soil characteristics, see Table 3. Adapted from McCallister and Petry, 1992.
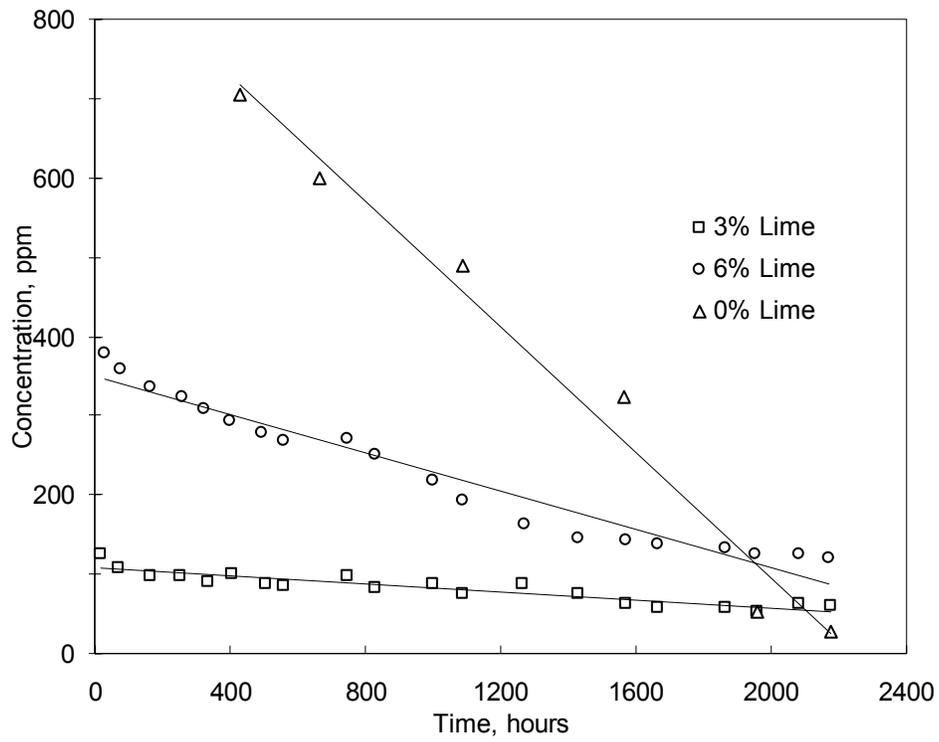
Figure 15(a). Calcium concentration in leachate during 90 days of leaching of Site 1 soil (compacted ±3% OMC) untreated and stabilized with 3 and 6% lime. For soil characteristics, see Table 3. Adapted from McCallister and Petry, 1992.
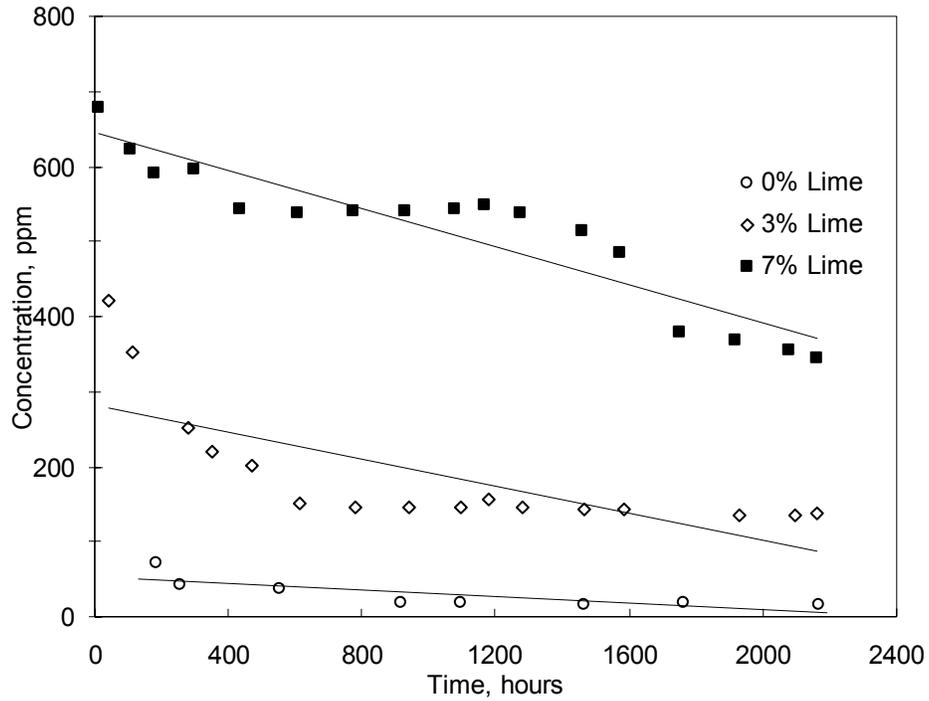
**Figure 15(b). Calcium concentration in leachate during 90 days of leaching of Site 2 soil (compacted ±3% OMC) untreated and stabilized with 3 and 7% lime. For soil characteristics, see Table 3. Adapted from McCallister and Petry, 1992.**
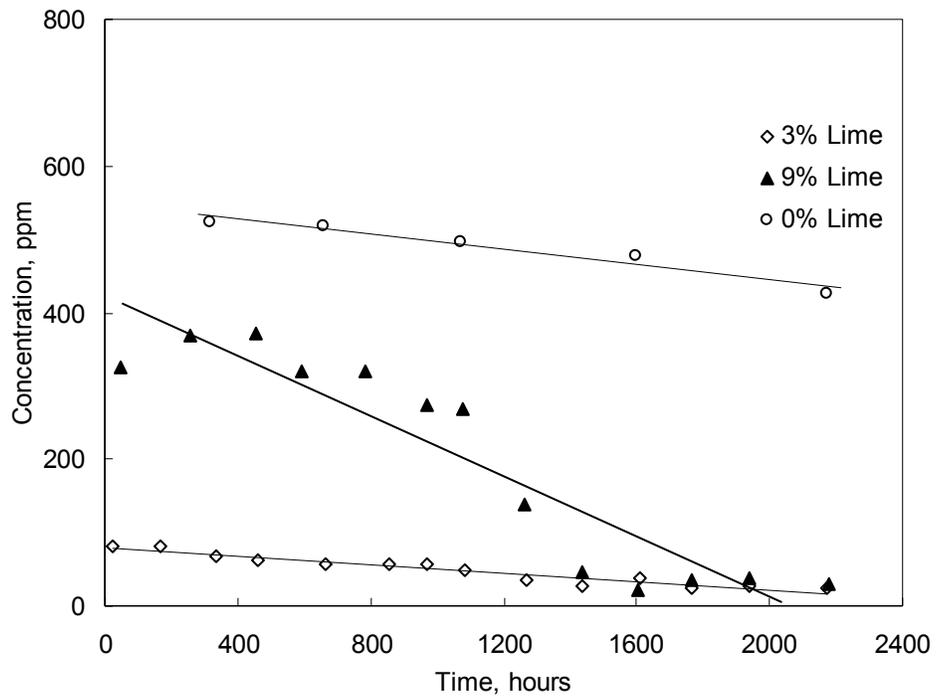
Figure 15(c). Calcium concentration in leachate during 90 days of leaching of Site 1 soil (compacted ±3% OMC) untreated and stabilized with 3 and 9% lime. For soil characteristics, see Table 3. Adapted from McCallister and Petry, 1992.
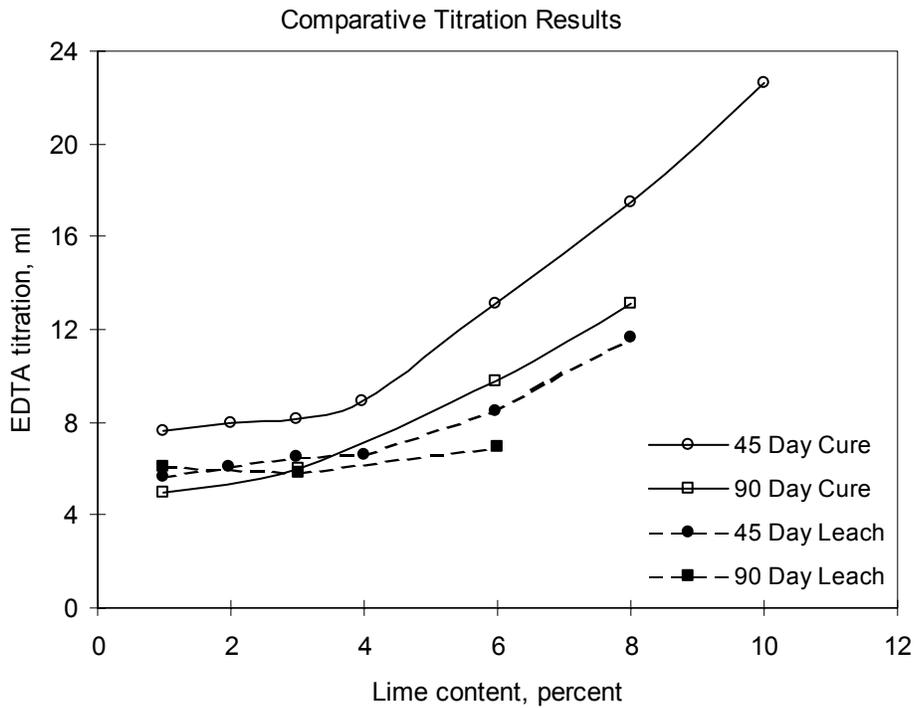
Figure 16. Amount of EDTA used for titration of calcium from Site 1 soil stabilized with various amount of lime and compacted at ±3% OMC. Samples not leached for 45 and 90 days were mellowed for the same period. Adapted from McCallister and Petry, 1990. The broken line passing through the origin emphasizes that the line goes through the origin at 4, 6, 8, and 10% lime content, but deviates when lesser amount is used.