TRANSPORTATION RESEARCH CIRCULAR

Number 180, September 1976

Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, Washington, D.C. 20418

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STATE OF THE ART: LIME STABILIZATION

Reactions, Properties, Design, Construction

Prepared by Transportation Research Board Committee on Lime and Lime-Fly Ash Stabilization

INTRODUCTION

Various forms of lime have been successfully utilized as a soil stabilizing agent for many years including products with varying degrees of purity. However, the most commonly used products are hydrated high calcium lime $Ca(OH)_2$, monohydrated dolomitic lime $Ca(OH)_2 \cdot MgO$, calcitic quicklime CaO, and dolomitic quicklime $CaO \cdot MgO$. The use of quicklime for soil stabilization has increased during the past few years; in the United States it now accounts for more than 10 percent of the total stabilization lime while in Europe quicklime is the major type used.

Many significant engineering properties of soils are beneficially modified by lime treatment. Although lime is primarily utilized to treat fine-grained soils, it also can be used to modify the characteristics of the fine fraction of more granular soils.

There are several objectives for lime treatment of soils such as to expedite construction, modify subgrade soils, and improve strength and durability of fine-grained soils.

Lime-treated soils have been used in pavement construction as modified subgrades, subbase materials, and base materials. The position of the lime-treated soil layer in the pavement system is controlled by the quality of the lime-treated soil and other pavement design considerations. Railroad subgrades have also been successfully stabilized with lime.

In this report, the major aspects of soil-lime treatment are considered. The report represents the state-of-the-art in lime treatment based on a comprehensive analysis of current practice and the technical literature. For those desiring more detailed information, an extensive listing of references has been included.

This report was prepared by Transportation Research Board Committee A2J03, Lime and Lime-Fly Ash Stabilization. Various Task Groups prepared the different sections of the report. The final version of the report was reviewed by Committee A2J03 prior to publication.

SOIL-LIME REACTIONS

General

The addition of lime to a fine-grained soil initiates several reactions. Cation exchange and flocculation-agglomeration reactions take place rapidly and produce immediate changes in soil plasticity, workability, and the immediate uncured strength and load-deformation properties. Depending on the characteristics of the soil being stabilized, a soil-lime pozzolanic reaction may occur. The pozzolanic reaction results in the formation of various cementing agents which increase mixture strength and durability. Pozzolanic reactions are time dependent; therefore, strength development is gradual but continuous for long periods of time amounting to several years in some instances. Temperature also affects the pozzolanic reaction. Temperatures less than 13 to 16° C (55 to 60° F) retard the reaction and higher temperatures accelerate the reaction (Ref 4).

Lime carbonation is an undesirable reaction which may also occur in soil-lime. Construction should be carried out in such a fashion that lime carbonation is minimized.

Cation Exchange and Flocculation-Agglomeration

Practically all fine-grained soils display cation exchange and flocculation-agglomeration reactions when treated with lime. The reactions occur quite rapidly when soil and lime are intimately mixed.

The general order of replaceability of the common cations associated with soils is given by the lyotropic series, $Na^+ < K^+ < Ca^{++} < Mg^{++}$ (Ref 50). Cations tend to replace cations to the left in the series and monovalent cations are usually replaceable by multivalent cations. The addition of lime to a soil in sufficient quantities supplies an excess of Ca^{++} and cation exchange will occur, with Ca^{++} replacing dissimilar cations from the exchange complex of the soil. In some cases the exchange complex may be Ca^{++} saturated before the lime addition and cation exchange does not take place, or is minimized.

Flocculation and agglomeration produce an apparent change in texture with the clay particles "clumping" together into larger sized "aggregates". According to Herzog and Mitchell (Ref 55) the flocculation and agglomeration is caused by the increased electrolyte content of the pore water and as a result of ion exchange by the clay to the calcium form. Diamond and Kinter (Ref 39) suggested that the rapid formation of calcium aluminate hydrate cementing materials are significant in the development of flocculation-agglomeration tendencies in soil-lime mixtures.

Soil-Lime Pozzolanic Reaction

The reactions between lime, water, and various sources of soil silica and alumina to form cementing type materials are referred to as soil-lime pozzolanic reactions. Possible sources of silica and alumina in typical soils include clay minerals, quartz, feldspars, micas and other similar silicate or alumino-silicate minerals, either crystalline or amorphous in nature.

When a significant quantity of lime is added to a soil, the pH of the soil-lime mixture is elevated to approximately 12.4, the pH of saturated lime water. This is a substantial pH increase compared to the pH of natural soils. The solubilities of silica and alumina are greatly increased at elevated pH levels (Ref 60).

In an early study of soil-lime reactions, Eades (Ref 43) suggested that the high pH causes silica to be dissolved out of the structure of the clay minerals, thereby becoming available to combine with the Ca^{++} to form calcium silicates and that this reaction will continue as long as $Ca(OH)_2$ exists in the soil and there is available silica. Diamond et al (Ref 41) postulated that the reaction processes in the highly alkaline soil-lime system involved a dissolution at the edges of the silicate particles followed by the precipitation of the reaction products.

Although the work of Eades (Ref 43) and Diamond et al (Ref 41) generally suggest a "through-solution" mechanism in which clay lattice components are "dissolved" from the clay structure and reprecipitated as CSH and CAH, direct reaction of the lime at the surface of clay mineral particles has not been ruled out. Recent work in the adsorption of lime by kaolinite and montmorillonite (Ref 40) as well as electron optical work on clay-lime-water systems (Ref 85) tends to support the idea that surface chemical reactions can occur and new phases may nucleate directly upon the surfaces of the clay particles. It is also possible that the reactions may occur by a combination of through-solution (solution-precipitation) and surface chemical (hydration-crystallization) processes.

An oversimplified qualitative view of some typical soil-lime reactions is summarized below:

$$Ca(OH)_2 \text{ ------------->} Ca^{++} + 2(OH)$$

$$Ca^{++} + 2(OH)^- + SiO_2 \text{ (Clay Silica) ------->} CSH$$

$$Ca^{++} + 2\ (OH)^- + Al_2O_3 \text{ (Clay Alumina) ---->} CAH$$

A wide variety of hydrate forms can be obtained, depending on reaction conditions, e.g., quantity and type of lime, soil characteristics, curing time, and temperature. Typical soil-lime reactions are:

Kaolinite + lime ---> CSH (C/S = 0.2-1) + CAH + CASH (Ref 80)

Kaolinite + lime ---> CASH (prehnite) (Ref 93)

Montmorillonite + lime ---> CSH (gel) ---> CSH (II) (Ref 91)

Montmorillonite + lime ---> CSH (gel) + hydrogarnet C_4AH_{13} (Ref 112)

Montmorillonite + lime ---> CSH (gel) + CSH (1) + tobermorite + hydrogarnet

Clay + lime ---> CHS (gel) and/or CSH (1) + C_4AH_{13} + C_3AH_6 (Ref 41)

where

$C = CaO$,
$S = SiO_2$,
$A = Al_2O_3$, and
$H = H_2O$.

The extent to which the soil-lime pozzolanic reaction proceeds is influenced primarily by natural soil properties. With some soils, the pozzolanic reaction is inhibited, and cementing agents are not extensively formed. Thompson (Ref 101) has termed those soils that react with lime to produce substantial strength increase, i.e., greater than 34.5 N/cm^2 (50 psi) following 28 day curing at 22.8° C (73° F), as reactive and those that display limited pozzolanic reactivity, less than a 34.5 N/cm^2 (50 psi) strength increase, are called nonreactive.

Some of the major soil properties and characteristics which influence the lime-reactivity of a soil, i.e., ability of the soil to react with lime to produce cementitious materials, are soil pH, organic carbon content, natural drainage, presence of excessive quantities of exchangeable sodium, clay mineralogy, degree of weathering, presence of carbonates, extractable iron, silica-sesquioxide ratio, and silica-alumina ratio. Detailed summaries concerning the effects of soil properties on lime reactivity are contained in Refs 53, 54, and 101. It is emphasized that the main factors controlling the development of cementitious materials in a lime treated soil are the inherent properties and characteristics of the soil. If a soil is nonreactive, extensive pozzolanic strength development will not be achieved regardless of lime type, lime percentage, or curing conditions of time and temperature.

Those desiring more extensive and detailed background information on basic soil-lime reactions should refer to the "Interpretive Review" by Diamond and Kinter (Ref 39) and a recent comprehensive publication by Stocker (Ref 95).

Summary

Soil-lime reactions are complex and not completely understood at this time. However, sufficient basic understanding and successful field experience are available to provide the basis of an adequate technology for successfully utilizing soil-lime stabilization under a wide variety of conditions. Future research findings will further augment our technology and permit more refined engineering decisions to be made concerning lime treatment of soils.

PROPERTIES AND CHARACTERISTICS OF LIME-TREATED SOILS

In general, when mixed with lime all fine-grained soils exhibit improved plasticity, workability and volume change characteristics; however, not all soils exhibit improved strength, stress-strain, and fatigue characteristics. It should be emphasized that the properties of lime-soil mixtures are dependent on many variables (Refs 100 and 101). Soil type, lime type, lime percentage, and curing conditions including time, temperature, and moisture are the most important variables. More important, however, the effect produced by any given change in a given variable is dependent on the levels of the other variables.

At present only limited information is available concerning some of the properties of lime-treated soils. Nevertheless, in order to effectively utilize these treated soils as a structural material, it is necessary to evaluate and summarize the existing knowledge concerning the properties of soil-lime mixtures.

Compaction Characteristics

The compaction characteristics, i.e., maximum density and optimum moisture, are important for two basic reasons. First of all, an adequate level of compaction must be obtained in order to achieve satisfactory results. Secondly, and possibly more important, is the fact that density is used for field control.

When compacted with a given effort, soil-lime mixtures have a lower maximum density than the original untreated soil and the maximum density normally continues to decrease as the lime content is increased.

In addition, the optimum moisture content increases with increasing lime contents (Fig. 1). Similarly, if the mixture is allowed to cure such that substantial cementing occurs the density would be further decreased and the optimum moisture increased.

Thus, moisture-density relationships are constantly changing, and it is important that the proper curve be utilized in field construction. Thus, if curing has occurred, it may be impossible to achieve density; however, it is important to realize that it is not necessary to achieve that density because the reduction is not due to poor compaction but rather to the fact that the material is different.

Plasticity and Workability

Substantial reduction in plasticity, i.e., reduced plasticity index PI, increased shrinkage limit, is produced by lime treatment, and in many cases the soil may become nonplastic. Generally, soils with a high clay content or exhibiting a high initial PI require greater quantities of lime for achieving the nonplastic condition, if it can be achieved at all. The first increments of lime addition are generally most effective in reducing plasticity, with subsequent additions being less beneficial (Ref 100). The reduced plasticity of the lime-treated soil and its silty and friable texture cause a significant improvement in workability and expedite subsequent manipulation and working of the treated soil. Figure 2 and Table 1 illustrate the manner in which lime influences the plasticity characteristics.

Volume Change

Swelling potential and swelling pressures normally are significantly reduced by treating clay with lime. These reduced swell characteristics are generally attributed to decreased affinity for water of the calcium saturated clay and the formation of a cementitious matrix which resists volumetric expansion. CBR-swell values of lime treated soils vary, but it is not uncommon to decrease swell to less than 0.1 percent compared to values of 7 to 8 percent for the untreated soil (Table 2). Typical expansive pressures (Ref 49) are shown in Fig 3.

Shrinkage due to moisture loss from the stabilized soil is of importance relative to the problem of shrinkage cracking. Lime treatment improves the shrinkage and swell characteristics of the treated materials. Figure 4 contains data (Ref 37) for typical Illinois soils.

Field moisture contents of lime treated soils suggest that the moisture content changes in the stabilized material are not large and the in-situ water content stabilizes at approximately optimum (Ref 106). Theoretical calculations based on laboratory shrinkage data as well as field service data from many areas indicate that for typical field conditions shrinkage will not be extensive (Ref 106).

Strength

The strength of lime-soil mixtures can be evaluated in many ways. The unconfined compression test is the most popular procedure while the stabilometer and CBR tests are used to a lesser extent. These methods, however, are definitely not the most applicable or desirable. Only limited data are available concerning the tensile properties of lime-soil mixtures (Refs 78, 82, 105, and 109), and additional effort is needed to evaluate the tensile characteristics of lime-treated materials.

It should be emphasized that the strength of a soil-lime mixture is dependent on many variables and that it varies substantially (Refs 100 and 101). Soil type, lime type, lime percentage, curing conditions of time and temperature, and the interactions between these variables are the major factors influencing strength (Refs 78, 82, and 109).

A distinction must be made with respect to curing. An immediate beneficial strength effect occurs with the addition of lime due to the immediate reactions, i.e., cation exchange, flocculation, and agglomeration. The long-term strength gain is primarily related to the pozzolanic reaction. Thus, it is necessary to separate the discussion into cured and uncured strength.

Uncured Strength

Immediately after the addition of lime a substantial improvement in strength and stability can be expected (Refs 84 and 110). These immediate effects can be considered to be an expedient for construction when soft, highly plastic, cohesive soils create mobility problems for wheeled vehicles (Fig 5) or do not provide satisfactory subgrade support for pavement construction operations.

Examples of the immediate effect of lime treatment on cone index, CBR, and unconfined compressive strength are shown in Fig 6. From this figure it is apparent that substantial improvements in strength can be realized. In some cases these increases may amount to several hundred percent.

Cured Strength

Unconfined Compression. Unconfined compressive strengths of typical fine-grained soils compacted at optimum moisture content and density (ASTM D2166) range from about 17 N/cm^2 (25 psi) to more than 207 N/cm^2 (300 psi) depending on the nature of the soil. Soil-lime mixture strength increases for Illinois soils cured 28 days at 22.8° C (73° F) range up to approximately 183 N/cm^2 (265 psi) with many soils displaying increases greater than 70 N/cm^2 (100 psi). Extended curing of 56 days at 22.8° C (73° F) of the same mixtures produced strength increases for some soil-lime combinations that exceeded 430 N/cm^2 (625 psi). Prolonged curing for 75 days at 48.9° C (120° F) of the AASHTO Road Test embankment soil treated with

Figure 1. Typical moisture-density relationships (Ref 84).

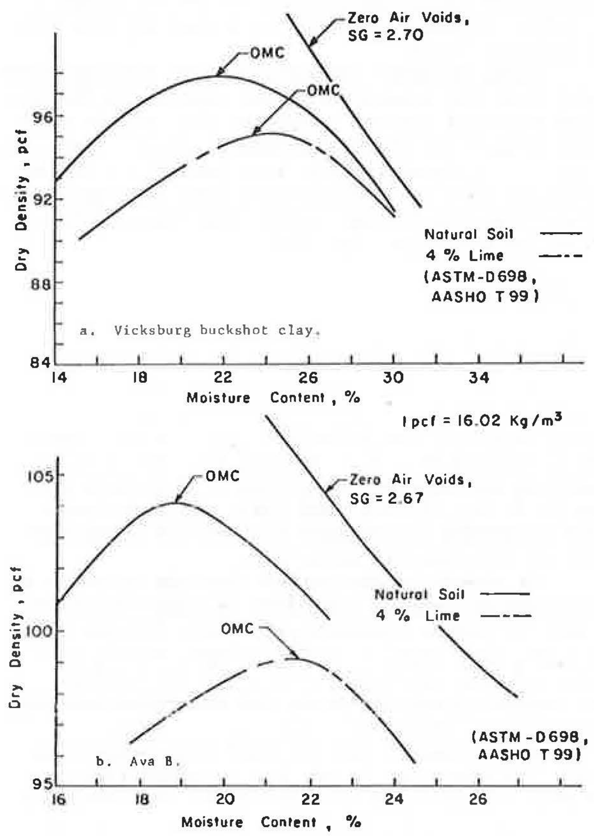


Figure 2. Effect of lime on plasticity characteristics of montmorillonite clays (Ref 56).

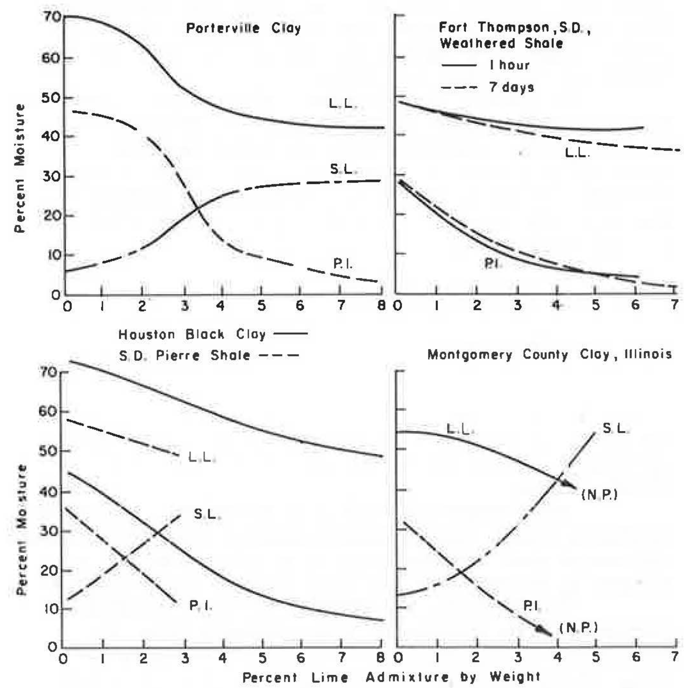


Table 1. Influence of lime on plasticity properties (Ref 100).

Soil	AASHO Class	Liquid Limit (LL) or Plasticity Index (PI), %					
		Percent Lime					
		0		3		5	
		LL	PI	LL	PI	LL	PI
Bryce B	A-7-6(18)	53	29	48	21	NP	
Cisne B	A-7-6(20)	59	39	NP		—	
Cowden B	A-7-6(19)	54	33	47	7	NP	
Drummer B	A-7-6(19)	54	31	44	10	NP	
Elliott B	A-7-6(18)	53	28	42	19	NP	
Fayette B	A-7-5(17)	50	29	NP		—	
Hosmer B_2	A-7-6(11)	41	17	NP		—	
AASHO Road Test	A-6(18)	25	11	27	6	27	5
Huey B	A-7-6(17)	46	29	40	9	NP	
Sable B	A-7-6(16)	51	24	NP		—	

NP = Nonplastic

Figure 3. Swell pressure-density relations for lime-treated Porterville clay (Ref 49).

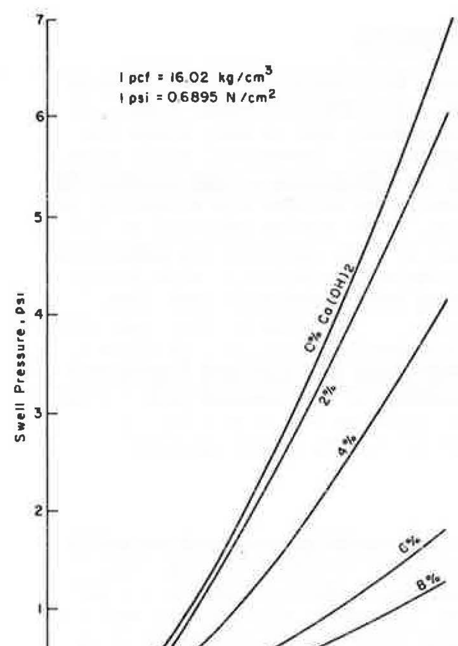


Figure 4. Influence of plasticity index of natural soil on first cycle shrinkage (Ref 37).

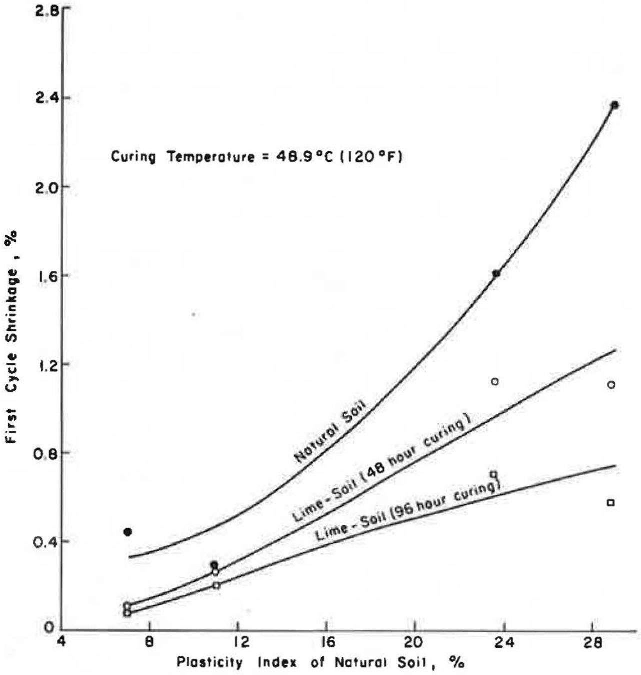
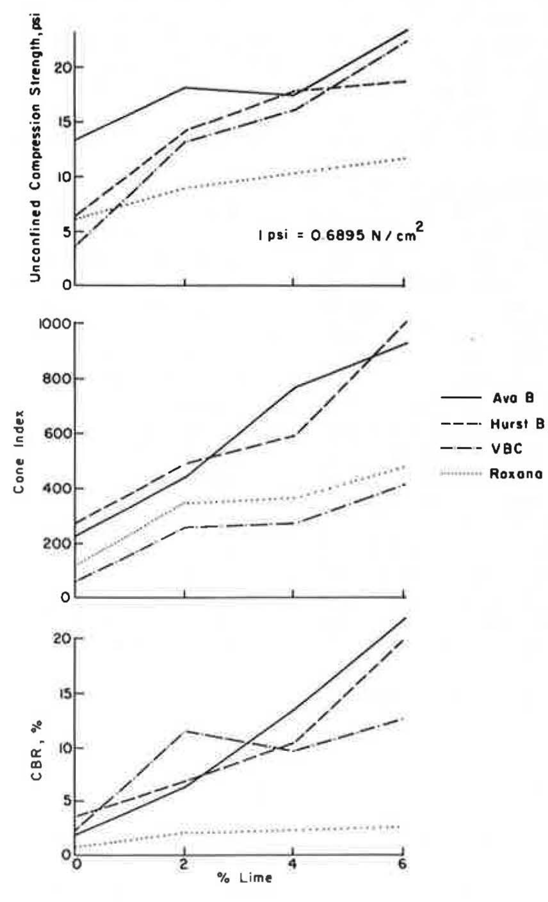


Figure 5a. Partially completed stabilized subgrade resists rutting during rain—Dallas-Fort Worth Airport.

Figure 5b. Comparison of ruts in untreated and lime-treated subgrade.

Figure 6. Immediate effects of lime treatment on strength (Ref 84).



5 percent lime produced an average compressive strength of 1090 N/cm^2 (1580 psi). Field data indicate that with some soil-lime mixtures, strength continues to increase with time up to and in excess of ten years. Typical results for various densities are shown in Fig 7.

The difference between the compressive strengths of the natural and lime-treated soil has been used as an indication of the degree to which the soil-lime pozzolanic reaction has proceeded (Ref 101). Substantial strength increase indicates that the soil is reactive with lime and can probably be stabilized to produce a quality paving material.

Shear Strength. Unconsolidated and undrained type triaxial testing have been utilized to partially simulate field service conditions.

The major effect of lime on the shear strength of a reactive fine-grained soil is to produce a substantial increase in cohesion with some minor increase in the angle of internal friction. At the low confining pressures normally considered to exist in a flexible pavement structure, the cohesion increase is of the greatest significance. For materials such as soil-lime mixtures which are characterized by very high cohesion, it is difficult to effectively evaluate the angle of internal friction.

For the typical lime reactive Illinois soils, the angle of internal friction for soil-lime mixtures ranged from 25° to 35° (Ref. 103). The cohesion of the mixtures was substantially increased compared to the natural soils and cohesion continued to increase with increased unconfined compressive strength. Using the linear regression equation shown in Fig. 8, cohesion values can be estimated from unconfined compressive strength results.

It is apparent that large shear strengths can easily be developed in cured soil-lime mixtures. It has been demonstrated that if high quality mixtures are used in typical flexible pavement structures, the strengths would be adequate to prevent shear failure (Ref. 103). Shear-type failures generally have not been observed and reported for field service conditions.

Tensile Strength. Tensile strength properties of soil-lime mixtures are of concern in pavement design because of the slab action that is afforded by a material possessing substantial tensile strength. Two test procedures, indirect tensile and flexural, have been used for evaluating the tensile strength of soil-lime mixtures.

The indirect tensile test is essentially a diametral compression test in which the material fails in tension along the loaded diameter of the cylindrical test specimen. Details and an evaluation of the test procedure for soil-lime mixtures are presented in Refs 2, 78, 82, 105, and 109.

Typical results (Fig 9) indicate that the mixtures can possess substantial tensile strength. The ratio of indirect tensile strength to unconfined compressive strength in one study (Ref 105) was found to be approximately 0.13, while in another study (Ref 109) it was found to be much lower as indicated by the following regression equation:

$$S_T = 6.89 + 50.6\ q_u$$

where

S_T = tensile strength, psi

q_u = unconfined compressive strength, ksi

The most common method used for evaluating the tensile strength of highway materials has been the flexural test. Typical flexural strengths of soil-lime mixtures (Ref 96) subjected to various curing conditions are shown in Table 3. Indirect tensile strengths are shown for comparison purposes. For a specific mixture, the ratio of the flexural strength to indirect tensile strength decreases as strength increases and the ratio is apparently not the same for all soil-lime mixtures.

If the ratio of flexural strength to indirect tensile strength is taken as approximately 2, a realistic estimate of flexural strength is 25 percent of the unconfined strength. The ratio is approximately equivalent to those reported for lime-flyash-aggregate and soil-cement mixtures.

California Bearing Ratio. The CBR testing procedures have been extensively used to evaluate the strength of lime stabilized soils. Many agencies have arbitrarily adopted this technique because of their familiarity with the test. In reality, however, the CBR test is not appropriate for characterizing the strength of cured soil-lime mixtures.

Extensive CBR tests have been conducted (Ref 99) with various representative Illinois soils including soils that reacted well with lime and also less reactive fine-grained soils.

Lime-treated soils were cured for 48 hours at 48.9° C (120° F) and companion specimens which had not been cured were placed in the 96-hour soaking cycle immediately after compaction. The 48-hour curing period is approximately equivalent to 30 days at 21.1° C (70° F) and the mixtures that were not cured prior to soaking had little opportunity to develop cementitious products from the soil-lime pozzolanic reaction. The improvements in engineering properties of the no-cure soil-lime mixtures were therefore primarily due to the cation exchange, flocculation, and agglomeration produced by the addition of lime. Test results for the natural soils and the soil-lime mixtures are presented in Table 2. The CBR increases of the no-cure soil-lime mixtures show the benefits that can be obtained from stabilization without prolonged curing. It is apparent that the no-cure specimens have not developed extensive cementing action.

The CBR values for many of the soil-lime mixtures cured for 48 hours at 48.9° C (120° F) are quite large and definitely indicate the extensive development of cementing agents. For those mixtures that display CBR values of 100 or more, the test results have little practical significance and are not meaningful as a measure of strength or stability. In general, these materials would also exhibit high compressive and tensile strengths, and these types of tests would provide a better strength evaluation. If extensive cementing action has not developed due to either lack of curing time or non-reactivity of the treated soil, CBR values may serve as a general measure of strength; but even in these cases the use of the CBR test is questionable.

It is evident that lime treatment of fine-grained soils produces increased CBR irrespective of the length of curing and lime-reactivity of the soil.

Stress-Strain Characteristics

Stress-strain properties are essential for properly analyzing the behavioral characteristics of a pavement structure containing a soil-lime mixture structural layer. The marked effect of lime on the compressive stress-strain properties of fine-grained soils is shown in Fig 10. The failure stress is increased, and the ultimate strain is decreased for soil-lime mixtures relative to the natural soil. As with strength it is necessary to separate the discussion with regard to whether the soil-lime has been cured or not since immediate beneficial effects

Figure 7. Influence of density on the strength of cured soil-lime mixtures (Ref 99).

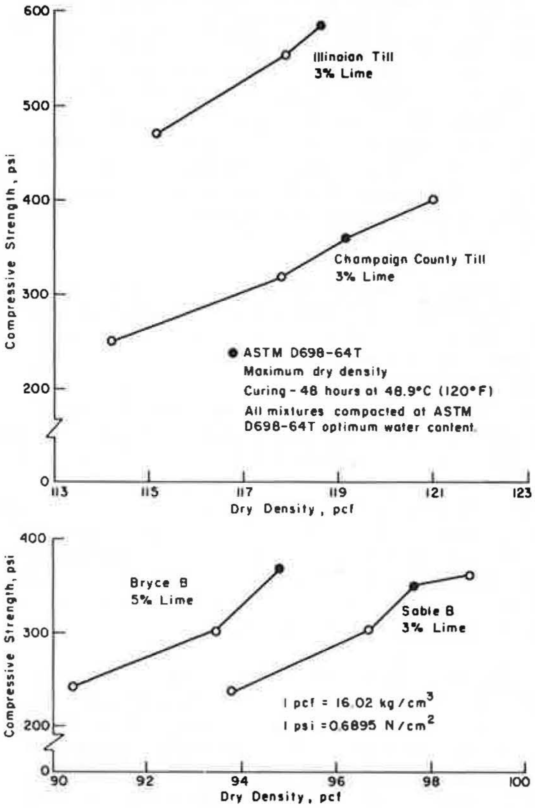


Figure 8. Cohesion vs unconfined compressive strength of soil-lime mixtures (Ref 103).

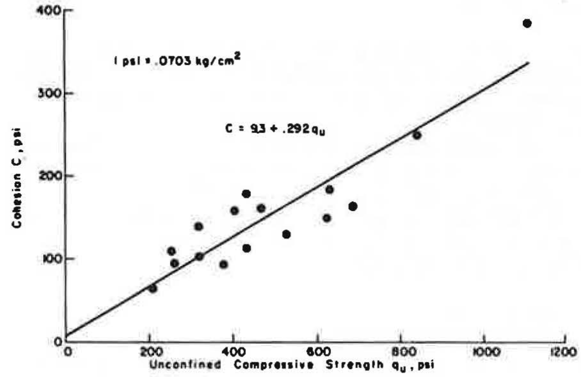


Figure 9. Indirect tensile strength of cured soil-lime mixture (Ref 105).

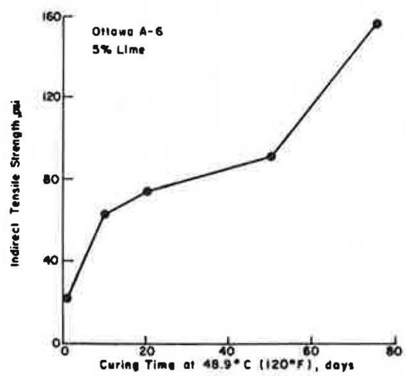
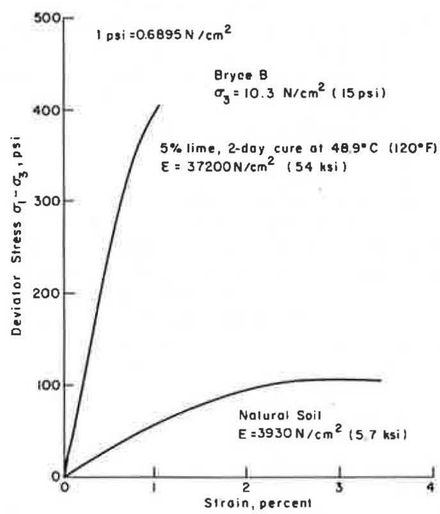


Table 2. CBR values for selected soils and soil-lime mixtures (Ref 99).

Soil	Natural Soil CBR, %	Natural Soil Swell, %	Percent Lime	Soil-Lime Mixtures: No Curing[1] CBR, %	No Curing[1] Swell, %	48 Hours Curing, 48.9° C (120° F) CBR, %	48 Hours Curing Swell, %
Good Reacting Soils							
Accretion Gley 2	2.6	2.1	5	15.1	0.1	351.0	0.0
Accretion Gley 3	3.1	1.4	5	88.1	0.0	370.0	0.1
Bryce B	1.4	5.6	3	20.3	0.2	197.0	0.0
Champaign Co. Till	6.8	0.2	3	10.4	0.5	85.0	0.1
Cisne B	2.1	0.1	5	14.5	0.1	150.0	0.1
Cowden B	7.2	1.4	3	—	—	98.5	0.0
Cowden B	4.0	2.9	5	13.9	0.1	116.0	0.1
Cowden C	4.5	0.8	3	27.4	0.0	243.0	0.0
Darwin B	1.1	8.8	5	7.7	1.9	13.6	0.1
East St. Louis Clay	1.3	7.4	5	5.6	2.0	17.3	0.1
Fayette C	1.3	0.0	5	32.4	0.0	295.0	0.1
Illinoian B	1.5	1.8	3	29.0	0.0	274.0	0.0
Illinoian Till	11.8	0.3	3	24.2	0.1	193.0	0.0
Illinoian Till	5.9	0.3	3	18.0	0.9	213.0	0.1
Sable B	1.8	4.2	3	15.9	0.2	127.0	0.0
Non-Reactive Soils							
Fayette B	4.3	1.1	3	10.5	0.0	39.0	0.0
Miami B	2.9	0.8	3	12.7	0.0	14.5	0.0
Tama B	2.6	2.0	3	4.5	0.2	9.9	0.1

[1]Specimens were placed in 96-hour soak immediately after compaction.

Figure 10. Typical stress-strain curves for natural and lime-treated soil (Ref 103).



occur which relate to improved workability and construction.

Uncured Soil-Lime

Figure 11 shows typical improved stress-strain characteristics which occur without curing and indicates the general nature of the modification attained from lime treatment.

As indicated in Fig 11, substantial increases in modulus of deformation can be expected. Figure 12 illustrates typical stress-strain relationships for soil and soil-lime which were compacted on the wet side of optimum to simulate a wet field condition during construction.

Cured Soil-Lime

As a result of an extensive study of representative Illinois soils stabilized with lime (Ref 103), it was possible to develop a generalized compressive stress-strain relation for cured soil-lime mixtures (Fig 13). The mixtures studied appeared to be strain susceptible, and the ultimate strain at maximum compressive stress was approximately 1 percent, regardless of the soil type or curing period.

Modulus of Deformation or Elasticity. It was found (Ref 103) that the compressive modulus of elasticity at a confining pressure of 1.05 kg/cm^2 (15 psi) could be estimated from the unconfined compressive strength of the lime-soil mixture according to the following relation:

$$E = 9.98 + .124\ q_u$$

where

E = compressive modulus of elasticity, ksi
q_u = unconfined compressive strength, psi

For soil-lime pavement layers possessing high shear strength, the flexural stresses in the mixture may be the controlling design factor. In view of this fact, flexural moduli of elasticity have been evaluated for typical cured soil-lime (Ref 103).

Typical Illinois soils were stabilized with lime, and beams with dimensions of 5.08 cm x 5.08 cm x 22.86 cm (2 in. x 2 in. x 9 in.) were prepared and cured for 48 and 96 hours at 48.9° C (120° F). After curing, strain gauges were attached to the mid-portion of the beams and the beams were tested under third-point loading conditions.

The modulus of elasticity in flexure was calculated from the moment-curvature relationships for the beams, and the relationship between the modulus of elasticity and the flexural strength was calculated (Fig 14). For the range of data considered, it was concluded that the regression equation shown in Fig 14 can be used to estimate the flexural modulus of elasticity. It should be noted that flexural moduli were substantially larger than compressive moduli for the same mixture.

Repeated compressive loading data for soil-lime mixtures are limited. Fossberg (Ref 45), utilizing a montmorillonitic clay treated with 10 percent lime, studied the influence of deviator stress and confining pressure on resilient modulus. The specimens were prepared at extremely high water contents and low densities. Consequently the data are not directly comparable with field conditions. The general relation between resilient modulus and principal stress ratio appeared to be linear and resilient moduli in excess of 69,000 N/cm^2 (100,000 psi) were noted for some test conditions, even under the rather unfavorable testing conditions involving high water content and low density.

Maxwell and Joseph (Ref 67) used a field vibratory testing procedure for evaluating the strength of an airfield pavement section containing a 15.2-centimeter (6-inch) lime-stabilized subgrade and an 20.3-centimeter (8-inch) lime-stabilized clay-gravel subbase. Based on periodic field-velocity measurements, computed elastic moduli for the stabilized subgrade ranged from 114,000 N/cm^2 (165,000 psi) following construction to 392,000 N/cm^2 (568,000 psi) approximately 2½ years after construction. Similar data for the lime-treated subbase were 135,000 N/cm^2 (196,000 psi) after construction and 696,000 N/cm^2 (1,010,000 psi) 2½ years later.

Poisson's Ratio. Only limited data are available for lime-soil mixtures. Reported values at stress levels less than 25 percent of ultimate compressive strength ranged from 0.08 to 0.12 with an average of 0.11 (Ref 99). These values are in agreement with those previously reported for rock, lime-flyash-aggregate mixtures, and soil-cement. At higher stress levels, greater than 50 to 75 percent of ultimate compressive strength, Poisson's ratio increased, ranging from 0.27 to 0.37 with an average of 0.31. A similar type of behavior has been noted for lime-flyash-aggregate mixtures. The influence of stress level, expressed as a percent of ultimate compressive strength, on Poisson's ratio for soil-lime mixtures is shown in Fig 15.

General. Since the properties of a soil-lime mixture change with increased curing time, it may not be justified to conduct elaborate tests to precisely evaluate properties that will change due to field curing effects. It may be more desirable to use unconfined compressive strength or the indirect tensile test for evaluating the quality of the mixtures. Use of correlations in place of testing is discouraged since these correlations depend on the conditions for which they were developed and can produce large errors. Correlations should be used only when there is no other alternative or the desired property cannot be measured and then only with caution.

Fatigue Characteristics

The flexural strength of soil-lime mixtures is important to its use in subbase and base courses. Flexural fatigue data developed for typical Illinois soils are shown in Fig 16.

The response curves are typical of fatigue in general and are similar to the curves normally obtained for similar materials such as lime-flyash-aggregate mixtures and concrete. The fatigue strengths at 5 million stress repetitions of the lime-soil mixtures varied from 41 to 66 percent of the ultimate flexural strength with an average of 54 percent.

More important is the behavior of lime-treated mixtures when subjected to repeated applications of tensile stresses such as in the indirect tensile test or the direct tensile test. Preliminary fatigue experiments using the indirect tensile test indicated that this test is quite applicable to the study of lime-treated materials (Ref 81).

Soil-lime mixtures continue to gain strength with time and the ultimate strength of the mixture is a function of curing period and temperature. The magnitudes of the stress repetitions applied to the mixture are relatively constant throughout its design life. Therefore, as the ultimate strength of the material increases due to curing, the stress level, as a percent of ultimate strength, will decrease and

Table 3. Tensile strength properties of soil-lime mixtures (Ref 99).

Soil	Percent Lime	Curing Time, Hours*	Flexural Strength σ_F, N/cm^2 (psi)	Indirect Tensile Strength σ_T, N/cm^2 (psi)	σ_F/σ_T
Bryce B	5	24	63 (92)	29 (42)	2.2
		48	72 (105)	37 (53)	2.0
		96	84 (122)	61 (88)	1.4
Champaign County Till	3	48	48 (69)	**	—
		96	64 (93)	**	—
Fayette C	5	24	45 (66)	32 (46)	1.4
		96	114 (166)	87 (126)	1.3
Illinoian Till, Sangamon County	3	24	59 (86)	24 (35)	2.5
		48	113 (164)	63 (92)	1.8
		96	139 (202)	73 (106)	1.9
Sable B	3	48	43 (63)	**	—
		96	53 (77)	**	—
Wisconsin Loam Till	3	24	57 (83)	24 (35)	2.4
		48	97 (140)	43 (63)	2.2
		96	108 (157)	54 (78)	2.0

* At 48.9° C (120° F).
**Test not conducted.

Figure 11. Immediate effects of lime treatment on modulus of deformation (Ref 84).

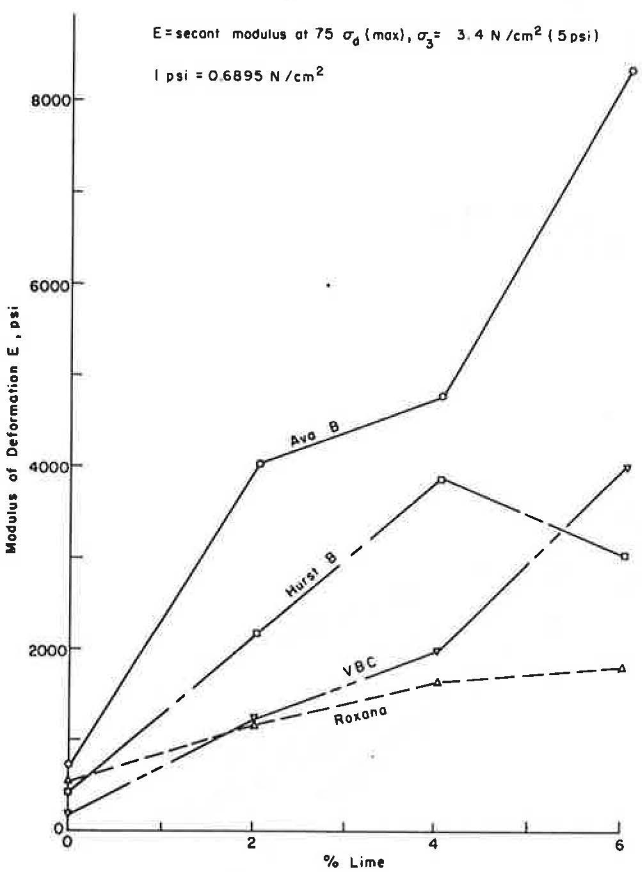


Figure 12. Typical stress-strain curve illustrating immediate effects of lime treatment (Ref 84).

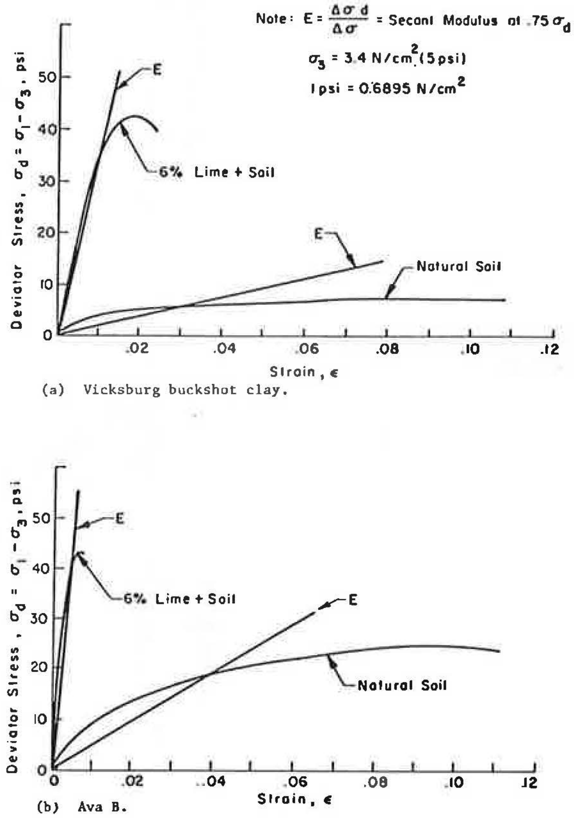


Figure 13. Generalized stress-strain relationship for cured soil-lime mixtures (Ref 103).

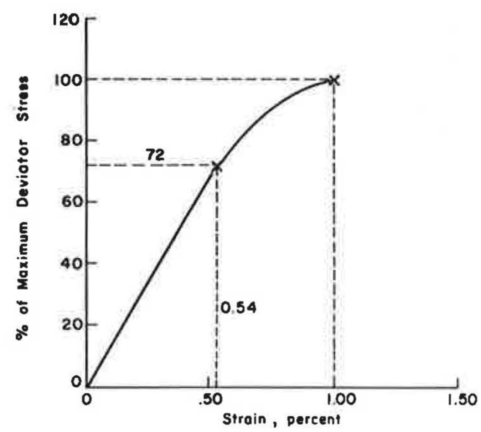


Figure 14. Relationship between flexural strength and flexural modulus for soil-lime mixtures (Ref 99).

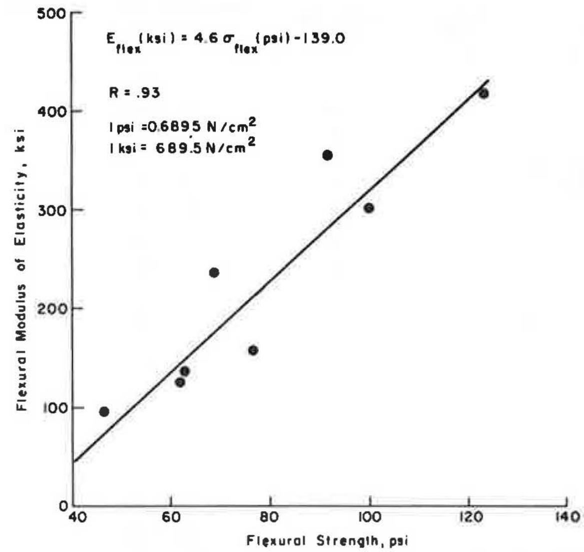


Figure 15. Influence of stress level on Poisson's ratio (Ref 99).

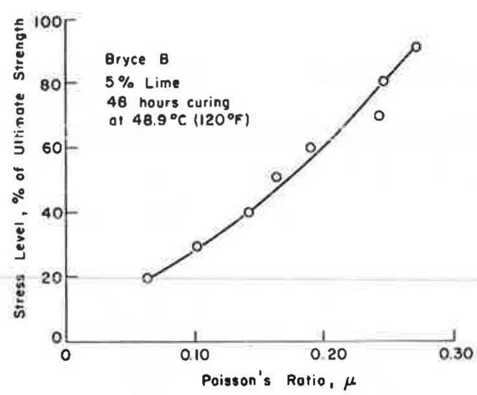
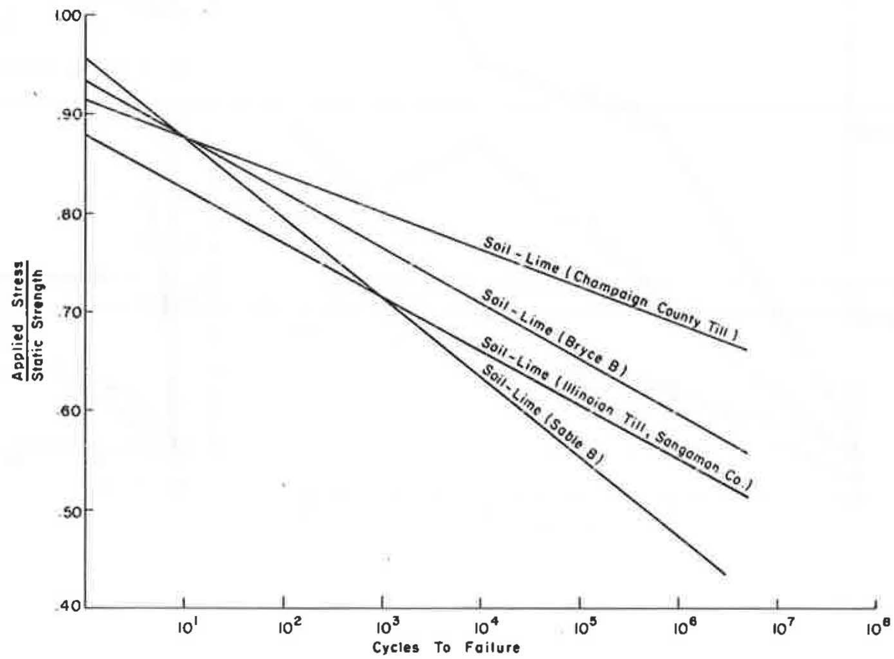


Figure 16. Flexural fatigue response curves (Ref 96).



the fatigue life of the mixture will increase.

Durability

The major durability consideration for soil-lime mixtures is the resistance to cyclic freezing and thawing. Prolonged exposure to water produces only slight detrimental effects and the ratio of soaked to unsoaked compressive strength is high at approximately 0.7 to 0.85 (Ref 106). Figure 17 shows the general relation between soaked and unsoaked strengths for typical lime stabilized Illinois soils. The soaked specimens seldom achieved 100 percent saturation, and in most cases the degree of saturation was in the range of 90 to 95 percent. Similar response to soaking has been noted in extensive studies conducted by the Road Research Laboratory, England (Ref 42).

In zones where freezing temperatures occur, rreeze-thaw damage may occur. The damage is generally characterized by volume increase and strength reduction as shown in Figs 18 and 19. The interrelation between length changes and compressive strength decreases is presented in Fig 20. The validity of using initial unconfined compressive strength as a measure of freeze-thaw resistance is demonstrated in Fig 21. Average rates of strength decrease for the typical mixtures were 6.21 N/cm^2/cycle (9 psi/cycle) and 12.4 N/cm^2/cycle (18 psi/cycle) for 48- and 96-hour curing at 48.9° C (120° F), respectively (Ref 36).

A study (Ref 107) has shown that some soil-lime mixtures display autogenous healing properties. If the stabilized soil has the ability to regain strength, or heal, with time, the distress produced during winter freeze-thaw cycles will not be cumulative since autogenous healing during favorable curing conditions would serve to restore the stability of the material. This phenomenon is illustrated in Fig 22. Confirming field data on autogenous healing have been presented by McDonald (Ref 68).

Durable soil-lime mixtures can be obtained when reactive soils are stabilized with lime. Although some strength reduction and volume change may occur, the residual strength of the stabilized materials is adequate to meet field service requirements. Durability considerations must be taken into account in establishing the mix design and selecting design strength parameters.

Variability of Properties

Analyses of testing error associated with repeat strength determinations of identical soil-lime mixture specimens have been reported by Liu and Thompson (Ref 63). The standard deviations for unconfined compression, indirect (split) tensile, and flexural strengths increased with increased strength and the average coefficients of variation. In general, the testing errors were approximately of the same magnitude, coefficients of variation of 11 to 12 percent, for the different testing procedures studied. This variation was for specimens prepared, cured, and tested in the laboratory. The variation for soil-lime mixtures constructed in the field would be substantially greater (Ref 66).

Factors contributing to testing variability include: a) heterogenous nature of soils; b) nonuniformity of mixtures; c) slight deviations in sample preparation and testing techniques; d) small variations in curing temperature and time; and e) density variations.

Moving from the laboratory to a field construction site, it could be expected that more variation would be introduced as a result of the relatively uncontrolled construction process as compared to the carefully controlled laboratory conditions. Additional variation may also be introduced with time during construction. The variation in material properties introduced along the roadway includes variation introduced by the environment, changes in the constituents of the mixture, changes in contractor or construction technique, and various other factors.

This variability should be recognized and considered in the evaluation of soil-lime mixtures.

Summary

An attempt has been made to summarize the basic characteristics and properties of soil-lime mixtures with respect to their engineering uses. These properties vary significantly depending on the type of soil, method and quality of construction, and type and length of curing. Thus, at this time it is not possible to define the actual properties. Only values can be provided. The use, evaluation, and mixture design procedures should be developed in terms of intended use, objectives, and test conditions. In addition, the evaluation should be based on meaningful tests which provide fundamental engineering properties rather than empirical test results. An attempt should also be made to recognize and consider the inherent variation in soil-lime mixtures.

SOIL-LIME MIXTURE DESIGN

General

The major objective of the mixture design process is to establish an appropriate lime content for construction. It is important to note that the primary variable that can be altered is lime percentage since the inherent properties and characteristics of the soil are essentially fixed. Because of the many varied applications of lime treatment of soils, several mixture design procedures have been developed which are described in this section. The general principle of soil-lime mixture design is that the mixture should provide satisfactory performance when constructed in a desired position in the pavement structure or the subgrade. It is apparent that a wide range of soil-lime mixtures of varying quality can be successfully used to accomplish differing lime treatment objectives. Design lime contents generally are based on an analysis of the effect of various lime percentages on selected engineering properties of the soil-lime mixture. Engineering properties which are considered, depending on the stabilization objectives, are Atterberg limits, i.e., liquid limit, plastic limit, and plasticity index, swell potential, and strength of cured or uncured mixtures.

Mixture design criteria are needed to establish the quantity of lime required to produce an acceptable quality mixture. For some stabilization objectives and soils, acceptable soil-lime mixtures may not be produced regardless of the lime percentage used.

Laboratory Testing Procedures

Many different laboratory testing procedures have been utilized in the various mixture design methods. Specific details of the various procedures have not been included in this report, however, general considerations are summarized below.

Test methods which have been used in the design of soil-lime mixture include (1) Atterberg limits, (2) California Bearing Ratio, (3) Hveem stabilometer or R-value, (4) swell tests, and (5) unconfined compression. Laboratory testing involves soil-lime mixture preparation, specimen preparation,

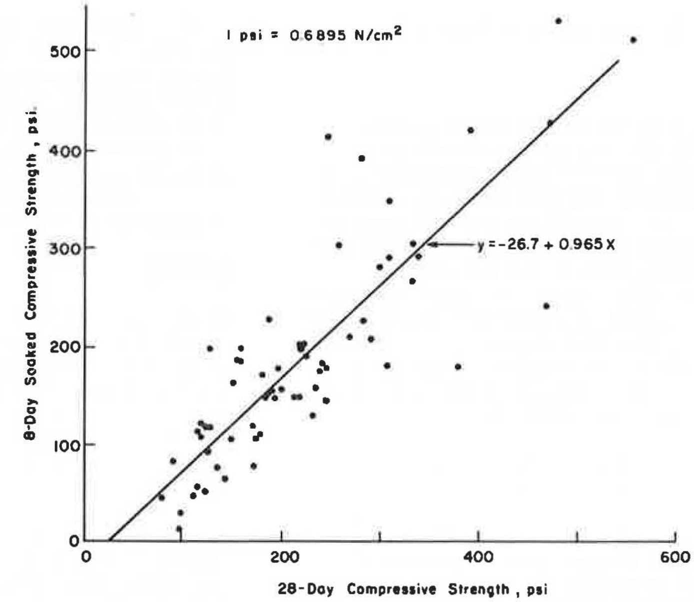


Figure 17. Influence of soaking on the strength of cured soil-lime mixtures (Ref 106).

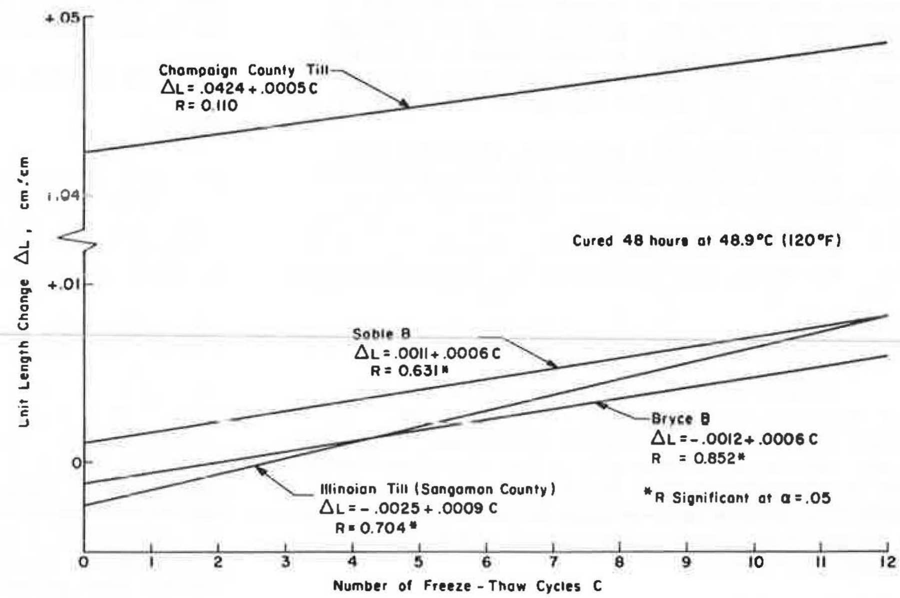


Figure 18. Influence of freeze-thaw cycles on unit length change (48-hour curing) (Ref 36).

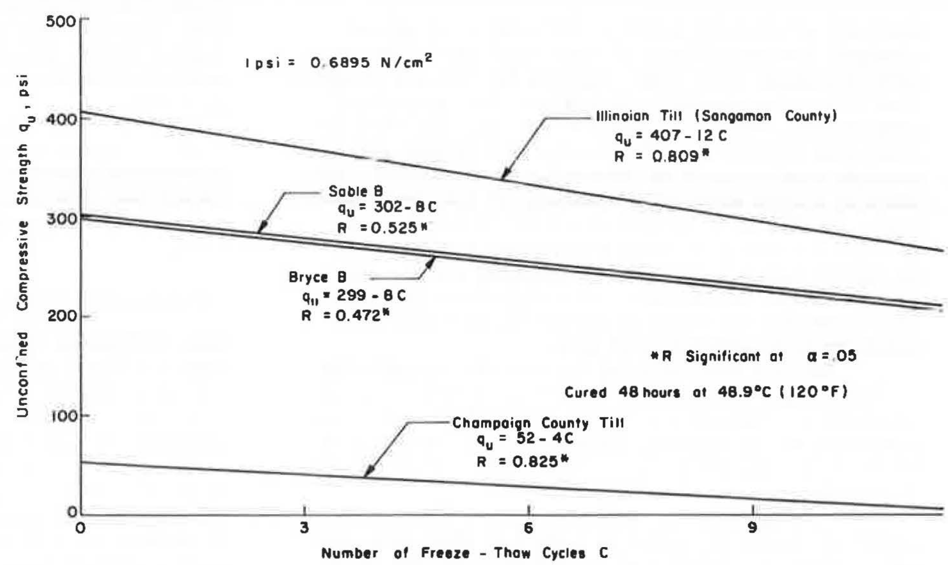


Figure 19. Influence of freeze-thaw cycles on unconfined compressive strength (Ref 36).

Figure 20. Relationship between unit length change and strength decrease with freeze-thaw cycles (Ref 36).

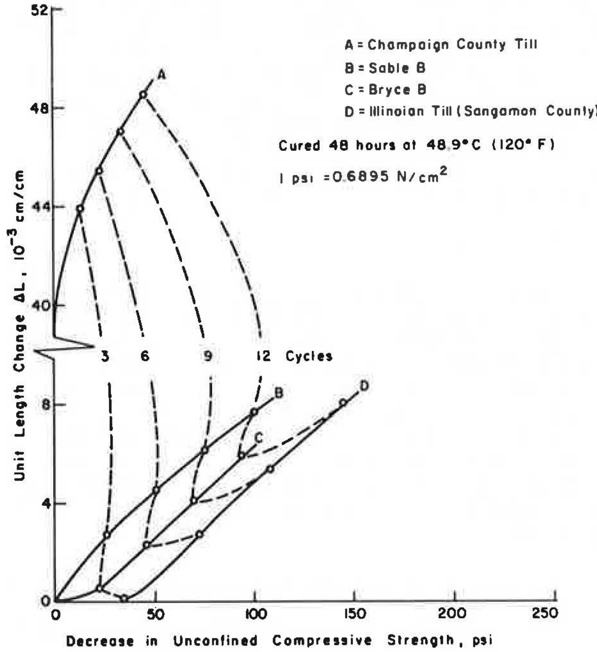


Figure 21. Influence of initial unconfined compressive strength on the residual strength after freeze-thaw cycles (Ref 36).

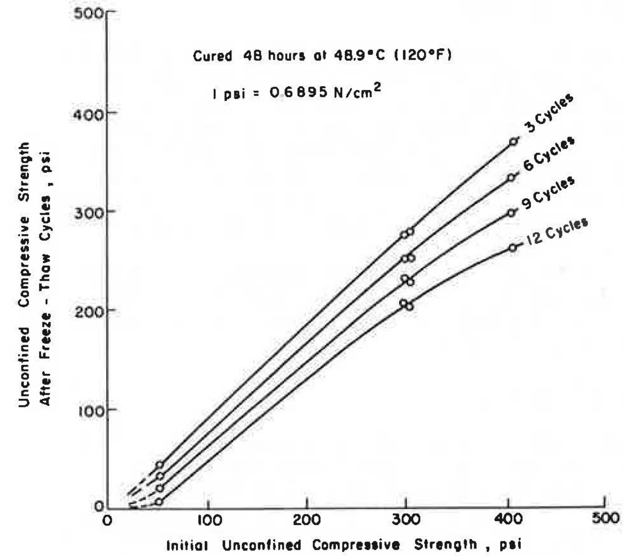


Figure 22. Influence on cylic freeze-thaw and intermediate curing on unconfined compressive strength (Ref 107).

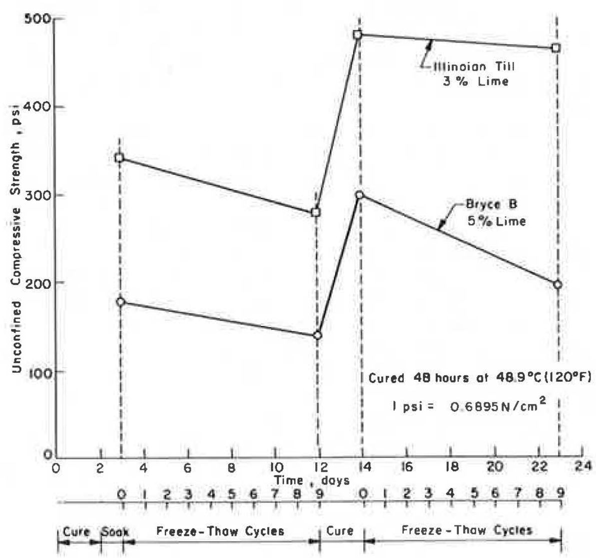
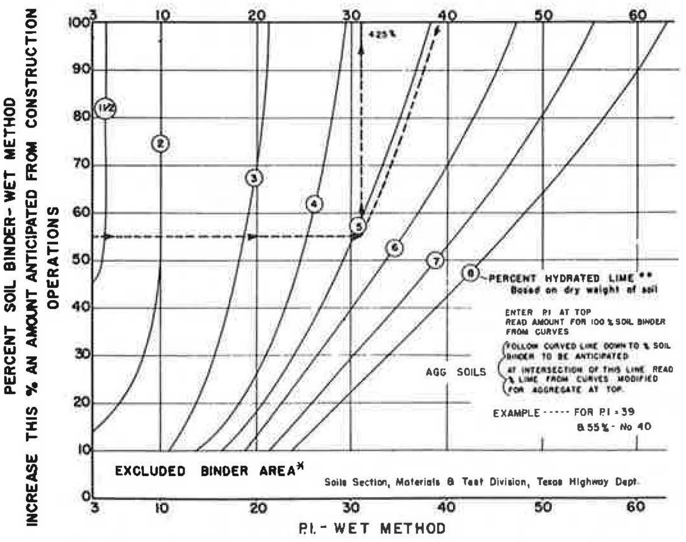


Figure 23. Recommended amounts of lime for stabilization of subgrades and bases (Ref 72).



*Exclude use of chart for materials with less than 10% - No 40 and cohesionless materials (P.I. less than 3)

**Percent of relatively pure lime usually 90% or more of Ca and/or Mg hydroxides and 85% or more of which pass the No 200 sieve. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as 1/2 of above percentages. Reference to cementing strength is implied when such terms as "Lasting Effects" and "Temporary Results" are used.

Note: These percentages should be substantiated by approved testing methods on any particular soil material.

curing, and testing.

Mixture Preparation

Lime contents generally are specified as a percentage of the dry weight of soil, although a few agencies specify on a volume basis. Soil-lime mixtures are normally prepared first by dry mixing the proper amounts of soil and lime and then blending the required amount of water into the mixture. In most procedures, mixtures are prepared at or near optimum moisture content as determined by AASHTO T-99, T-180 or T-212.

Frequently the soil-lime mixture is allowed to mellow one hour or some other designated time prior to conducting Atterberg limit tests or preparing test specimens.

Specimen Preparation

Strength test specimens are generally cylindrically shaped. Diameter and heights vary substantially ranging from 35.6 mm (1.4 inches) in diameter by 71.1 mm (2.8 inches) high to 15.2 cm (6 inches) in diameter by 20.3 cm (8 inches) in height. Since the length to diameter ratios (ℓ/d ratios) vary, it is recommended that compressive strength values be corrected to an ℓ/d ratio of 2 for comparison purposes.

The density of the compacted specimens must be carefully controlled because the strength of a cured soil-lime mixture is greatly influenced by density (Fig 6) and small density variations may make it difficult to accurately evaluate the effect of other variables such as lime percentage and curing conditions. Thus, the compactive effort should always be specified since some test methods specify AASHTO T-99 or the equivalent and other procedures specify AASHTO T-180 or T-212.

Curing Conditions

Time, temperature, and moisture conditions during the curing period vary significantly. Some agencies cure at room temperatures while others cure at elevated temperatures, e.g., 48 hours at 48.9° C (120° F). Normally elevated temperature curing is of shorter duration than ambient curing. Many procedures specify that the specimens should be cured in a sealed container while others (AASHTO T-220) require a moist curing cycle followed by a drying and capillary wetting cycle. It should be noted that in some procedures no curing period is required.

The great disparity in curing conditions makes it very difficult to compare the results obtained from different testing methods. Thus, mixture quality criteria developed for a particular test procedure should not be arbitrarily adopted for analyzing test results obtained from a different test method.

Testing

Procedures used to evaluate soil-lime specimens usually involve conventional tests. For example, the Atterberg Limits (AASHTO T-89, T-90), California Bearing Ratio (AASHTO T-193), and R-Value (ASTM D2844) are used for many different types of materials. There is probably more variation in unconfined compression testing than any other procedure. Thus, details concerning specimen size, rate of loading, etc. should be specified in the description of any test method which is not standardized.

Mixture Design Criteria

Mixture design criteria are needed to evaluate the adequacy of a given soil-lime mixture. Criteria will vary depending on the stabilization objectives and anticipated field service conditions, i.e., environmental factors, wheel loading considerations, design life, etc. It is thus apparent that mixture design criteria may range over a broad scale and should be based on a careful consideration of the specific conditions associated with the stabilization project.

Types of Criteria

Current mixture design criteria can be classified into two broad categories. The first category relates to those situations where the major stabilization objectives are PI reduction, improved workability, immediate strength increase, and reduced swell potential. To a large extent, these property improvements are produced by the cation exchange and flocculation-agglomeration reactions which occur quite rapidly. Mixture design criteria for this category of stabilization might typically include some of the following requirements:

(1) no further decrease in PI with increased percentage of lime,
(2) acceptable PI reduction for the particular stabilization objective,
(3) acceptable swell potential reduction, and
(4) CBR and R-Value increase sufficient for anticipated uses.

It is difficult to establish actual quantitative values for the above requirements because in many cases they must be established relative to the properties of the untreated soil and the specific job conditions.

The second category of criteria is concerned with strength improvement produced by the pozzolanic reaction between the soil and lime. For example, if the mixture is to be used as a subbase or base course in the pavement structure, it must possess minimum strength and durability. Thus, mixture design criteria normally specify that the cured mixture meet a minimum strength requirement and the design lime content is that percentage which produces maximum strength for given curing conditions.

Most current minimum strength criteria are specified in terms of compressive strength. The minimum strength requirements generally are higher for base materials than for subbase materials since stress and durability conditions differ for various depths in the pavement structure.

Typical current mixture design criteria are presented in the section entitled Current Mixture Design Procedures.

Experience and Evaluation

Mixture design criteria can be validated only on the basis of actual field performance. McDowell's extensive publications (Refs 72 through 77) concerning Texas experiences, Anday's summary (Ref 3) of Virginia projects, and McDonald's recent reports (Refs 68 through 71) are examples of extensive validation activities for widely separated geographic areas with drastically different climatic conditions.

Mixture design criteria developed for use with a particular mixture design procedure and geographic location must be applied indiscriminately to other areas. Careful consideration should be given to all aspects of the problem before adopting any criteria.

Current Mixture Design Procedures

Selected current mixture design procedures are summarized below. As discussed, mixture design procedures consider specimen preparation, curing conditions, testing procedures, and mixture design criteria. More detailed information concerning the mixture design procedures can be obtained by consulting the various references listed in this section.

California Procedure

California's current design procedure is based on stabilometer test data developed for mixtures containing various lime percentages. The general procedure is as follows:

1. Soil-lime mixtures are prepared at various lime percentages. The mixture moisture content is adjusted to approximately optimum (AASHTO T-180) and the moist mixture is loose cured for 24 hours.
2. Stabilometer samples are compacted using the California kneading compactor (California Test Method 301). The compacted specimens are not cured.
3. The compacted specimens are tested using the stabilometer (California Test Method No. 312) to determine the R-value.
4. Depending on the intended use of the mixture, the lime percentage required to develop an R-value in the range of 60 to 80 is determined.
5. The lime percentage is increased approximately 1 percent to compensate for field construction variability.

Eades and Grim Procedure

The pH mixture design concept developed by Eades and Grim (Ref 44) involves, to a certain extent, a strength based criterion. The basic thrust of the pH procedure is to add sufficient lime to the soil to insure a pH of 12.4 for sustaining the strength-producing, lime-soil pozzolanic reaction. The pH procedure, as developed by Eades and Grim, is summarized below.

1. Representative samples of air-dried, minus No. 40 soil to equal 20 g of oven-dried soil are weighed to the nearest 0.1 g and poured into 150-ml (or larger) plastic bottles with screw tops.
2. Since most soils will require between 2 and 5 percent lime, it is advisable to set up five bottles with lime percentages of 2, 3, 4, 5, and 6. This will insure, in most cases, that the percentage of lime required can be determined in 1 hour. Weigh the lime to the nearest 0.01 g and add it to the soil. Shake to mix soil and dry lime.
3. Add 100 ml of CO_2-free distilled water to the bottles.
4. Shake the soil-lime and water until there is no evidence of dry material on the bottom. Shake for a minimum of 30 seconds.
5. Shake the bottles for 30 seconds every 10 minutes.
6. After 1 hour, transfer part of the slurry to a plastic beaker and measure the pH. The pH meter must be equipped with a Hyalk electrode and standardized with a buffer solution having a pH of 12.00.
7. Record the pH for each of the soil-lime mixtures. If the pH readings go to 12.40, the lowest percent lime that gives a pH of 12.40 is the percent required to stabilize the soil. If the pH does not go beyond 12.30 and 2 percent lime gives the same reading, the lowest percentage which gives a pH of 12.30 is that required to stabilize the soil. If the highest pH is 12.30 and only 1 percent lime gives a pH of 12.30, additional test bottles should be started with larger percentages of lime.

Thompson and Eades (Ref 108) have demonstrated that for typical Illinois soils, the lime percentage determined by the pH test was approximately the same as the lime percentage producing maximum compressive strength. Recent work by Harty (Ref 53), however, indicates that the lime percentage obtained from the pH procedure does not produce maximum cured compressive strength for tropical and subtropical soils. There are limitations to the pH procedure in that, (1) the technique does not establish whether the soil will react with lime to produce a substantial strength increase, and (2) strength data are not generated for use in evaluating mixture quality.

Eades and Grim (Ref 44) recognized the need for supplemental strength data and have stated, "The one-hour 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 calcium silicates, and their formation varies with the mineralogical components of the soil, a strength test is necessary to show the percentage of strength increase."

Illinois Procedure

The Illinois procedure considers two types of stabilization objectives:

1. Soil-lime stabilization in which the mixture will be utilized as a base or subbase material in the pavement system, and
2. Subgrade modification and expediting construction.

The procedures are outlined below.

Soil-lime Stabilization. The mixture design procedure is based on unconfined compressive strength test data. Specimens with a 5.1 centimeter (2 inch) diameter and a 10.2 centimeter (4 inch) height of the natural soil and soil-lime mixtures are prepared at optimum moisture content and maximum dry density (AASHTO T-99). The soil-lime specimens, prepared at various lime treatment levels, are cured for 48 hours at 48.9° C (120° F) prior to testing.

The compressive strength of the soil-lime mixture with 3 percent lime must be at least 34.5 N/cm^2 (50 psi) greater than the compressive strength of the natural soil. The design lime content is designated as the lime percent above which further increases do not produce significant additional strength. For field construction, the lime content is increased 0.5 to 1.0 percent to offset the effects of field variability. Minimum strength requirements are 69 N/cm^2 (100 psi) for subbase and 103 N/cm^2 (150 psi) for base course. These minimum strengths relate to AASHTO coefficients of relative strength of 0.12 for subbase materials and 0.11 for base course materials.

Subgrade Modification. The mixture design procedure for lime modification is based on the effect of lime on the plasticity index of the soil. Optional CBR testing can also be conducted if desired.

AASHTO Methods T-89 and T-90 are utilized to determine the liquid limit, plastic limit, and plasticity index of the soil treated with various percentages of lime. The lime-soil-water mixture is loose cured for one hour prior to testing. A plot of plasticity index versus lime content is prepared. The design lime content may be designated as (1) that lime content above which no further appreciable reduction in PI occurs, or (2) a minimum lime content which produces an acceptable PI reduction.

Depending on the stabilization objectives, CBR tests may also be conducted to evaluate the stability and/or swell properties of the lime-treated soil. Curing and soaking of the CBR specimens prior to testing is optional depending on the stabilization objectives. If appropriate, the design lime content may be changed based on the CBR data, stability values, or swell properties.

For field construction, the design lime content is increased 0.5 to 1.0 percent to offset the effects of field construction variability.

Louisiana Procedure

Lime contents for soil-lime mixtures to be used as base or subbase courses are determined in accordance with LDH Designation TR 433-70, "Determining the Minimum Lime Content for Lime-Soil Treatment." Quality requirements, expressed in terms of minimum unconfined compressive strength, are 69 N/cm^2 (100 psi) for base course and 34.5 N/cm^2 (50 psi) for subbase courses.

Soil-lime mixtures of various lime contents are prepared at optimum moisture content (LDH TR 418) and specimens 15.2 cm (6 in.) in diameter and 20.3 cm (8 in.) in height are compacted to maximum dry density (LDH TR 418).

The curing cycle for the compacted soil-lime mixture is:

1. seven days in moist room,
2. air dried 8 hours at 60° C (140° F),
3. eight hours of cooling, and
4. ten day capillary soaking at a confining pressure of 0.69 N/cm^2 (1 psi), AASHTO T-212 procedure.

Following curing, the specimens are tested in unconfined compression at a rate of 3.81 mm/minute (0.15 in./minute). The minimum lime content providing adequate unconfined compressive strength, i.e., 69 N/cm^2 (100 psi) for base, 34.5 N/cm^2 (50 psi) for subbase, is determined from the test data.

Oklahoma Procedure

Oklahoma's standard procedure for determining the optimum lime content is the Eades and Grim Procedure. As an alternate, a plasticity index reduction test procedure, as outlined below, is used. The basic objective of Oklahoma's lime treatment is to modify subgrade soils without any specific strengthening objective.

1. Soil-lime mixtures with lime contents of 3, 5, 7, and 10 percent are prepared at the AASHTO T-99 optimum moisture content for the soil.
2. The soil-lime mixtures are loose cured in a moisture room for 48 hours.
3. The cured soil-lime mixture is then dried in accordance with AASHTO T-87 paragraph 4(a).
4. The liquid limit, plastic limit, and plasticity index PI are determined in accordance with AASHTO Methods T-89 and T-90, respectively.
5. A plot of PI versus percent lime is prepared. The percent lime which reduces the PI by two points per one percent increase in lime is considered to be the optimum lime content for the soil-lime mixture. Any lime content at or below the optimum lime content which gives the desired modification may be recommended by the engineer. The PI should be reduced to a maximum value of 10.

South Dakota Procedure

Initial lime requirements are established based on a pH procedure (Test No. SD 128) which is similar to the Eades and Grim Procedure. Supplemental strength data are developed by evaluating the CBR of various soil-lime combinations compacted at optimum moisture content (AASHTO T-99) to maximum dry density.

The South Dakota technique (Test No. SD 107) is similar to AASHTO T-193. If the CBR of the soil-lime mixture with no curing except for the 96-hour soaking period is 3 to 4 times greater than the CBR of the natural soil, the soil-lime mixture is considered to be of adequate quality for use as a pavement layer (AASHTO coefficient of relative strength = 0.05).

Texas Procedure

The soil-lime mixture design procedure used by the State Department of Highways and Public Transportation is AASHTO T-220 which provides for the determination of the unconfined compressive strength of soil-lime mixtures. The procedure suggests strength criteria of 69 N/cm^2 (100 psi) for base construction and 34.5 N/cm^2 (50 psi) for subbase construction.

Details of the procedure are included in AASHTO T-220, however, a general outline of the procedure is presented below.

1. Based on the grain size and plasticity index data, the lime percentage is selected from Fig. 23.
2. Optimum moisture and maximum dry density of the mixture are determined in accordance with appropriate sections of AASHTO T-212 or Tex-121-E. The compactive effort is 50 blows of a 4.54 kg (10 lb) hammer, with a 45.7 cm (18 inch) drop.
3. Test specimens, 15.2 cm (6 inches) in diameter and 20.3 (8 inches) in height are compacted at optimum moisture content to maximum dry density.
4. The specimens are placed in a triaxial cell (AASHTO T-212 or Tex-121-E) and cured in the following manner:

   a. seven days at room temperature,
   b. remove cells and dry at a temperature not to exceed 60° C (140° F) for about six hours or until one-third to one-half of the molding moisture has been removed,
   c. cool the specimens for at least 8 hours, and
   d. subject the specimens to capillarity (section 6 of AASHTO T-212 or Tex-121-E) for 10 days.

5. The cured specimens are tested in unconfined compression in accordance with sections 7 and 8 of AASHTO T-212 or Tex-121-E.

Relative to Fig 23, the Texas Procedure notes that the percentages should be substantiated by approved testing methods on any particular soil material. The results of the unconfined compression strength testing can be used for the purpose of substantiation.

Thompson Procedure

Thompson (Ref 104) has developed a mixture design process for lime-treated soils in which different procedures are proposed for lime modified soils and soil-lime mixtures.

The lime modification procedure is utilized when the stabilization objectives are to expedite construction and produce subgrade modification, e.g., CBR increase, decreased swell potential, and decreased plasticity. Soil-lime mixtures which display significant compressive strength increases, 34.5 N/cm^2 (50 psi) minimum, can be utilized as base and subbase materials depending on the soil-lime mixture properties and pavement service requirements.

A flow diagram illustrating the mixture design process is shown in Fig 24. Quality criteria for the soil-lime mixtures were established based on considerations of pavement structural behavior and durability requirements. The soil-lime quality criteria are summarized in Table 4.

The development of the mixture design process and the detailed testing procedures are contained in Ref 104. It is emphasized that the lime-modified soil mixture design process can be utilized for reactive soils if the stabilization objectives are primarily to expedite construction or modify the subgrade.

Virginia Procedure

Virginia's mixture design procedure, VTM-11 Virginia Test Method for Lime Stabilization, is based on the cured compressive strength of soil-lime mixtures stabilized with various amounts of lime. The procedure is summarized below.

1. Proctor sized specimens at various lime percentages are prepared at approximately optimum moisture content and maximum dry density (AASHTO T-99), compaction test conducted with 6 percent lime.
2. Specimens are cured in sealed containers at high humidity for 72 hours at 48.9° C (120° F).
3. The soil-lime specimens are tested in unconfined compression using a loading rate of 1089 kg/minute (2,400 pounds/minute) or approximately 1.3 kg/cm^2/minute (19 psi/minute).
4. Virginia criteria require a minimum compressive strength of 10.5 kg/cm^2 (150 psi) for soil-lime mixtures tested in accordance with the above procedure.

Summary

Design lime contents generally are based on an analysis of the effect of varying lime percentages on selected engineering properties of the soil-lime mixture. The basic components of a mixture design procedure generally are:

1. method for preparing the soil-lime mixture,
2. procedure for preparing and curing specimens,
3. testing procedures for evaluating a selected property or properties of the cured soil-lime mixture, and
4. appropriate criteria for establishing the design lime content.

It is important to note that different design lime contents for the same soil may be established depending on the objectives of the lime treatment and the mixture design procedure utilized. Mixture design procedures should be flexible enough to allow the exercise of judgment when unusual stabilization objectives are contemplated.

LIME STABILIZATION CONSTRUCTION

Introduction

The modern version of lime stabilization is less than 30 years old, but considerable advancement has been made in construction procedures during these past three decades. This progress of this method of stabilization was due to the efforts of many engineers and scientists and can be summarized as follows:

1. basic and applied research by numerous state highway departments, governmental agencies, and universities;
2. education by worldwide publication of research studies and construction reports of actual lime stabilization projects; and
3. equipment manufacturer's recognition of the potential of lime stabilization and development of equipment to meet the needs of the contractor.

Twenty-five years ago there were two basic stabilizers that could be adapted to lime stabilization, but today there are approximately twenty different types of equipment designed primarily for this stabilization.

With the growth of lime stabilization throughout the world for many climatic conditions, a diversity of applications has developed and a variety of construction techniques has evolved. This variation has been due to such factors as type of soil, degree of stabilization required, complexity of project, ecological restraints, and type of pavement design. For example, some heavy clay soils are very reactive to lime and can be completely pulverized with only one pass of a traveling mixing unit; however, this is the exception to the rule, as the stabilization of a heavy gumbo clay usually requires much more manipulation and curing than a low-plastic granular material. Modification of soil, e.g., drying out of wet soil with lime to expedite construction, is less involved than completely stabilizing a heavy clay to be used as a part of the pavement structure.

Projects may range from maintenance activities for which only a few bags of lime are required (Fig 29) to vast interstate highways or airfield pavements requiring thousands of tons of bulk lime. Because of dusting, projects located in urban areas generally require the use of lime slurry rather than dry lime. Thus, with the growing emphasis on ecology the trend is toward a greater use of a lime slurry and some engineers are now discouraging the use of dry lime except in very localized areas.

Finally, when lime is used in pavement design to reduce overall thickness, the stabilized layer must be built under tight construction specifications, whereas requirements are more lenient when lime is merely used to form a working table.

Regardless of the specific application of soil-lime, the following basic steps are involved in the construction procedure: soil preparation, lime spreading, mixing and watering, compaction and finishing, and curing. These basic steps, along with the more significant variations, are discussed in detail. Since this is a state-of-the-art report, undoubtedly there will be more variations as lime stabilization continues to expand throughout the world.

Lime Stabilization Methods

Basically, there are three recognized lime stabilization methods, including in-place mixing, plant mixing, and pressure injection.

In-place Mixing

In-place mixing may be subdivided into three methods:

1. mixing lime with the existing materials already a part of the construction site or pavement (Fig 25),
2. off-site mixing in which lime is mixed with borrow and the mixture is then transported to the construction site for final manipulation and compaction (Fig 26), and
3. mixing in which the borrow source soil is hauled to the construction site and processed as in method number 1.

The following procedures are utilized for in-place mixing:

1. One increment of lime is added to clays or granular base materials that are easy to pulverize. The material is mixed and compacted in one operation, and no mellowing period is required.
2. One increment of lime is added and the mixture is allowed to mellow for a period of 1 to 7 days to assist in breaking down heavy clay soils.
3. One increment of lime is added for soil modification and pulverization prior to treatment

Table 4. Tentative soil-lime mixture compressive strength requirements (Ref 104).

Anticipated Use	Residual Strength Requirement,[1] N/cm^2 (psi)	Strength Requirements for Various Anticipated Service Conditions[2]: Extended Soaking, 8 days, N/cm^2 (psi)	Cyclic Freeze-Thaw[5]: 3 Cycles, N/cm^2 (psi)	7 Cycles, N/cm^2 (psi)	10 Cycles, N/cm^2 (psi)
Modified subgrade	13.8 (20)	34.5 (50)	34.5 (50)	62.1 (90) 34.5 (50)	82.7 (120)
Subbase					
Rigid pavement	13.8 (20)	34.5 (50)	34.5 (50)	62.1 (90) 34.5 (50)*	82.7 (120)
Flexible pavement					
Thickness of cover[3]					
25.4 cm (10 in.)	20.7 (30)	41.4 (60)	41.4 (60)	68.9 (100) 41.4 (60)*	89.6 (130)
20.3 cm (8 in.)	27.6 (40)	48.3 (70)	48.3 (70)	75.8 (100) 51.7 (75)*	96.5 (140)
12.7 cm (5 in.)	41.4 (60)	62.1 (90)	62.1 (90)	89.6 (130) 68.9 (100)*	110 (160)
Base	68.9 (100)[4]	89.6 (130)	89.6 (130)	117 (170) 103 (150)*	138 (200)

[1]Minimum anticipated strength following first winter exposure.

[2]Strength required at termination of field curing (following construction) to provide adequate residual strength.

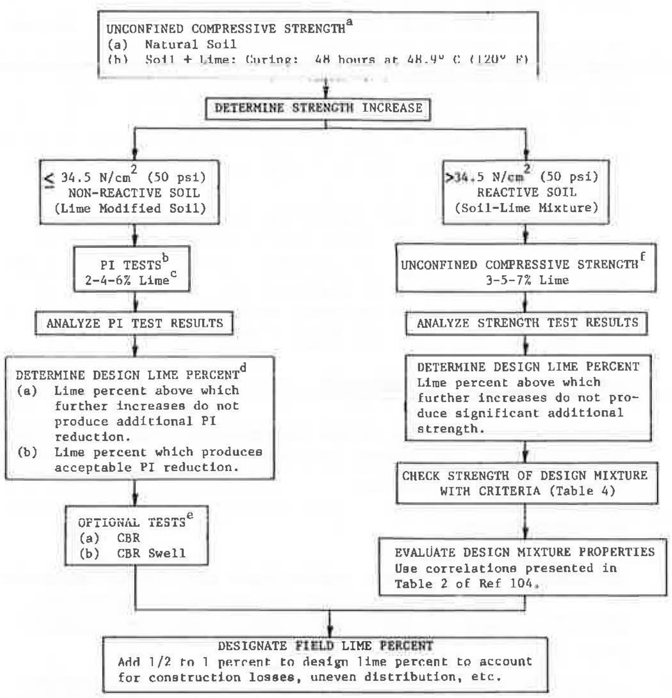
[3]Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.

[4]Flexural strength should be considered in thickness design.

[5]Number of freeze-thaw cycles expected in the soil-lime layer during the first winter of service.

*Freeze-thaw strength losses based on 6.9 N/cm^2/cycle (10 psi/cycle) except for 7-cycle values indicated by an * which were based on a previously established regression equation.

Figure 24. Proposed mixture design process for lime-treated soils (Ref 104).



[a]All specimens compacted at optimum water content to maximum dry density. Lime treatment level for b may be 5 percent or as determined by "pH procedure." See footnote f if desired.

[b]PI Tests conducted one hour after mixing lime-soil-water. Mixture is not cured prior to testing.

[c]In some cases more closely spaced treatment levels may be appropriate.

[d]Criteria a or b may be applied depending on the stabilization objective.

[e]Conduct tests at design lime content. Curing of CBR specimens prior to soaking is optional depending on stabilization objective. If swell is not reduced to a satisfactory level, additional CBR tests may be conducted at higher lime contents. Design lime content may be increased if further swell reduction is obtained. Swell considerations are of great importance for lime modified subgrades.

[f]Specimens compacted at optimum moisture content to maximum dry density. Additional and/or different lime percentages may be required for some soils. An estimate of approximate optimum lime content may be obtained by applying "pH test procedure" developed by Eades and Grim (Ref 44).

Figure 25. In-place mixing of lime-stabilized subgrade—Oregon.

Figure 26. Off-site mixing pads for Mississippi River levee repair project—Arkansas.

Figure 27a. Deep stabilization of access road—Dallas-Fort Worth Airport. After lime spreading the plow cuts to a depth of 61 cm (24 inches).

Figure 27b. Tractor plow pulled by a second tractor for deep stabilization.

Figure 27c. Root plow for scarifying to a depth of 46 cm (18 inches).

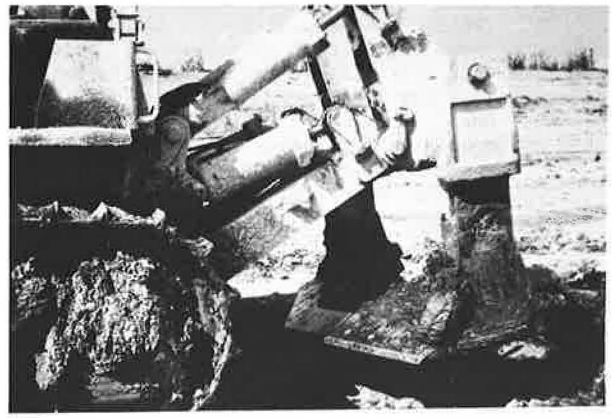


Figure 28. Plant mixing pug mills.

(a) Lime-treated gravel with lime fed by screw conveyor—South Dakota (Ref 21).

(b) Lime-cement-flyash-aggregate base course—Newark Airport.

Figure 29. Application of lime by the bag for a small maintenance project-Texas.

Figure 30. Application of lime by a bulk pneumatic truck for levee repair project.

with cement or asphalt.

4. One increment of lime is added to produce a working table. Proof rolling is required in lieu of pulverization and density requirements.

5. Two increments of lime are added for soils which are extremely difficult to pulverize. Between the applications of the first and second increments of lime, the mixture is allowed to mellow.

6. Deep stabilization which has been accomplished by one of two approaches (Ref 98).

a. One increment of lime is applied to modify soil to a depth of 24 inches (Fig. 27). Greater depths are possible but to date have not been attempted. A second increment of lime is added to the top 15 to 30 cm (6 to 12 in.) for complete stabilization. Plows and rippers are used to break down the large clay chunks in the deep treatment. Heavy disc harrows and blades are also used in pulverization of these clay soils. In frost zones, the use of small quantities of lime for soil modification under some circumstances may result in a frost susceptible material which in turn can produce a weak sublayer.

b. One increment of lime is applied for complete stabilization to a depth of 46 cm (18 in.). Mechanical mixers are now available to pulverize the lime-clay soil to the full depth by progressive cuts as follows: first pass cut to a depth of 15 cm (6 in.), second to 23 cm (9 in.), third to 30 cm (12 in.), fourth to 38 cm (15 in.), and then a few passes to a depth of 46 cm (18 in.) to accomplish full pulverization. The full 46 cm (18 in.) is compacted from the top by vibratory and conventional heavy rollers.

Plant Mixing

The plant-mix operation usually involves hauling the soil to a central plant where lime, soil, and water are uniformly mixed and then transported to the construction site for further manipulation (Fig 28).

The amount of lime for either method is usually predetermined by test procedures. Specifications may be written to specify the actual strength gain required to upgrade the stabilized soil, and notations can be made on the plans as to the estimated percent of lime required. This note should also stipulate that changes in lime content may be necessary to meet changing soil conditions encountered during construction.

Pressure Injection

Pressure injections of lime slurry to depths of 2 to 3 meters (7 to 10 feet) for control of swelling and unstable soils on highways and under building sites are usually placed on 1.5-meter (5-foot) spacings, and attempts are made to place horizontal seams of lime slurry at 20- to 30-cm (8- to 12-in.) intervals. The top 15- to 30-cm (6- to 12-in.) layer should be completely stabilized by conventional methods. Pressure injection will not be considered in detail since the technology is different and is outside the scope of this report. Additional information and detail can be obtained from Refs 58 and 113.

Construction Steps

Soil Preparation

The in-place subgrade soil should be brought to final grade and alignment. The finished grade elevation may require some adjustment due to the potential fluff action of the lime stabilized layer resulting from the fact that some soils tend to increase in volume when mixed with lime and water. This volume change may be exaggerated when the soil-lime is remixed over a long period of time, especially at moisture contents less than optimum moisture. The fluff action is usually minimized if adequate water is provided and mixing is accomplished shortly after lime is added. For soils that tend to fluff with lime, the subgrade elevation should be lowered slightly or the excess material trimmed. Trimming can usually be accomplished by blading the material onto the shoulder of embankment slopes.

This blading operation is desirable to remove the top 6.4 mm (¼ inch) since this material often is not well cemented due to lime loss experienced during construction. Excess rain and construction water may wash lime from the surface, and carbonation of lime may occur in the exposed surface.

If dry lime is used, ripping or scarifying to the desired depth of stabilization can be accomplished either before or after lime is added. If the lime is to be applied in a slurry form, it is desirable to scarify prior to the addition of lime.

Lime Application

Dry Hydrated Lime. Dry lime can be applied either in bulk or by bag. The use of bagged lime is generally the simplest but also the most costly method of lime application. Bags, 22.7 kg (50 lb), are delivered in dump or flatbed trucks and placed by hand to give the required distribution (Fig 29). After the bags are placed, they are slit and the lime is dumped into piles or transverse windrows across the roadway. The lime is then leveled by either hand raking or by means of a spike-tooth harrow or drag pulled by a tractor or truck. Immediately thereafter, the lime is sprinkled to reduce dusting.

The major disadvantages of the bag method are the higher cost of lime because of bagging costs, greater labor costs, and slower operations. Nevertheless, bagged lime is often the most practical method for small projects or for projects in which it is difficult to utilize large equipment.

For large stabilization projects, particularly where dusting is no problem, the use of bulk lime has become common practice. Lime is delivered to the job in self-unloading transport trucks (Fig 30). These trucks are large and efficient, capable of hauling 13,300 to 21,800 kg (15 to 24 tons). One type is equipped with one or more integral screw conveyors which discharge at the rear. In recent years pneumatic trucks have increased in popularity and are preferred over the older auger-type transports. With the pneumatic units the lime is blown from the tanker compartments through a pipe or hose to a cyclone spreader or to a pipe spreader bar mounted at the rear (Fig 31). Bottom-dump hopper trucks have also been tried, but they are undesirable because of difficulty in unloading and obtaining a uniform rate of discharge.

With the auger trucks, spreading is handled by means of a portable, mechanical-type spreader attached to the rear or through metal downspout chutes or flexible rubber boots extending from the screw conveyors. The mechanical spreaders incorporate belt, screw, rotary vane, or drag chain conveyors to distribute the lime uniformly across the spreader width. When boots or spouts are used instead, the lime is deposited in windrows; but due to lime's lightness and flowability, the lime becomes distributed rather uniformly across the spreading lane. Whether mechanical spreaders, downspouts, or boots are used, the rate of lime application can be regulated by varying the spreader opening, spreader drive speed, or truck speed so that the required amount of lime can be applied in one or more passes.

With the pneumatic trucks, spreading is generally handled with a cyclone spreader mounted at the rear, which distributes the lime through a split chute or with a spreader bar equipped with several large downspout pipes. Fingertip controls in the truck cab permit the driver to vary the spreading width by adjusting the air pressure. Experienced drivers can adjust the pressure and truck speed so that accurate distribution can be obtained in one or two passes.

When bulk lime is delivered by rail, a variety of conveyors can be used for transferring the lime to transport trucks; these include screw, belt or drag-chain conveyors, bucket elevators, and screw elevators. The screw-type conveyors are most commonly used, with large diameter units, 25.4 to 30.5 cm (10 to 12 inches) being recommended for high speed unloading. To minimize dusting, all types of conveyors should be enclosed. Rail car unloading is generally facilitated by means of poles and either mechanical or air-type vibrators.

Lime has also been handled through permanent or portable batching plants, in which case the lime is weigh-batched prior to loading. Generally, a batching plant set-up would only be practical on exceptionally large jobs.

Obviously, the self-unloading tank truck is the least costly method of spreading lime, since there is no rehandling of material and large payloads can be carried and spread quickly.

Dry Quicklime. Quicklime may be applied in bags or bulk. Due to its higher cost, bagged lime is only used for drying of isolated wet spots or on small jobs. The distribution of bagged quicklime is similar to that of bagged hydrate, except that greater safety emphasis is needed. First the bags are spaced accurately on the area to be stabilized, and after spreading, water is applied and mixing operations started at once. The fast watering and mixing operation helps minimize the danger of burns. Quicklime may be applied in form of pebble, approximately 9.5 mm (3/8 inch), granular, or pulverized. The first two are more desirable as less dust is generated during spreading.

Bulk quicklime may be spread by self unloading auger or pneumatic transport trucks, similar to those used for dry hydrate. In addition, however, due to its coarser size and higher density, quicklime may also be tailgated from a regular dump truck with tailgate opening controls to assure accurate distribution (Fig. 32).

Because quicklime is anhydrous and generates heat upon contact with water, special care should be taken during stabilization to avoid lime burns. Where quicklime is specified, the contractor should provide the engineer, for review, a detailed safety program covering precautions to be exercised and emergency treatment to be available on the jobsite. The program should include protective equipment for eyes, mouth, nose, and skin as well as a first-aid kit with an eyeball wash. This protective equipment should be available on the jobsite during spreading and mixing operations. The contractor should actively enforce this program for the protection of the workers and others in the construction area.

Slurry Method. In this method lime and water are mixed into a slurry. Historically, hydrated lime has been used in slurries. Nevertheless, quicklime could potentially be used providing that adequate equipment was developed for preparing the slurry. At the present time, this process involves a two-step operation in which a quicklime paste is first prepared and then additional water added to form the slurry. The hydrated lime-water slurry is mixed either in a central mixing tank (Fig 33), jet mixer (Fig 34), or in a tank truck. The slurry is spread over the scarified roadbed by a tank truck equipped with spray bars (Fig 35). One or more passes may be required over a measured area to achieve the specified percentage based on lime solids content. To prevent run-off and consequent non-uniformity of lime distribution that may occur under certain conditions, it may be necessary to mix the slurry and soil immediately after each spreading pass (Fig 36).

A typical slurry mix proportion is 907 kg (1 ton) of lime and 1.9 m^3 (500 gallons) of water which yields about 2.3 m^3 (600 gallons) of slurry containing 31 percent lime solids. At higher concentrations there is difficulty in pumping and spraying the slurry. Forty percent solids is a maximum pumpable slurry.

The actual proportion used depends upon the percent of lime specified, type of soil, and its moisture condition. Where small lime percentages are required, the slurry proportions may be reduced to 907 kg (1 ton) of lime per 2.6 to 3.0 m^3 (700 to 800 gallons) of water. Where the soil moisture content is near optimum, a stronger lime concentration normally would be required.

In plants employing central mixing, agitation is generally accomplished by using compressed air and a recirculating pump, although pug mills have also been used. The most typical slurry plant incorporates slurry tanks large enough to handle whole tank truck loads of hydrated lime, approximately 18,100 kg (20 tons). For example, on one job two 57-cubic meter (15,000 gallon) tanks, 3-meter diameter by 8-meter length (10-foot diameter by 26-foot length) were used, each fitted with a 20-centimeter (8-inch) perforated air line mounted along the bottom. The air line was stopped 46 cm (18 inches) short of the end wall, thereby providing maximum agitation in the lime feeding zone. A typical batch consisted of 38 m^3 (10,000 gallons) of water, charged first, and 18,100 kg (20 tons) of lime, producing about 45 m^3 (12,000 gallons) of slurry in less than 25 minutes. Loading of the tank trucks was handled by a standard water pump, with one slurry tank being unloaded while the slurry was being mixed in the other tank.

On another job the contractor used a similar tank and air line, but in addition made use of a 10-cm (4-inch) recirculating pump for mixing; the same pump loaded the tank trucks. To keep the lime from settling, the contractor devised a hand-operated scraper fitted with air jets.

Still another job involved a much smaller tank, approximately 9 m^3 (2400 gallons), mounted below a lime bin and weigh-batcher. A typical batch consisted of 1800 kg (2 tons) of lime and 4 m^3 (1000 gallons) of water, producing enough slurry for one tank truck. Mixing was accomplished with air jets and a 7.6-centimeter (3-inch) recirculating pump.

The newest and most efficient method of slurry production which eliminates batching tanks involves the use of a compact jet slurry mixer. Water at 5 kg/cm^2 (70 psi) pressure and hydrated lime are charged continuously in a 65:35 (weight) ratio into the jet mixing bowl, where slurry is produced instantaneously. The mixer and auxiliary equipment can be mounted on a small trailer and transported to the job readily, giving great flexibility to the operation (Ref 16).

In the third type of slurry set-up, measured amounts of water and lime are charged separately to the tank truck, with the slurry being mixed in the tank either by compressed air or by a recirculating pump mounted at the rear. The water is metered and the lime proportioned volumetrically or by means of weight batchers. Both portable and permanent batching plants are used. Mixing with air is accomplished at the plant. The air jets are turned on during the

Figure 31. Distribution of lime from bar spreader-Wisconsin.

Figure 32. Spreading of granular quicklime on canal relining project—California (Ref 18).

Figure 33. Slurry mixing plant using recirculating pump for mixing.

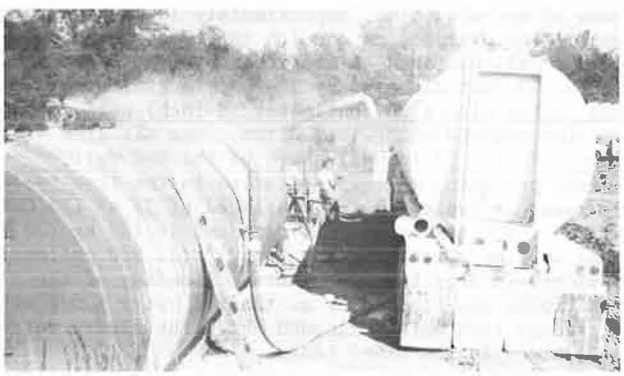


Figure 34. Jet slurry mixing plant-Dallas County, Texas (Ref 16).

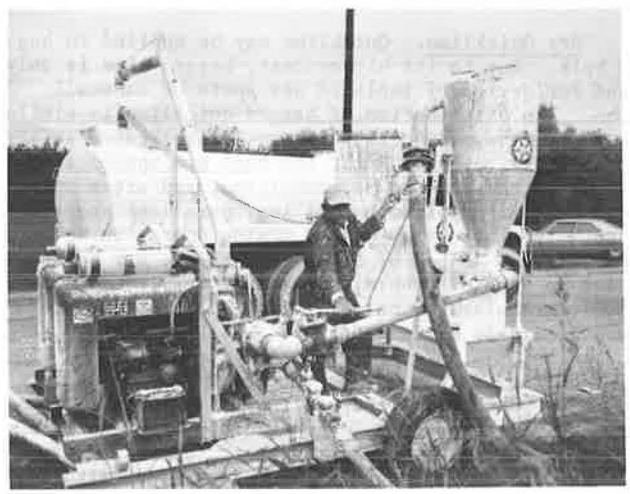


Figure 35. Spreading of lime slurry.

(a) Stabilization of stone base (Ref 16).

(b) Recirculation pump on top of 2.3 m^3 (6000 gal) wagon agitates slurry.

Figure 36. Grader-scarifier cutting slurry into stone base.

loading operation, and remain on until the slurry is thoroughly mixed which takes about 10 to 15 minutes. The use of a recirculating pump, however, permits mixing to occur during transit to the job. Generally, 5, 8 or 10-centimeter(2, 3, or 4-inch) pumps are used in this operation, with the slurry being recirculated through the tank by means of a perforated longitudinal pipe extending the length of the tank and capped at one end.

Spreading from the slurry distributors is effected by gravity or by pressure spray bars, the latter being preferred due to better distribution. The use of spray deflectors is also recommended for good distribution. The general practice in spreading is to make either one or two passes per load. However, several loads may be needed in order to distribute the required amount of lime. The total number of passes will depend on the lime requirement, optimum moisture of the soil, and type of mixing employed. Windrow mixing with the grader generally requires several passes.

Double Application of Lime. In some areas where extremely plastic, gumbo clay (PI of 50+) abounds, it may prove advantageous to add the requisite amount of lime in two increments to facilitate adequate pulverization and obtain complete stabilization. For example, 2 or 3 percent lime is added first, partially mixed, then the layer is sealed and allowed to cure for up to a week. The remaining lime is then added preparatory to final mixing. The first application mellows the clay and helps in achieving final pulverization and the second application completes the lime-treatment process.

Advantages and Disadvantages of Different Types of Application

Listed below are some of the advantages and disadvantages of the various lime application procedures.

1. Dry Hydrated Lime. Advantages: (a) dry lime can be applied two or three times faster than a slurry; and (b) dry lime is very effective in drying out soils. Disadvantages: (a) dry lime produces a dusting problem which makes its use undesirable in urban areas; and (b) the fast drying action of the dry lime requires an excess amount of water during the dry, hot seasons.

2. Quicklime. Advantages: (a) more economical as it contains approximately 25 percent more available lime; (b) greater bulk density so storage silos can be smaller in size; (c) faster drying action in wet soils; (d) faster reaction with soils; and (e) due to faster drying, construction season can be extended, both spring and fall. Disadvantages: (a) field hydration less effective than commercial hydrators, producing a coarser material with poorer distribution in soil mass; (b) quicklime requires more water than hydrate for stabilization, which may present a problem in dry areas; and (c) greater susceptibility to skin and eye burns.

3. Slurry Lime. Advantages: (a) dust-free application is more desirable from an environmental standpoint; (b) better distribution is achieved with the slurry; (c) in the lime slurry method, the lime spreading and sprinkling operations are combined, thus reducing job costs; and (d) during summer months slurry application pre-wets the soil and minimizes drying action. Disadvantages: (a) application rates are slower; high capacity pumps are required to achieve acceptable application rates; (b) extra equipment is required and thus costs are higher; (c) extra manipulation may be required for drying purposes during cool, wet, humid weather, which could occur during the fall, winter, and spring construction season; and (d) not practical for use with very wet soils.

Pulverization and Mixing

To obtain satisfactory soil-lime mixtures adequate pulverization and mixing must be achieved. For heavy clay soils two stage pulverization and mixing may be required while for other soils one stage mixing and pulverization may be satisfactory. This difference is due primarily to the fact that the heavy clays are more difficult to break down.

Two-stage Mixing. Construction steps in two-stage mixing consist of preliminary mixing, moist curing for 24 to 48 hours (or more) and final mixing or remixing. The first mixing step distributes the lime throughout the soil, thereby facilitating the mellowing action. For maximum chemical action during the mellowing period, the clay clods should be less than 5 cm (2 inches) in diameter. Prior to mellowing the soil should be sprinkled liberally to bring it up to at least two percentage points above optimum moisture in order to aid the disintegration of clay clods. The exception to excess watering would be in cool, damp weather when evaporation is at a minimum. In hot weather, however, it may be difficult to add too much water.

After preliminary mixing, the roadway should be sealed lightly with a pneumatic roller as a precaution against heavy rain, since the compacted subgrade will shed water, thereby preventing moisture increases which might delay construction. Generally, in 24 to 48 hours the clay becomes friable enough so that desired pulverization can be easily attained during final mixing. Additional sprinkling may be necessary during final mixing to bring the soil to optimum moisture or slightly above (Fig 37). In hot weather more than optimum moisture is needed to compensate for the loss through evaporation.

Although disc harrows (Fig 38) and grader scarifiers are suitable for preliminary mixing, high-speed rotary mixers (Fig 39) or one-pass travel plant mixers (Fig 25) are required for final mixing. Motor graders are generally unsatisfactory for mixing lime with heavy clays.

One-stage Mixing. Both blade and rotary mixing or a combination have been used successfully in projects involving granular base materials. However, rotary mixers are preferred for more uniform mixing, finer pulverization, and faster operation. They are generally required for highly plastic soils which do not pulverize readily and for reconstructing worn-out roads in order to pulverize the old asphalt.

Blade Mixing. When blade mixing is used in conjunction with dry lime, the material is generally bladed into two windrows, one on each side of the roadway. Lime is then spread on the inside of each windrow or down the center line of the road. The soil is then bladed to cover the lime. After the lime is covered, the soil is mixed dry by blading across the roadway. After dry mixing is completed, water is added to slightly above the optimum moisture content and additional mixing is performed. To assure thorough mixing by this method, the material should be handled on the mold board at least three times.

When blade mixing is used with the slurry method, the mixing is done in thin lifts which are bladed to windrows. One practice is to start with the material in a center windrow, then blade aside a thin layer after the addition of each increment of slurry, thereby forming side windrows. The windrowed material is then bladed back across the roadway and compacted, provided that its moisture content is at optimum.

A second practice is to start with a side windrow, then blade a thin, 5-centimeter (2-inch) layer across the roadway, add an increment of lime, then blade this layer to a windrow on the opposite side of the road. On one job this procedure was repeated several times until all the material was mixed and bladed to the new windrow. Since by this time only half of the lime had been added, the process was repeated, moving the material back to the other side. This procedure is admittedly slow, but it provides excellent uniformity.

Rotary Mixing. When high-speed rotary mixers or one-pass travel plant mixers are used, the lime is generally spread evenly on the entire roadway, and mixing starts from the top down. Depending upon the type of equipment used and the soil involved, complete mixing can normally be accomplished in one to three passes. If needed, water is added during mixing to obtain the desired moisture content, generally optimum. The water may be added by sprinkling trucks or by spraying into the mixing chamber of the mixer. The latter method has considerable merit, since the intimate contact of lime, water, and soil facilitates chemical breakdown and pulverization.

The traveling windrow-mixing type machine, commonly referred to as the soil-through-machine type, may also be used for one-stage mixing if adequate pulverization and mixing can be achieved in one pass.

Central Mixing. Pre-mixing of lime with granular base materials is becoming popular on new construction projects, particularly where submarginal gravels are utilized. Since the gravel has to be processed anyway to meet gradation specifications, it is a relatively simple matter for the contractor to install a lime bin, feeder, and pug mill at the screening plant. On one project a small pug mill was installed at the head pulley of the collecting belt conveyor (Fig 28a) and at another operation a larger pug mill plant was utilized (Fig 28b). The general practice is to add the optimum moisture at the pug mill, thereby permitting immediate compaction after laydown.

Pulverization and Mixing Requirements

Pulverization and mixing requirements are generally specified in terms of percentages passing the 1-1/2-inch or 1-inch screen and the No. 4 sieve. Typical requirements are 100 percent passing the 1-inch and 60 percent passing the No. 4, exclusive of non-slaking fractions. However, in some applications the requirements are relaxed. For example, the South Dakota Department of Transportation only requires 100 percent passing the 1-1/2-inch screen with no requirement for the No. 4 sieve. Other specifications may only require 40 to 50 percent passing the No. 4 sieve.

In certain expedient construction operations formal requirements are eliminated, and the "pulverization and mixing to the satisfaction of the engineer" type clause is employed.

Compaction

For maximum development of strength and durability, lime-soil mixtures should be properly compacted. Many agencies require at least 95 percent of AASHTO T-99 density for subbases and 98 percent for bases. Some agencies have required 95 percent AASHTO T-180 maximum density. Although such densities can be achieved for more granular soil-lime mixtures, it is difficult to achieve this degree of compaction for lime-treated fine-grained soils.

If a thick soil-lime lift is to be compacted in one lift, many specifications require 95 percent of AASHTO T-99 maximum density in the upper 15 to 23 centimeters (6 to 9 inches) and lower densities are accepted in the bottom portion of the lift. To achieve high densities necessitates compacting at approximately optimum moisture content with approved compactors. Granular soil-lime mixtures are generally compacted as soon as possible after mixing, although delays of up to two days are not detrimental, especially if the soil is not allowed to dry out and lime is not allowed to carbonate. Fine-grained soils can also be compacted soon after final mixing, although delays of up to four days are not detrimental. When longer delays, e.g., two weeks or more, cannot be avoided, it may be necessary to incorporate a small amount of additional lime into the mixture, e.g., 1/2 percent, to compensate for losses due to carbonation and erosion.

Various rollers and layer thicknesses have been used in lime stabilization. The most common practice is to compact in one lift, using the sheepsfoot roller (Fig 40) until it "walks out," followed by a multiple-wheel pneumatic roller (Fig 41). In some cases, a flat wheel roller is used in finishing. Single lift compaction can also be accomplished with vibrating impact rollers (Fig 42) or heavy pneumatic rollers, with light pneumatic or steel rollers being used for finishing. When light pneumatic rollers are used alone, compaction is generally done in thin lifts, usually less than 15 centimeters (6 inches). Slush rolling of granular soil-lime mixtures with steel rollers is not recommended.

During compaction light sprinkling may be required, particularly during hot, dry weather, to compensate for evaporation losses.

Curing

Maximum development of strength and durability also depends on proper curing. Favorable temperature and moisture conditions and the passage of time are required for curing. Temperatures higher than 4.4 to 10° C (40 to 50° F) and moisture contents around optimum are conducive to curing. Although some specifications require a 3 to 7-day undisturbed curing period, other agencies permit the immediate placement of overlying paving layers if the compacted soil-lime layer is not rutted or distorted by the equipment. This overlying course maintains the moisture content of the compacted layer and is an adequate medium for curing.

Two types of curing can be employed, moist and asphaltic membrane. In the first, the surface is kept damp by sprinkling (Fig. 43) with light rollers being used to keep the surface knitted together. In membrane curing, the stabilized soil is either sealed with one shot of cutback asphalt at a rate of about .45 to 1.1 liters/sq m (0.10 to 0.25 gal/sq yd) within one day after rolling or primed with increments of asphalt emulsion applied several times during the curing period. A common practice is to apply two shots the first day, and one each day thereafter for four days, at a total rate of .45 to 1.1 liters/sq m (0.10 to 0.25 0.25 gal/sq yd). The type of membrane used, amount, and number of shots vary considerably. Generally, it is difficult to apply more than 0.76 liters (0.2 gal) of asphalt prime because the lime stabilized layer is relatively impervious after compaction.

Measurement and Payment

Measurement and payment considerations in the contract documents are typically incorporated in the manner illustrated below. Particular attention should be given to the water item since abnormally large quantities are used in soil-lime construction operation.

Figure 37. Watering of lime-treated clay on airport project—Kansas City, Missouri (Ref 9).

Figure 38. Mixing with disc harrow.

Figure 39. Mixing with rotary mixers.

(a) Rotary mixers on project in Dallas County, Texas.

(b) Train of rotary mixers on Dallas-Fort Worth Airport.

Figure 40. Compacting lime-treated materials with sheepsfoot roller.

(a) Self-propelled sheepsfoot roller.

(b) Double sheepsfoot roller.

Figure 41. Pneumatic roller completes compaction of lime-cement-flyash base, Newark Airport.

Method of Measurement

1. Lime to be measured in tons.
2. Processing of the lime-treated layer to be measured by the square yard.
3. Water used for mixing, compacting, finishing, and curing to be measured in units of 4 cubic meters (1000 gallons).
4. Bituminous materials used for curing seals to be measured by the ton or gallon.

Basis of Payment

1. Lime to be paid for at unit bid price per ton of material accepted in place.
2. Processing of the lime-treated material to be paid for at the unit bid price per square yard of material completed in place.
3. Water to be paid for at unit bid price per 0.38 cubic meters (100 gallons) of material used on the project.
4. Bituminous membrane to be paid for at unit bid price per ton or gallon of material used for curing purposes.

Field Quality Control

Adequate quality control is essential to obtain a soil-lime mixture which will meet the stabilization objectives and provide the desired performance. There are many factors which should be considered in the quality control of soil-lime construction.

Factors typically considered in soil-lime construction and procedures for field use are listed below.

1. Depth of Lime Treatment. Since lime elevates the pH of the soil, phenolphthalein, a color-sensitive indicator solution can be sprayed on the soil to determine the presence of lime (Fig 44). If lime is present, a reddish-pink color develops.
2. Pulverization. The degree of pulverization attained in field mixing is evaluated using selected sieve sizes. Most specifications are based on the 1-inch and the No. 4 sieves. The processed material is "dry sieved" to determine the percent passing. Care should be taken to insure that the plus No. 4 material fraction is not really an agglomerated soil-lime mixture which can be easily broken down by a simple kneading action to pass the No. 4 sieve.
3. Lime Spread Rate. In dry lime spreading operations, the spread rate is established in terms of pounds of lime per unit area of surface. A simple procedure for measuring the actual field spreading rate is to place a 1-square meter or 1-square yard piece of canvas or other suitable material on the grade and then after the lime has been spread determine the weight of lime on the 1 square meter or square yard.
4. Slurry Composition. To accurately determine the quantity of lime slurry required to provide a desired amount of lime solids, it is necessary to know the slurry composition. The most convenient method of checking lime-slurry composition is to determine the specific gravity of the slurry, either by using a hydrometer or a volumetric-weight procedure.
5. Lime Content. Lime content is specified in all soil-lime construction. An ASTM procedure (ASTM D3155-73) has been developed for determining the lime content of uncured soil-lime mixtures. The procedure is rapid and easy to conduct. Other methods of determining lime content are also used and are discussed in the proceeding section on design.
6. Density. Conventional procedures, i.e., sand cone, rubber balloon, nuclear, (Fig 45) are used to determine the in-situ density of compacted soil-lime mixtures. It is very important to recognize that the proper moisture-density relation for the soil-lime mixture be used in the density control operation. The moisture-density relation for a soil-lime mixture may change relative to such factors as curing time. For example, if a soil-lime layer is reworked at some later date following initial construction the maximum dry density and optimum moisture content for the mixture probably will be different from the original mixture.
7. Moisture Content. Conventional procedures, oven drying and nuclear methods (Fig 45) can be used for moisture determinations. In calibrating the nuclear equipment consideration should be given to the presence of the lime in the mixture.
8. Mixing Efficiency. The thoroughness and efficiency of the field mixing operation is of interest. A simple procedure for evaluating mixing efficiency is: (a) secure a sample of the field mixed soil-lime material; (b) halve the sample; (c) prepare strength specimens (unconfined strength is normally satisfactory) from one portion; (d) completely "re-mix" the other portion of the field mixture to insure almost "100 percent mixing;" (e) prepare strength specimens from the "re-mixed" material; (f) cure both sets of strength specimens and test them; and (g) calculate the mixing efficiency, as follows: mixing efficiency, % = field mixed strength/lab mixed strength x 100. For mixed in-place operations mixing efficiencies normally range from 60 to 80 percent. In some types of soil-lime mixing operations lower values may be acceptable.

Specification References

Many agencies have developed specifications and special provisions for soil-lime construction. A comprehensive listing of current specifications and special provisions is presented below.

1. AASHTO - Guide Specifications for Highway Construction, 1968, (Sec. 307 on lime-treated subgrade).
2. U. S. Department of Transportation (FAA) 150/5370A "Standard Specifications for Construction of Airports," Item P-155 "Lime-Treated Subgrade," May 1968.
3. U. S. Corps of Engineers, "Engineering and Design Manual - Soil Stabilization for Roads and Streets" (also AFM 88-7, Chapter 4), June 1969.
4. U. S. Corps of Engineers, "Guide Specification for Military Construction - Lime Stabilized Base Course, Subbase or Subgrade for Roads and Streets," CE 807.32, December 1961 (partly revised February 1971).
5. National Lime Association, "Lime Stabilization Construction," Bulletin 326, 1972.
6. State Specifications or special provisions for the following states: Alabama, Arkansas, Arizona, California, Colorado, Florida, Georgia, Idaho, Illinois, Iowa, Kansas, Louisiana, Maryland, Minnesota, Mississippi, Missouri, Nebraska, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Tennessee, Texas, Utah, Virginia, Wisconsin, Wyoming, etc.

Field Variability

Complete soil-lime construction will display variations in engineering properties such as strength and modulus of elasticity. Such variability is typical of all field construction operations. Major factors contributing to field variability in soil-lime construction are:

1. variations in properties of the soil encountered along the grade,

Figure 42. Vibrating roller completes compaction of subgrade—Virginia.

Figure 43. Moist curing of lime stabilized subgrade—Blytheville, Arkansas.

Figure 44. Checking uniformity of mixing with phenolphthalein solution.

Figure 45. Determination of moisture and density with nuclear gauge—Wisconsin.

2. variability in lime spreading and distribution,

3. variability in pulverization and mixing, and

4. moisture and density variations in the compacted soil-lime layer.

As indicated in the Field Quality Control Section, it is essential to monitor all aspects of soil-lime construction to assure that the desired quality of construction is secured and an acceptable level of uniformity is achieved (Fig. 44).

Summary

This section attempts to describe and summarize modern soil-lime construction procedures and equipment. It is anticipated that these procedures will change rapidly as new pieces of equipment and new uses for lime are developed. Nevertheless, it is felt that this section provides a comprehensive summary and description of lime stabilization construction at the time this report was prepared.

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