# Lime-Soil Mixtures

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The over-all objective of the project described is to investigate various admixtures for chemical stabilization of soils; however, this report is limited to a summary of the published knowledge of lime-soil mixtures. It was prepared from current literature and was written to aid the highway engineer in developing a more thorough understanding of lime-soil stabilization. Other chemicals will be investigated and reported at a later date.

First, the binder material itself, lime, is discussed. The various types of limes and their chemical properties are covered rather thoroughly. Additional information is given on the methods of manufacturing lime, on the availability of different limes, and on the specifications for the control of lime to be used for stabilization purposes. Then the relatively limited data on the basic actions of lime and soil (ion exchange, cementing action and carbonation) are summarized. Other sections cover the physical changes (plasticity, density, strength, etc.) produced by the actions of limes and soils in lime-soil mixtures and lime-pozzolan-soil mixtures.

One section covers current construction practices, another section deals with the field performance of lime-soil stabilized roads. The reviewed literature continually indicated that there are certain limitations to stabilizing soils with limes. These limitations are also discussed. Finally, a number of research projects are suggested that should alleviate some of the existing lack of knowledge of lime-soil mixtures.

An annotated bibliography on lime-soil mixtures, containing all available published literature to July 1960, is included.

●SINCE the beginning of modern road construction, highway engineers have strived continuously to produce better pavements at lower costs. Although various methods have been tried, one successful method has been the stabilization of locally available soils with a binder material. Increased interest has been shown in lime lately as one of these binders. It is relatively inexpensive and can often be used to produce both a chemical change and a cementing action that will improve the soils.

Lime-soil mixtures are soils that have had their physical characteristics changed and/or the soil grains cemented together by action of lime with the aid of water. They include fine-grained soils, granular soils and even existing "gravel roads" that contain appreciable amounts of suitable clays. Lime-soil mixtures also include those soils, especially granular, which can be stabilized with lime only when another material, pozzolan, has been added so that the cementing action may take place. Lime can be used with a wide variety of soils ranging from plastic clays to pit-run gravel and has been used in the improvement of weak, undesirable subgrades as well as in the construction of subbases and bases for highway and airfield pavements.

Although there has been a growing interest in the use of lime for stabilizing soils in recent years, its use is not a new development. It is one of the oldest man-developed construction materials. Various groups of people had used it even before the Romans used it more than 2,000 yr ago in construction of subbases for their elaborate road system. Not only did the Romans develop a technology of using lime, but they even used a pozzolanic material, pozzolana, to improve the cementing action.

The history of modern road construction records little use of lime until after World War II. Primarily, this was due to misleading data and to the resulting wrong conclusions that had been drawn early in the modern construction period. McDowell reports: "Prior to 1945, field experiments were conducted in a number of states (including the midwest) without consideration of control of mixing, compacting and curing. Most of these jobs were used as open surface roads and resulting performances were disappointing. One such job in Texas probably delayed development of lime stabilization in that state for ten years." (59-8). However, as research data on lime-soil mixtures were collected and as lime-soil roads were constructed under more rigid specifications the performance of this type of road material has improved. He continues, "These same materials that failed on one job in this state (Texas), when used on another nearby job, have given splendid performance under medium heavy traffic for a period of 14 years to date." After a late beginning, lime-soil stabilization is slowly spreading in the United States and each year is being used in ever greater quantities by more states.

Considerable literature has been published on the stabilization of soils with lime. Articles have appeared in numerous technical publications in foreign languages as well as in English. These publications are listed subsequently in an annotated bibliography. Not only would it be an arduous task to read all of these articles, but also to some extent, it would be wasted effort as many articles repeat similar data and information. To conserve effort, the following sections contain a digest of these articles. They were written for the engineer who knows little or nothing about lime-soil mixtures and for the engineer who wishes to extend his knowledge of the subject.

This publication is not a treatise on lime-soil mixtures, as few exact numerical data are given. Many references are listed, though, throughout the work. When more detailed data are desired on a particular subject the reader can quickly determine which articles are most pertinent and can read them for details.

## LIMES

In a restricted scientific sense, "lime" is the oxide of calcium, CaO, but rarely is the word used in such a limited way. It is generally used as an all-inclusive term, commonly referring not only to calcium oxide but also to its many derivatives. In order to identify specifically the various chemical forms of calcium oxide other terms are used. For example, the hydrate of calcium oxide is known as slaked lime. Because a large number of chemical derivatives of calcium oxide exist, cognizance should be made of the different terms and their meaning.

### Types and Properties

Lime is commercially produced by "lime-burning" or calcining crushed limestone. Hot gases supplied by burning gas, coal or oil are passed over the crushed limestone to reduce the calcium carbonate in the stone to the oxide of calcium.

$$21 \text{ kcal.} + CaCO_3 \rightleftharpoons CaO + CO_2$$

The calcium oxide (CaO) produced is known as calcia or more commonly as high-calcium lime. Sometimes dolomite or dolomitic limestone, a carbonaceous rock similar to limestone but containing some magnesium carbonate ($CaCO_3 + MgCO_3$), is lime-burned. In this case the product is called dolomitic lime (CaO + MgO). The oxides of calcium and/or magnesium are usually known as quicklime or unslaked lime. In the presence of moisture, quicklime will slake and will also react with carbon dioxide in the air to produce a non-active powdery substance called "air-slaked lime." Therefore, it is necessary to reduce the exposure of quicklime to moisture and air.

The temperature of the lime-burning process depends on the chemical composition of the stone. Calcium carbonates are broken down at temperatures around 900 C and magnesium carbonates at temperatures about 550 C. If the temperatures are too high an overburned product will result. Overburned quicklimes hydrate slowly due to the increased crystallinity of the oxides at high temperatures. Overburning affects the reactivity of dolomitic limes more than high-calcium limes. Dolomitic limes that are overburned are called "dead-burned" dolomite. If the lime-burning temperatures are too low the quicklime will have a core of the original carbonate which renders it undesirable for stabilization purposes.

Quicklime readily reacts with water to produce calcium hydroxide which is commonly known as slaked lime or hydrated lime.

$$CaO + H_2O \longrightarrow Ca(OH)_2 + 15.3 \text{ kcal.}$$

The hydration of quicklime is generally performed by adding sufficient water to quicklime to satisfy its chemical affinity for water. Dolomitic quicklime does not hydrate as readily as high-calcium quicklime as most of the magnesium oxide ($MgO$) remains in a free state. The resulting lime, $Ca(OH)_2 + MgO$, is termed normal hydrated or monohydrated dolomitic lime. In recent years the hydration process of dolomitic quicklime has been improved to yield a more highly hydrated lime. (See Table 1 for a clarification of these terms.) On the basis of physical tests most high-calcium limes and monohydrated limes are classified as Type N or "normal hydrated" limes. The dihydrate lime is usually referred to as a Type S or "special hydrated" lime.

Waste lime has also been used to stabilize soils. This type of lime is usually a by-product of different manufacturing processes. One type of waste lime is collected from the draft used in the calcining process for the production of lime. This type of waste lime is usually stored in the open and may be partially hydrated and reacted with carbon dioxide from the air. Another type of waste lime is obtained as a by-product when acetylene gas is produced from calcium carbide. It is completely hydrated and may or may not be reacted with carbon dioxide. Usually, waste limes are relatively cheap but non-uniform in quality.

Commercially produced limes are not chemically pure and have slightly different properties than theoretically pure calcium and magnesium oxides and their hydrates. The properties of these limes are given in Tables 2 and 3.

TABLE 1

DEFINITIONS OF TYPES OF LIMES

Lime Produced From Limestone

$CaO$—calcia or high-calcium quicklime
$Ca(OH)_2$—hydrated high-calcium lime

Lime Produced From Dolomite or Dolomitic Limestone

$CaO + MgO$—dolomitic quicklime
$Ca(OH)_2 + MgO$—normal hydrated or monohydrated dolomitic lime
$Ca(OH)_2 + Mg(OH)_2$—pressure hydrated or dihydrated dolomitic lime

TABLE 2

PROPERTIES OF THEORECTICALLY PURE LIMES

| | Quicklime | | Hydrated Lime | |
|---|---|---|---|---|
| Chemical Name | Calcia or Calcium Oxide | Magnesia or Magnesium Oxide | Calcium Hydroxide | Magnesium Hydroxide |
| Chemical formula | $CaO$ | $MgO$ | $Ca(OH)_2$ | $Mg(OH)_2$ |
| Crystalline form | Cubic | Cubic | Hexagonal | Hexagonal |
| Melting point | 2570 C | 2800 C | - | - |
| Decomposition point | - | - | 580 C | 345 C |
| Boiling point | 2850 C | 3600 C | - | - |
| Heat of solution at 18 C | +18.33 kg-cal | - | +2.79 kg-cal | -0.0 kg-cal |
| Molecular weight | 56.09 | 40.32 | 74.10 | 58.34 |
| Specific gravity | 3.40 | 3.65 | 2.34 | 2.4 |

TABLE 3

PROPERTIES OF COMMERCIAL LIMES

(a) Quicklime

| Chemical Composition | High Calcium, % | Dolomitic, % |
|---|---|---|
| CaO | 92.25 - 98.00 | 55.50 - 57.50 |
| MgO | 0.30 - 2.50 | 37.60 - 40.80 |
| $CO_2$ | 0.40 - 1.50 | 0.40 - 1.50 |
| $SiO_2$ | 0.20 - 1.50 | 0.10 - 1.50 |
| $Fe_2O_3$ | 0.10 - 0.40 | 0.05 - 0.40 |
| $Al_2O_3$ | 0.10 - 0.50 | 0.05 - 0.50 |
| $H_2O$ | 0.10 - 0.90 | 0.10 - 0.90 |
| Specific gravity | 3.2 - 3.4 | 3.2 - 3.4 |
| Specific heat at 100 F, Btu per lb | 0.19 | 0.21 |
| Bulk density (pebble lime), pcf | 55 - 60 | 55 - 60 |

(b) Hydrates

| | High Calcium | Monohydrated Dolomitic | Dihydrated Dolomitic |
|---|---|---|---|
| Principal chemical composition | $Ca(OH)_2$ | $Ca(OH)_2 + MgO$ | $Ca(OH)_2 + Mg(OH)_2$ |
| Specific gravity | 2.3 - 2.4 | 2.7 - 2.9 | 2.4 - 2.6 |
| Specific heat at 100 F, Btu per lb | 0.29 | 0.29 | 0.29 |
| Bulk density, pcf | 25 - 35 | 25 - 35 | 30 - 40 |

## Specifications

Tentative specifications for limes to be used in soil stabilization have been written by only a few state highway departments. Usually, they are fairly brief and are based primarily on the specifications for masonry purposes as developed by the American Society for Testing Materials and also from local experience. The following ASTM Specifications have been used to specify the physical and chemical composition of limes:

| | |
|---|---|
| ASTM C 5-26, | "Quicklime for Structural Purposes." |
| ASTM C 6-49, | "Normal Finishing Hydrated Lime" with Section 4 (Popping and Pitting) and Section 5 (Plasticity) omitted. |
| ASTM C 207-49, | "Hydrated Lime for Masonry Purposes" with Section 3 (Residue, Popping and Pitting) and Section 4 (Plasticity) omitted. |
| ASTM C 110-49, | "Physical Testing of Quicklime and Hydrated Lime." |
| ASTM C 50-27, | "Sampling, Inspection, Packing and Marking of Quicklime and Lime Products." |
| ASTM C 25-47 | "Chemical Analysis of Limestone, Quicklime and Hydrated Lime." |

## Availability, Size and Method of Shipment

Lime is manufactured throughout most of the United States. However, the lime-producing deposits of limestone are somewhat more abundant in the eastern and central United States. Dolomite, on the other hand, is concentrated mainly in New England and the Middle West and in many instances occurs in the same deposit with limestone.

Commercial quicklime is available in the following standard sizes:

1. Large lump lime—quicklime as it comes from the kiln with a maximum size of 8 in. in diameter.
2. Pebble or crushed lime—sizes of particles range from 2 1/2 in. to dust.
3. Ground, screened or granular lime—sizes of particles range from 1/4 in. to fine particles.
4. Pulverized lime—a product of more intensive grinding in which substantially

all the particles pass the No. 20 sieve and 85 to 95 percent pass the No. 100 sieve.

5. Specially ground lime—quicklime more finely ground than pulverized lime that is obtainable for special application.

The normal grades of hydrated lime will have 95 percent or more of the material passing the No. 200 sieve, and for special purposes hydrated lime may be obtained as fine as 99.5 percent passing the No. 325 sieve.

Hydrated lime is generally shipped in paper bags weighing 50 lb net, but may also be shipped in the bulk. Quicklime is available in 80-lb multiwalled paper bags or in the bulk. Pebble lime, crushed lime and lump lime are generally shipped in the bulk.

Quicklime has an economical advantage over hydrated lime. Not only is the cost of quicklime per ton 15 to 20 percent less than bagged hydrated lime, but also quicklime contains about 25 percent more calcium oxide or magnesium oxide than hydrated lime. These differences, dependent on the source of the lime, result in a 50 to 65 percent lower cost of quicklime on an equivalent basis. However, in some instances the lower cost of quicklime, on an equivalent basis, may be offset by the increased cost of handling the more active quicklime.

## ACTION OF LIME IN SOILS

Several types of chemical reactions take place when lime is mixed with a moist soil. Usually, a number of reactions take place at the same time in the lime-soil mixture which make it difficult to separate and analyze each of them. However, some of these reactions have been identified and are understood to a certain extent. The most important of these reactions for stabilization seem to fall into three general categories that are discussed herein. Other reactions may be important to soil stabilization but they have not been identified at this time. Basic investigations of all of these phenomena are continuing and a better understanding of the fundamental actions of lime in soil should be forthcoming.

### Ion Exchange and Flocculation

When lime and a moist cohesive soil are mixed together and allowed to cure in a loose condition for a period of time (commonly referred to by many engineers as "rotting", because of the odor produced during the curing time), the soil becomes friable and attains a silty-like condition. This phenomenon is due to one of the following two conditions or possibly to a combination of them. In one, a base-exchange reaction occurs with strong calcium cations (positively charged) of the lime replacing the weaker metallic ions, such as sodium and hydrogen, on the surface of the clay particle. Another process is the crowding of additional calcium cations of the lime onto the surface of the clay. Although ions of other types exist on the clay particle, a preponderance of the desirable calcium cations will be on the particle surface. Both processes materially change the number of electrical charges on the surface of the clay particle. Because the bond between two clay particles is dependent upon the charge and the size of the ions, the preponderance of the divalent calcium ions that have replaced the univalent ions attract the soil particles together. As this reaction takes place the soil becomes more friable and the plasticity is lowered. This chemical reaction between the lime and the soil takes place rapidly when the mixture is in the loose state and is usually completed within a few days after mixing.

The lime-soil reaction that reduces the plasticity and "loosens" the soil has been used by the engineer as an aid in highway construction in two different manners. Highly plastic clays and very water-sensitive soils, such as loess, are difficult to work and compact into a desirable subgrade while wet. Where these wet soil conditions exist, either because of excess rain or naturally wet soil, some corrective measures must be undertaken to improve the workability of the soil. When lime is added to the wet soil, the soil becomes more friable, its plasticity is reduced and it drys out rapidly so that it can be satisfactorily compacted. When the lime-soil mixture is compacted, it is little affected by heavy rains. In fact, on some projects that have encountered prolonged rains, lost time has been made up through the use of lime.

This lime-soil reaction has also been used to aid the common types of binders in the stabilization of highly plastic clays. Portland cement and bituminous materials can be used effectively only with soils that can be easily pulverized and are friable; otherwise, the soil grains cannot be completely coated with the stabilizing material and poor stabilization results. Because soils with liquid limits greater than about 30 and plasticity indexes greater than approximately 12 cannot be pulverized effectively, they are usually unsuitable for stabilizing with bituminous materials or portland cement. However, if lime is first added to these plastic soils, the plasticity is reduced and the soil can be more easily pulverized. Then, the binder will adequately coat the soil grains and effectively stabilize these highly plastic soils (51-2, 52-4, 52-9, 54-3, 57-1, 59-3, 59-5).

## Cementing Action

Another important lime-soil reaction produces a cementing action between the soil particles. Very little is understood of the exact reaction that takes place, but apparently the calcium in the lime reacts with certain soil minerals to form new compounds. Usually, aluminous and silicious minerals in the soil react with the lime to produce a gel of calcium silicates and aluminates that tends to cement the soil particles in a manner similar to that produced by the hydration of portland cement.

The minerals in the soil that react with lime to produce a cementing compound are known as pozzolans. The type and amount of pozzolans and thus the amount of reactivity with the lime vary from soil to soil. When desirable quantities of pozzolanic compounds are not present in the soil, pozzolanic materials such as fly ash, many times will help produce the desired reaction with the lime.

The lime-cementing action in soil is a slow reaction which requires considerably more time than would be needed for the hydration of portland cement. The rate of cementation is influenced to a great extent by the amount and type of pozzolans, as well as the type of clay mineral in the soil, and by climatic conditions. In addition, the mixture of soil and lime must be thoroughly compacted; otherwise, the desirable cementation will not take place (48-5, 51-2, 52-4, 52-9, 56-3, 57-1, 58-12, 59-6, 59-8).

## Carbonation

A third important lime reaction involves the absorption of carbon dioxide ($CO_2$) from the air. The carbon dioxide reacts with calcium hydroxide in the lime to form calcium carbonate. In other words, this is a reversal of the lime-producing process. Not only do these carbonates form weak cements but they also deter pozzolanic action and prevent normal strength gains.

Care should be taken to prevent the lime from being carbonated by a reaction with carbon dioxide from the air. Lime must be specially protected while in storage and in shipment prior to its use with the soil. Carbonation is most active in industrial areas where the carbon dioxide content in the air is much greater than in the rural areas (52-4, 52-9, 57-1, 59-8).

# PHYSICAL PROPERTIES OF LIME-SOIL MIXTURES

Through its chemical reactions, lime affects certain physical properties of soils. There is considerable lack of factual data and some disagreement exists between the available data. However, it is generally agreed that lime influences the following physical characteristics of a soil: grain size distribution, soil plasticity, volume change, field moisture equivalent, soil pressure, compaction and optimum moisture content, strength and durability.

In many instances it is difficult to evaluate the influence of lime on soil due to the lack of desirable criteria or standards for comparisons. These criteria can only be developed after a thorough knowledge of the characteristics of lime-stabilized soils is obtained. Continuing investigations in the field of lime-soil stabilization should greatly increase present day knowledge and provide the standards for economical design and construction.

## Grain Size Distribution

One of the first physical changes which takes place in a fine-grained soil when lime is added is an agglomeration or flocculation of the clay particles. This produces a coarser and more friable soil. As an example (59-7), a clay with 10 percent lime changed so much in gradation after 14 days of initial curing that it was classified as a sandy loam, and after 240 days it was classified as a sand. In another instance (59-3), the amount of loess passing the No. 200 sieve was reduced from 88 percent to 58 percent in only 7 days with an addition of 5 percent lime. This phenomenon is also reflected by a change in soil classification; for example, an A-7-6 (16) soil was changed with six percent lime in 14 days to an A-4 (6) soil (59-7).

The particles that are changed the most in size by lime are the fine clay particles as they tend to react with lime more than the larger individual sandy-like materials. In most instances, fine clay particles have aggregated with lime into particles larger than those passing the No. 200 sieve and have materially increased the amount of material retained on the No. 200 sieve. There are some indications that this aggregate is not entirely water-resistant. After a period of soaking in water, a small portion of the aggregated particles tends to break down. The remaining particles are quite hydrophobic, though, and will retain their aggregation after long periods of soaking.

The amount of agglomeration is influenced by a number of different factors, of which the most important one is the type of soil. Plastic soils tend to agglomerate more than silty or sandy soils. In addition, the agglomeration appears to be influenced by the amount of lime, with more agglomeration occuring as more lime is added to the soil. Also, increased intial curing time and possibly the type of lime are factors affecting the amount of agglomeration. Quickline may be more effective than hydrated lime (58-11, 59-2, 59-7).

## Soil Plasticity

Another noticeable phenomenon that is mentioned in almost every article on lime stabilization is the ability of the lime to change the plasticity of the soil. Both the plastic limit and the liquid limit of the soil are affected. The plastic limit of a soil is increased as additional amounts of lime are added to the soil. This bears out early findings in the ceramic field that hydrated lime increases the amount of water needed to develop plasticity in clay pastes.

The liquid limit normally decreases with increased amounts of lime. Although this decrease is usual, it does not occur in all soils. In some soils a distinct increase in the liquid limit is produced by adding lime. In general, but not always, the liquid limit is reduced in the more plastic clays and is increased in the less plastic soils.

Regardless of whether the liquid limit decreases or increases, the increase in plastic limit is such that the plasticity index is usually reduced with the addition of small amounts of lime. The plasticity index of many highly plastic clays may be reduced 50 to 80 percent with small quantities of lime. As an outstanding example of this (59-7), a clay with a liquid limit of 51 and a plasticity index of 30 became non-plastic in two days with only 6 percent lime. It should be noted here that in a few rare instances the plasticity indexes of slightly plastic soils have been increased a little by the addition of lime.

The amount of reduction in the plasticity index obtained in a soil as lime is added depends on many factors, but primarily on the type of soil. The plasticity indexes of highly plastic clays are usually reduced a considerable amount with only a small amount of lime. However, the less plastic soils are only slightly affected by the addition of lime; for example, the plasticity index of a loess may be reduced from five to only two with 5 percent lime. The amount of lime also influences the extent of reduction in the plasticity index. As the amount of lime is increased, the plasticity index of the soil is decreased.

The plasticity index is also influenced by the length of time the lime reacts with the soil and the type of lime. A sizable reduction is usually noticed within the first few hours after lime is added, and within 2 to 3 days almost all of the change in plasticity of the soil will have taken place. Some further reduction in the plasticity index will generally take place when longer reaction times are allowed, but it is small when compared with that which takes place in the first few days. Although little data are available, it appears that the reduction in the plasticity index is influenced some by the type of lime used. Quicklime usually brings about a reduction in plasticity faster than hydrated lime. Waste lime also reduces the plasticity index, but the time needed for reduction is substantially longer than that needed by other types of lime (48-2, 49-3, 51-2, 52-9, 57-1, 59-5, 59-7).

## Volume Change

Lime tends to reduce the volume changes that take place in soils. As the lime content in the soil increases, the shrinkage limit increases and the shrinkage ratio decreases. The shrinkage limit and the plasticity index of a soil appear to be related. As the plasticity index tends to drop when the lime content increases, the shrinkage limit increases; and when there is little further change in the plasticity index there is little change in the shrinkage limit. Lime also materially influences the swelling of soils. In one test (58-8) when the specimens were subjected to a load of 1 psi with excess water present, an originally highly plastic soil (PI = 37) did not swell but actually consolidated about 1 1/2 percent.

Additional amounts of lime will produce decreasing volume changes up to an optimum lime content. Little additional reduction in volume change is produced by adding lime in amounts larger than this optimum value. Limes have a greater influence on reducing volume changes in soils that readily change volume with water than in soils that originally have small volume changes (49-3, 55-7, 58-8, 59-7).

## Field Moisture Equivalent and Soil Pressure

A small amount of available data indicates that as the lime content increases in a plastic soil the field moisture equivalent increases. One experimenter (52-4) has recorded that the pressure produced by a soil swelling in restrained samples with an excess of water was materially reduced by adding lime. The swell pressure in a clay, predominantly montmorillonite, was reduced from approximately 7 psi to 1 psi with 8 percent lime (52-4, 59-7).

## Compaction and Optimum Moisture Content

When compacted with the same effort, a lime-soil mixture has a lower standard AASHO T99 density than the original soil without lime; and as the lime content increases, the density tends to decrease even more. The decrease in unit weight is small and averages about 2.5 percent for most soils. In some soils, though, such as micaceous silt, the decrease in unit weight may be as much as 5 percent when approximately 5 percent lime is used. It is interesting to note that all investigators of this property except one (48-2) report that the unit weight of the mixture decreases as the lime content is increased. This one investigator reported that for two soils, of 11 he investigated, the addition of lime tended to produce an increase in the unit weight (1.2 percent increase with 5 percent lime). As the soils were derived from different rock minerals no explanation was given of this unusual phenomenon.

As lime is added to a soil the optimum moisture content tends to increase. Usually the initial increase in moisture content is rather significant even when small amounts of lime are used. In some instances there may be as much as a 25 percent increase in optimum moisture content (12 to 15 percent water content) with the addition of only 2 to 3 percent lime. Once the large initial increase in optimum moisture content takes place, additional lime produces only a slight increase in the optimum moisture content; that is, there usually is little difference in optimum moisture contents of a soil with 5 percent lime and with 7 percent lime.

In addition to the amount of lime used, compaction of lime-soil mixtures is influenced by the type of lime. Soils with quicklime usually have a slightly higher optimum moisture content than soils compacted with hydrated lime. On the other hand, the type of lime does not seem to influence the unit weight in any significant amount; that is, a soil treated with either quicklime or with hydrated lime in the same amount has about the same density. The change in density of a soil, as lime is added, apparently cannot be correlated with the type of soil, the plasticity index or with the dry density of the raw soil.

At moisture contents near optimum for the lime-soil mixtures the unit weight of a raw soil, obtained by the AASHO T99 compaction test, is usually less than the unit weight of the soil treated with lime obtained with the same compactive effort and moisture content. This indicates that lime-soil mixtures have greater compactability than the raw soils at higher moisture contents. Contrary though, lime-soil mixtures are less compactable at lower moisture contents and have a lower unit weight than the raw soil at the same moisture content.

A word of caution should be given here. Although the density of a soil tends to decrease with additional amounts of lime, it should not be assumed that the strength of lime-soil mixtures is lowered. This is not true. For example (52-8), an Illinoian drift soil with no lime had a standard proctor unit weight of about 120 pcf and a compressive strength of approximately 80 psi. The same soil with 5 percent lime had a lower standard proctor unit weight of about 114 pcf and a compressive strength of approximately 140 psi. Lime-soil mixtures are one material to which the general thought "when the density increases the strength also increases" does not always apply. It usually applies, though, if at the same lime content additional compactive effort is used to produce higher densities. When the Illinoian drift (as previously described) with 5 percent lime was compacted with a greater compactive effort to a density of approximately 119 pcf, the specimen had a compressive strength of approximately 280 psi. Lime-soil mixtures then usually have substantially higher strengths when they are compacted to a higher density with a greater compactive effort (48-2, 49-1, 49-3, 52-8, 52-9, 56-3, 59-3, 59-7).

## Strength

A number of different types of tests have been used to evaluate the strength of lime-soil mixtures: unconfined compression, California bearing ratio, Hveem stabilometer, extrusion, triaxial and even the Proctor penetration needle. Of these tests, the unconfined compression test is the most popular. The trends in results obtained by these different tests usually have been similar; that is, if the unconfined compression tests indicate an increase in strength, so does the CBR test. However, the percent change in magnitude of the strength values varies considerably with the different test methods. When one strength test indicates a certain percent strength change, another test for the same material and conditions may indicate more or less of a percent change. In some instances the indicated change in strength by a particular test was so out of proportion that wrong conclusions could have been drawn.

Unlike many soil stabilizers, there appears to be no optimum lime content that will produce a maximum strength in a lime-stabilized soil under all conditions. Some data, however, have been presented that indicate the relationship between the strength and the lime content in the soil to be such that an optimum lime content does exist. Such data were usually obtained for only one particular length of curing time. If a different curing time was used a different optimum lime content would be indicated. For instance, after 7 days of moist curing a particular soil may have an optimum lime content of 5 percent; with 28 days of curing the optimum lime content may be 8 percent; and after a year there would probably be no optimum content indicated in the normal range of lime used. Strength tests have not been used primarily to obtain the desirable lime content, but they have been used to determine if a mixture hardens sufficiently and to indicate the influence of various factors on the lime-soil mixtures.

The chief factors affecting the strength of lime-soil mixtures are lime content, type of lime, type of soil, density and the time and type of curing. Most of these factors are interrelated. Except in specific cases, no one of these factors is a great deal more important than another.

Lime Content.—In general, the strength of lime-soil mixtures increases as the lime content in the soil is increased. As previously stated, there may or may not be an optimum lime content, depending primarily on the length of curing (48-5, 49-3, 52-8, 59-7, 59-8).

Types of Lime.—One group of investigators (56-3, 57-3) has indicated that the type of lime influences the strength of lime-soil mixtures. They have presented data to show that dolomitic limes produce higher strengths in lime-plastic soil mixtures than high-calcium limes. For the same soil and conditions these two types of limes produced about the same strength at low lime contents; but at the higher lime contents the dolomitic lime-soil mixtures increased in strength, whereas the high-calcium lime-soil mixtures remained about the same or decreased slightly. Quicklimes were more effective than hydrated limes in equivalent amounts for stabilizing soils. Of the hydrated-dolomitic limes, monohydrated lime (Type N) produced greater strength in soils than the dihydrated-dolomitic lime (Type S).

The foregoing evaluation of the effects of different types of limes on the strength of lime-stabilized soils did not consider the lime content as influenced by the time of curing. Inasmuch as this factor is very important, it may be possible that with optimum periods of curing there would be little difference in the strength of high-calcium lime and dolomitic lime-stabilized soils. In fact, some outstanding engineers believe that in the long run high-calcium lime will produce as high a strength as dolomitic lime and may even be more desirable for stabilizing certain soils (discussion, 56-3).

Since the exact composition of commercial limes varies among deposits, it is usually desirable to evaluate the various locally available types of lime for strengthening a particular soil prior to stabilization. In this manner, it may be determined which type of lime, if any, is best suited for the particular soil. Indications are that in some instances, by using the most desirable type of lime the same strength can be obtained with one-third as much lime as would be needed of another type of lime (56-3, 57-3).

Type of Soils.—The amount of strength increase in a soil that can be produced by adding lime is dependent on the pozzolans in the soil. When desirable pozzolans are available they react readily with the lime to improve the strength of the lime-soil mixture. However, if the soil has a small amount or no pozzolans, little improvement in strength is obtained by adding the lime. No chemical analyses are now available that will indicate the amount and type of pozzolans available in a particular soil that are suitable for reacting with lime. Because the amount of desirable compounds varies from soil to soil, each soil should be evaluated by some physical testing method(s) to determine its suitability for stabilization with lime. This is the only dependable manner now available by which the suitability of soils for stabilization with lime can be determined.

Usually, clays are more reactive with lime than other soils and are generally increased in strength materially when lime is added. In many cases only a small amount of clay is needed in the soil for reaction with lime. The strength of silts, some sands, caliche, sandy clays, plastic pit-run gravels, as well as clays, have been improved by the addition of lime. Usually higher strength, but not necessarily a larger percent increase in strength, is obtained with the larger size materials that have some clay for reaction with the lime. Lime-pit-run gravel mixtures probably have higher strengths than lime-clay mixtures.

Generally, the highly plastic soils are more reactive with lime, whereas soils with low plasticity react little with lime. This is not always true, however, as one investigator (52-8) reported that a sizeable increase in strength of a non-plastic pit-run gravel was obtained by the addition of 10 percent lime.

At least in one instance (55-7) it was reported that lime tended to decrease the strength of a couple of soils, predominantly loams. It is possible that lime has this effect on other types of soil even though it has not been reported in the literature (48-2, 48-5, 52-8, 52-9, 55-7, 57-3).

Density.—Few engineers recognize the importance of compaction in stabilizing soils with lime even though it is a very influential factor. The strength of a lime-soil mixture is increased materially when the mixture is compacted to a higher unit weight by a greater compactive effort. Strength is affected by density when the increased unit weight is produced by additional compactive effort. Strength is not related to the increased density that is produced by varying the lime content in the soil. This important relationship has been discussed to some extent in the section on "Compaction and Optimum Moisture Content," and is emphasized by McDowell (45-8) who says, "...densification is of critical importance." (48-5, 52-8, 56-1).

Time of Curing. —Lime-stabilized soils increase in strength with age in a manner similar to portland cement concrete. Usually, there is a rapid increase in strength of these mixtures at the beginning of the curing period, but as the curing progresses the rate of increase in strength becomes less and less. After considerable curing time the strengths of lime-soil mixtures still appear to be increasing very slightly. Tests (53-3) have indicated that lime-soil mixtures were increasing in strength after 4 yr of controlled laboratory curing. Even though the strength of lime-soil mixtures may increase with age indefinitely in the laboratory, it does not necessarily mean that this relationship exists when the mixtures are cured in the field under normal climatic conditions. In one instance, cores cut from a lime-soil road after 7 yr of curing had approximately the same strength as cores that were obtained when the road was only 2 yr old (53-3).

Lime-soil mixtures do not gain strength at the same rate as portland cement concrete. The gain in strength of lime-stabilized soil is slow and gradual under normal field curing conditions. Many times, 4 to 6 mo of curing are needed in the field for mixtures to obtain a major portion of their strength. In the laboratory the rate of gain in strength of lime-stabilized soils can be greatly increased by using favorable methods of curing, such as high temperatures. (See the following section.) Under favorable laboratory curing conditions strengths can be obtained in 2 wk that would require 3 mo of curing under normal field conditions (52-8, 53-3, 56-1 56-3, 59-8).

Type of Curing. —Various methods have been used to cure lime-soil mixtures. Primarily, the different methods of curing may be divided into two groups: (a) curing at varying moisture conditions or relative humidities, and (b) curing at normal or elevated temperatures. These methods of curing have been used in various manners by different groups. No one method has yet been developed that appears to be outstanding and no method has been adopted as the standard method for curing lime-soil mixtures.

Effect of Temperature. The rate of gain in strength in lime-soil mixtures is directly related to the temperature at which the compacted mixture is cured. When cured at low temperatures, the gain in strength is very slow; when cured at normal temperatures (approximately 70 F), the rate of gain in strength is greater; and when cured at high temperatures (140 F), lime-soil mixtures increase in strength quite rapidly with time. So rapid has been the strength gain in some instances (56-3), that at 140 F the same strength was obtained in 10 days as was obtained in 3 to 4 mo curing at 70 F.

Effect of Moisture. The humidity of the air during the curing of lime-soil mixtures appears to have some effect on the strength of the mixtures, but it is difficult to draw any conclusions regarding its effect. In some instances specimens cured at low humidity have higher strengths than specimens cured at high humidity. In other cases higher strengths were developed in those specimens cured at high humidity. Whatever the effect of moisture might be, it does not appear to influence the gain in strength of lime-soil mixtures as much as variations in curing temperature.

Data (48-2, 48-5) indicate that strengths higher than those produced by either moist curing or high-temperature curing can be obtained by various combinations of curing methods. If the mixtures are originally cured at normal or higher temperatures and then are moist cured for a period of time, they usually have relatively higher strengths. Some engineers believe that even greater strengths can be obtained in lime-soil mixtures by a drying and wetting cyclic curing procedure. No published data are available, though, to substantiate this thought.

In some instances it may not be desirable to cure lime-soil mixtures at high temperatures or in a cyclic manner even though very high strengths might be obtained. If the laboratory strength is greater than the strength of the mixture in the field and if the higher laboratory strength is used in designing a pavement, the pavement will be underdesigned and failure may occur (48-2, 48-5, 52-8, 56-3, 57-3, 58-8, 59-7).

## Durability

Although a lime-soil mixture should have high resistance to applied stress, it is perhaps even more important that it have good durability in order to perform satisfactorily in the field. The determination of the durability properties of a lime-soil mixture is a problem because it is difficult to simulate in the laboratory the detrimental action that is produced by weathering in the field. Many different tests have been used for this purpose. Usually, weathering has been simulated by cyclic action of: (a) heating and cooling, (b) wetting and drying, or (c) freezing and thawing. The length of time of the various phases of the cycle, as well as the temperature, the method of soaking, etc., vary from investigator to investigator. So wide are these variations that no standard method of testing the durability of lime-soil mixtures has been universally accepted to date.

Not only is there disagreement as to the type of action best suited to simulate weathering in the laboratory, but also investigators are not in agreement as to the physical properties most affected by cyclic weathering. Some tests evaluate durability in terms of the loss in weight of specimens that is produced by brushing. Other tests use the percent change in compression strength as the basis for evaluation. Of the few nondestructive tests that have been investigated, perhaps the most promising test is one that uses the soniscope to measure the change in velocity of pulse propagation. Not only do some investigators believe that the change in basic properties of the mixtures, as measured by the soniscope, is a good indicator of the change in durability, but they also like the relatively few number of laboratory specimens that are required for the test. Moreover, the method is not limited to use in the laboratory. With slight modification the soniscope can be used to evaluate a change in durability of lime-soil mixtures that are in service in a road.

Generally, the durability of lime-soil mixtures in the field has been satisfactory. This is not consistent, though, with the results that are indicated by certain laboratory tests which repeatedly predict poor performance of lime-soil mixtures. For instance, the results from standard freeze-thaw and wet-dry tests using brushed samples (AASHO Designations: T-135 and T-136), when compared to criteria developed for soil-cement mixtures, indicate that lime-soil mixtures have little resistance to weathering. So rapidly did the lime-soil mixtures deteriorate when subjected to these durability tests, that one investigator (51-3) stated: "hydrated lime... (was) among the most commonly available materials found to be unsuitable (as a) soil stabilizing material." Many reports, though, indicate that numerous lime-soil projects have performed exceedingly well in the road when protected with nothing more than a bituminous seal coat (58-9). One investigator (53-3) reports that after 7 1/2 yr of service, road sections constructed with commercial lime were in "excellent" condition. It appears then, that lime-soil mixtures when normally protected from weathering by a bituminous-wearing surface are more durable than indicated by most laboratory durability tests.

Because most of the durability tests do not accurately indicate the serviceability of lime-soil mixtures under actual road use, a more accurate test is strongly needed. Investigations are now being made that will lead, it is hoped, to a universally acceptable method of testing lime-soil mixtures that will accurately predict field performance.

Even though the existing methods of evaluating durability are not the most desirable, they have strongly indicated that the resistance of lime-soil mixtures to weathering is influenced by various factors such as: amount and type of lime, age, compaction and type of soil. These are probably not all of the factors that affect the weathering resistance of this material. Additional information is definitely needed for a thorough understanding of the durability characteristics of lime-soil mixtures.

Amount of Lime.—Lime-soil mixtures with high lime contents have considerably more resistance to deterioration than mixtures with small amounts of lime. Durability, then, tends to increase as the lime content is increased. Lime content is so critical that some engineers recommend quantities of at least 5 percent even though smaller amounts might produce desirable strengths in the soil.

Aging.—The durability of lime-soil mixtures is usually related to the length of time the mixture is cured before it is subjected to detrimental weathering. Durability increases with longer curing times. It is conceivable that a mix placed late in the year could develop satisfactory strength in the short curing period before cold weather but would have such poor durability that it would fail during the first winter. Long periods of warm weather curing are most desirable for improving the durability of lime-soil mixtures.

Compaction.—At a given lime content, higher density that is produced by increased compactive effort results in greater resistance to weathering.

Types of Lime.—Only very limited data have been reported on the influence of the types of lime on the durability of lime-soil mixtures. One investigator (57-3) indicates that, at the same lime content, specimens made with dolomitic quicklime possibly have more resistance to freeze-thaw and wet-dry tests than those made with dolomitic hydrated lime. The data are so limited, though, that the relative influences of other types of limes are not known and definite conclusions cannot be drawn.

Types of Soils.—Some available data indicate that there may be a relationship between the type of soil and the resistance of the lime-soil mixture to weathering. A friable loess may possibly be more durable than glacial drift, and glacial drift may possibly be more durable than a non-plastic river terrace gravel. These are only generalities and more data are needed before a definite statement can be made (51-3, 52-8, 53-3, 57-3, 58-12, 59-8).

## PHYSICAL PROPERTIES OF LIME-POZZOLAN-SOIL MIXTURES

When lime is added to many soils the mixture will not develop the desired strength even after considerable curing time. These non-reactive soils, however, can usually be stabilized satisfactorily with lime when a pozzolanic material is also added to the soil. The amount of cementation produced in a mixture by lime is related to the reactivity and amount of the pozzolanic material existing in the soil. When lime is added to soils containing little reactive pozzolanic material, not only may the rate of gain in strength be very slow, but also the increase in strength may be slight. In addition, the resistance to weathering may be virtually unchanged. These effects can usually be minimized, if not eliminated, by providing a material that will react with the lime to produce a cementing action. When a pozzolanic material such as fly ash is added to the soil an abundance of the pozzolans will be present, cementation with the lime will be assured, and the reaction will take place rapidly.

Many types of natural pozzolanic materials are available for commercial use. They are primarily siliceous materials containing certain chemical compounds that will react with lime and water at ordinary temperatures to form the necessary cementing compounds. (By themselves, natural pozzolanic materials are not cementitious.) Although a natural pozzolanic material of volcanic origin (pozzolana) has been used for more than 2,000 yr, the most common pozzolan and by far the most widely used at present in the United States is fly ash. This pozzolan is collected primarily from the flue gases produced in boilers burning powdered or ground coal. It is quite abundant in some areas and many times is considered to be a "waste product." The reactivity of fly ash varies from source to source. Tests, though, are available that will reasonably indicate the reactivity of fly ash with lime (58-2).

Materials other than fly ash are known to produce a similar pozzolanic reaction when mixed with lime, but little use has been made of them. In one instance dust from an expanded shale (58-3) acted as a satisfactory pozzolanic material in stabilizing a gravel. Finely ground raw shale, however, did not react pozzolanically. Apparently shale has to be "burned and finely ground" to react satisfactorily with lime.

The important question concerning the use of pozzolan is, "When is it necessary to use a pozzolan?" It appears that, to date, no known test on the natural soil can accurately indicate the compatibility of the soil with lime. Neither base exchange capacity, the pH of the soil, nor the plasticity characteristics seem to be satisfactory indicators (57-2). The only positive method that will indicate if lime by itself will improve a soil is to test the lime-soil mixture. If desired results are obtained, there is no need for pozzolanic materials to be added. However, if desired results are not obtained, a pozzolanic material and lime should be added to the soil and the mixture tested to determine if the pozzolanic material will aid the cementing action.

Many soils have an optimum ratio of lime to pozzolan, whereas other soils develop approximately the same strength over a wide range of lime to pozzolan ratios. In general, fly ash used in ratio of 1:9 to 2:8 by weight of lime to fly ash has been found to be satisfactory. For a specific lime-fly ash ratio, strengths tend to increase as the amount of lime-fly ash is increased. Greater strengths can be obtained, though, by correctly adjusting the lime-fly ash ratio than can be obtained by increasing the amount of lime-fly ash (56-2). The rate of reaction of the lime with the pozzolan is not an indication of the strength that will be developed when the mixture is used with a soil.

Lime-pozzolans together tend to affect the physical properties of soil in a manner similar to that of lime by itself. (See section on "Physical Properties of Lime-Soil Mixtures.") The exact magnitude of the change in strength and the rate of change in strength vary widely, and no direct relationship exists. In general, both lime-pozzolans and straight limes will reduce the magnitude of volume change of a soil, will lower the plasticity, will increase the strength, and will improve the resistance to weathering. In addition, soil stabilized with either material will gain strength with time at elevated temperature and under cyclic action. In many instances, soils containing lime and fly ash have increased in strength materially while undergoing a freeze-thaw test (58-7). In general, lime-pozzolan-soil mixtures are similar to lime-soil mixtures when the pozzolan is considered to be part of the soil (52-7, 53-4, 56-2, 58-2, 58-3, 58-7, 58-12, 58-13, 58-17).

## CONSTRUCTION METHODS

Until recently little attempt has been made to standardize methods for constructing lime-soil roads. Many times the construction was haphazard, but through the joint effort of several organizations, lime-soil stabilization construction methods have become more uniform (59-12). The sequence of operations in constructing lime-stabilized roads is generally the same wherever the project, but special techniques related to local experience, available equipment and specific conditions may necessitate some variation.

### Construction Techniques

The construction steps normally followed in constructing lime-soil stabilized subbases, subgrades, and bases are as follows:

Scarifying and Pulverizing the Soil.—The roadway is first brought to grade. If the natural material in the road is to be stabilized the upper portion is scarified to the depth that the lime-stabilized treatment is required. When the existing road material is not used, new soil is hauled to the road, dumped in place and pulverized. Scarification and pulverization of the soil may be accomplished by a motor grader. Where greater control of the depth and more thorough pulverization of this soil is desired a pulverizing mixer should be used.

Addition of Lime to the Soil.—Lime may be added to the soil in the form of a dry powder or wet slurry. Dry application of lime is accomplished by a mechanical spreader or by the dumping and spreading of bagged lime by hand in a controlled pattern on the roadway. When wet slurry is used, lime and water are premixed and spread together from a tank truck or distributor. Regardless of the method used for spreading the lime, uniformity of application and control of the quantity are essential.

Mixing of the Lime, Soil and Water.—Lime and soil are thoroughly mixed with a motor grader, pulverizing mixer, disc or some other type of mixing equipment. If water is needed it is added as the mixing progresses. This process of mixing and adding water is continued until the moisture content of the mixture is slightly above optimum and the lime is uniformly distributed throughout the soil.

Initial Curing.—Lime-plastic soil mixtures should cure in the loose state for 24 to 48 hr after mixing (59-12) or until the soil disintegrates easily in the hand and becomes friable. It is not intended that the mixture gain strength during this aging period, but only that the soil loses its plasticity. Initial curing is not required for nonplastic soils that are being stabilized with lime.

Final Mixing.—After the lime-soil mixture has initially aged it is remixed and repulverized. If needed, water may be added at this time to adjust the moisture content. This process is continued until optimum moisture is attained and all "clods" and "lumps" are broken down into a homogeneous mass.

Compaction and Shaping.—The lime-soil mixture is bladed to the appropriate thickness and is compacted until the desired density is attained. Satisfactory compaction may be accomplished in single or multiple lifts, depending on the thickness of treatment and the type of compaction equipment available. Pneumatic rollers and sheepsfoot rollers are primarily used during the initial compaction. These may be followed by shaping the surface of the top lift with a motor grader and then by final compaction with a steel-wheel roller. Field checks on the moisture content and the degree of compaction should be made at frequent intervals to insure adequate control.

Final Curing.—Lime-soil mixtures are cemented together only after final compaction and not during the first curing period. Ideal curing is produced by warm temperatures and by preventing the evaporation of moisture from within the compacted mixture. The latter is accomplished by applying water to the surface or by sealing the surface with an asphalt membrane. Lime-soil mixtures are usually moist cured for 5 to 7 days, but longer periods may be required if low air temperatures prevail.

Placement of the Wearing Surface.—If a lime-soil mixture is used as a base, some type of a wearing surface must be applied to prevent abrasion of the surface. Whether it be a surface treatment or a hot mix, it should not be constructed until the lime-soil base has adequately hardened and all loose material removed from the surface of the base.

## Costs

The cost of lime-soil stabilization varies with the depth of treatment, quantity of lime, geographical location, familiarity with construction procedures, etc. The reported prices for lime-soil stabilization average about $0.40 per sq yd. The cost for a 6-in. depth of stabilized material on large projects may be as low as $0.27 per sq yd. On smaller projects, however, such as parking lots, the cost may be as high as $0.50 to $0.55 per sq yd (59-2).

## Safety Precautions

Special safety precautions must be taken when handling lime to prevent injury to workmen. Hydrated lime is relatively safe but may cause irritations to people with sensitive skins. Quicklime, on the other hand, is quite dangerous in the presence of moisture because of its highly caustic nature. Even small amounts of perspiration on the skin will react with quicklime to cause severe skin burns. Quicklime is especially dangerous to the eyes.

Safety glasses, long sleeved shirts and relatively close fitting clothing should be worn by all personnel engaged in handling lime. If dusty conditions exist, filter masks should also be used to prevent excessive inhalation of lime dust. Special protective cream may be applied to the skin of construction personnel who are subjected to prolonged exposure of the lime dust.

All personnel should be instructed in first aid procedures for treating injuries that occur while lime is being handled. Special burn ointment, fresh water and eye wash glasses should be available at all times. All severe burns should receive immediate medical attention (52-2, 54-3, 57-9, 59-2, 59-5, 59-8, 59-12).

# FIELD PERFORMANCE OF LIME-SOIL STABILIZED ROADS

Information relating to the long-range field performance of lime-soil stabilized roads is limited. This lack of information on performance may be attributed to several factors, but particularly to the fact that the stabilization of soil with lime in the United States did not flourish until the end of World War II. Because of the limited number of years that lime has been used for soil stabilization, it is difficult to evaluate long-range field performance in terms of the number of years of satisfactory service.

Until recently there has been little attempt to correlate laboratory test results and the actual field performances of lime-soil stabilized roads. The available data are limited. This is probably related to the problems encountered in obtaining cores of lime-soil mixtures from the field that can be used in the laboratory for evaluating strengths and other physical properties. Generally, the few cores that have been obtained from lime-stabilized roads were very irregularly shaped and difficult to test in the laboratory. Therefore, because of the difficulties encountered in extracting satisfactory specimens, field performance has generally been evaluated by personal observations.

The most extensive data on the field performance of lime-soil stabilized roads have come from field tests conducted in Texas and other southern states. Some limited data are also available on several test sections that were constructed in the central and north central part of the United States. The reports on the field performance of most of these projects have indicated that they performed satisfactorily.

Much of the data relating to the field performance of lime-soil stabilized bases and subbases are limited to the treatment of old existing roadbeds containing plastic to highly plastic clays and a considerable amount of granular material. Only limited information, however, has been published on the performance of lime-stabilized, highly plastic fine-grained soils that contain no granular material. Some literature is also available on the successful treatment of wet subgrades with lime as an aid to construction.

Because of the variations in construction techniques, types and amounts of lime used, types of soil stabilized, etc., it is difficult to compare field performance of lime-soil stabilized roads on an individual basis. A brief description of a few of the reports on the field performance of lime stabilized roads has been included in Table 4. If detailed information on the performance of any of these projects is desired, it is suggested that the original reference be consulted.

## LIMITATIONS TO STABILIZING SOIL WITH LIME

Lime-soil mixtures have certain limitations that should be fully understood by the highway engineer before any design and construction of this type of stabilized road is undertaken. Many of these limitations are not unique with lime-soil mixtures, but are factors that must be considered in other types of soil stabilization work as well. Some of the more important limitations are briefly discussed in the following paragraphs.

### Climatic Conditions

To date, there are little data available on the exact influence of climatic conditions on the use of lime-soil mixtures. Satisfactory performance of these mixtures has been obtained in areas with relatively mild temperatures. There is some question, though, as to the performance of this material in the colder climates. Only a few projects have been constructed in these areas and little performance data are available. Until more knowledge of the influence of cold weather on lime-soil mixtures is obtained, the use of this material in colder climates will probably be limited.

Some investigations have indicated that air temperatures materially influence the curing rate of lime-soil mixtures in the field. The curing rates of lime-soil mixtures are relatively fast at high temperatures, but are fairly slow at colder temperatures. Normally, during the warmest weather a minimum of 7 days moist curing is required for the lime-stabilized road to attain sufficient strength to support normal traffic. The time required for development of adequate strength and durability at colder air temperatures is considerably longer. At very cold temperatures curing may practically cease with little strength being gained until the weather becomes warm again.

Freezing of lime-soil mixtures during curing may result in a permanent reduction in strength. Swelling usually occurs because of the expansion of the frozen moisture and because of the formation of ice lenses in the mixture. In the process of swelling, the bonds between lime-soil particles are broken, the mixture becomes loose and a permanent loss in strength results. To reduce this damage and to allow sufficient strength to develop, especially during the early stages of curing, it has been

TABLE 4

FIELD PERFORMANCE OF A FEW LIME-STABILIZED ROADS

| Reference No. | Location | Soil Types | Reported Field Performance |
|---|---|---|---|
| 59-7 | Nebraska | Highly plastic glacial clay | Satisfactory performance was observed after 2 yr service. |
| 58-9 | Perry Co., Missouri | Gravelly clays and silty clay loams | After 4 1/2 yr service, all sections had an appearance of good to excellent. The PI's increased during this time. |
| 57-4 | Mascoutah, Illinois | Highly plastic clay | Performance of this section was very good after 4 yr service. |
| | Engelmann Township, Illinois | Highly plastic clay | This section was in excellent condition after 5 yr service. |
| 56-7 | Mitchell Co., Kansas | Limestone gravel | The sections developed a few cracks after 1 yr of service. |
| 53-3 | Taylor, Texas | Taylor marl gravel | This section was holding up well after 5 yr use. |
| | Williamson Co., Texas | Granular soil | After 8 yr service, this section was in excellent condition. |
| | East of Taylor, Texas | Clay gravel | This road was used to serve light traffic for 5 yr. It was patched and resealed as many dry weather cracks had developed. |
| 48-4 | Texas | Old clay gravel base | After 2 yr service, the condition of the road was perfect. |

recommended that lime-soil mixtures not be constructed after September 15 or after 1 mo before a probable freeze (59-12).

Some experience has indicated that soils stabilized with lime are more resistant to damage by frost action than the same untreated soils (59-2). It is thought that soils stabilized with lime form a moisture-resistant barrier which tends to obstruct the penetration of capillary water and results in the formation of fewer disruptive ice lenses (59-2). However, the exact amount of damage by frost action that will occur depends on several factors, such as air temperatures, availability of moisture, type of soil, degree of compaction, quantity of lime used, etc. Thus, it is somewhat difficult to predict whether the material is frost susceptible or not (48-4, 54-3, 57-1, 59-2, 59-12).

## Permanency

A limited amount of data indicates that changes in various chemical and physical characteristics which take place originally when lime is added to a soil do not necessarily last indefinitely. Lime-soil mixtures are usually fairly effective in repelling some ground water. However, little is known of what happens when lime-soil mixtures are continually subjected to fluctuating ground water or to the percolation of water through the mixture for a long period of time. Some laboratory investigations have indicated that relatively few calcium ions are leached from a lime-soil mixture by distilled water (52-4). It is possible, however, that different reactions may take place when the mixture is leached with water containing sodium ions and other chemicals.

In many cases the plasticity indexes of lime-soil mixtures in the field have increased slightly with age (53-3). This might indicate that the original reduction in the plasticity index, gained immediately after mixing lime with the soil, may not be quite permanent. On the other hand, it may be a normal reaction. The increase in plasticity is slight and even after several years the plasticity index of most lime-soil mixtures is considerably lower than the plasticity index of the originally untreated soils. Also, the strengths of some lime-soil mixtures in the field have been found to increase for a considerable period of time and then decrease slightly (53-3). Whether these changes in physical characteristics are caused by inadequate lime, by reactions with certain chemicals in the water, or other factors, little is known at the present time (52-1, 52-4, 53-3, 58-9, 59-8, 59-10).

## Thickness of Treatment

The minimum depth of treatment of thickness required for a lime-soil base, subbase or treated subgrade is difficult to determine because of the large number of factors affecting the design of this type of pavement, and especially, because of the variations in strengths attained in the field. It is recommended by some investigators that lime-soil bases be not less than 6 in. thick to prevent excessive deflection under light traffic (54-3). Attempts have been made to use only 3- and 4-in. lime-stabilized bases, but any success achieved in these experiments proved to be short lived (54-3). Where lime-soil mixtures have been used for subbase and subgrade treatments, thickness has varied from a few inches to greater than 1 ft with varying success (52-3, 54-3, 56-6, 58-16).

## Resistance to Traffic Wear

Lime-soil mixtures have little or no resistance to traffic wear. Moving vehicles abrade the surface of unprotected bases, which results in the undesirable loss of material. If this is not prevented the thickness of the pavement may be considerably reduced and rapid deterioration of the pavement will take place. Lime-soil bases should be protected by an abrasion-resistant surface. Usually, a seal coat or a surface treatment is satisfactory. If additional strength is desired in the pavement an asphaltic concrete surface should be used (54-3, 58-10, 58-11).

## Cracking and Fluffing of Lime-Soil Mixtures

Cracking and fluffing are two objectionable features that often occur in lime-soil stabilized bases. Cracking may be caused by volume changes in underlying untreated subgrades, by volume changes in the lime-soil mixtures or by the application of heavy loads or heavy rolling during the curing period. Fluffing or loosening of the surface of a lime-soil mixture is related primarily to the curing and in some instances may be more detrimental than cracking.

Volume changes in untreated subgrades may cause serious crack damage to the overlying stabilized bases. These excessive volume changes may be minimized by high compaction and proper moisture control in the subgrade.

Even though the volume changes of certain soils are minimized by treatment with lime, some natural shrinkage of lime-soil mixtures may still occur and a few cracks will result (57-4, 59-7). Most data indicate that these cracks usually occur during the early stages of curing. The natural shrinkage of lime-soil mixtures may be more severe in soils originally having low plasticity indexes (59-8), but the exact amount will depend on the mineralogical composition of the treated material, quantity and type of lime used and curing conditions.

Cracking of lime-stabilized bases may also be caused by the application of heavy loads from vehicles or rollers during the curing period (59-8). In a few reported instances no detrimental effects occurred when heavy traffic was not restricted during the curing period (58-10, 58-11), but this is generally not the case. Usually, no traffic is permitted on the lime-stabilized material during curing. It is interesting to note that on a few projects light pneumatic-tired rollers have been used during curing to help keep the surface knitted together (59-8).

Detrimental "fluffing" or loosening of the surface of lime-soil mixtures often occurs, especially if the mixture is cured in the absence of moisture during hot weather. This loose material on the surface may prevent a tight bond between the lime-treated base and the surface course and will contribute to peeling of the surface treatment. In one instance an asphalt curing membrane peeled and some of the loosened lime-soil mixture was blown away because of a delay in applying a surface treatment (56-6).

To minimize most of the harmful effects of cracking and fluffing it is necessary to moist cure the mixture either by applying water to the surface or by sealing the surface with a curing membrane. If cracking or fluffing does occur during curing, it may be necessary to remove the loosened material from the surface with a motor grader, or to rework the surface prior to the application of a surface treatment. To prevent fluffing on one project (59-5), base material was placed on a lime-stabilized subgrade immediately after final compaction and the treated subgrade was moist cured by permitting water to seep through the base (56-6, 57-4, 58-8, 58-10, 58-11, 59-5, 59-7, 59-8).

## Construction Limitations

As with other material, construction techniques influence the performance of lime-soil mixtures. Many failures of lime-soil stabilized roads, especially those that occur along the outer edges of the pavements, have resulted from poor distribution of lime, inadequate depth control, lack of edge control and improper compaction. These could have been eliminated by proper construction techniques. In a few instances, to compensate for some of the irregularities that might occur in construction, more lime than was required for normal strength purposes was added to the soil (59-8). The use of excess quantities of lime in construction, however, should be avoided because of increased cost and the possibility that a strength reduction may occur in the mixture (56-1, 57-3). (56-1, 57-3, 59-8).

## Reworking Lime-Soil Mixtures

Experience has indicated that reworking of lime-soil mixtures should be avoided after the mixture has set unless additional lime is added. Some investigators have suggested that lime-soil mixtures be compacted within 2 to 4 days after mixing and that these mixtures not be reworked after 7 to 28 days without the use of additional lime (59-2, 59-8). The amount of additional lime added is usually small (59-2), approximately 1 percent. The time limit for reworking lime-soil mixtures without adding additional lime will depend on the field conditions and the quantity of lime originally added to the soil. In one instance, a mixture was finally compacted after a 4-wk delay without the use of any additional lime (58-5). It is not known, though, whether the performance of this road was satisfactory or not (48-5, 58-5, 59-2, 59-8).

# SUMMARY AND CONCLUSIONS

The reviewed literature, although not providing a comprehensive treatise on lime-soil mixtures, does provide valuable information for understanding the actions between lime and soil. The major portion of the reported data is related to the physical characteristics of the mixtures, for example, volume change, strength, durability, etc. Some of these physical properties are covered rather thoroughly, although much data are lacking. Information related to the influences of various types of lime, for example, is almost nonexistent. Also, little information is available that explains the chemical action that takes place to produce these physical changes. Almost all of the information that is available has been obtained in the laboratory. Only meager data are available concerning field tests and field performance of lime-soil mixtures. In other words, most of the reported work has been accomplished through applied research in the laboratory. Little basic research on lime-soil mixtures has been reported.

The literature indicates that lime can be used successfully to stabilize soil within limitations. Lime will modify the soil, strengthen it, and will improve its durability when properly used. Although lime is not a panacea for soil stabilization, when its limitations are considered it can be and has been used successfully in road construction.

The effectiveness of lime depends on the reactions desired and is strongly related to the type of soil that is to be stabilized. If an ionic change is desired to lower the plasticity of the soil and thus make it more friable and easier to handle, the soil originally has to be medium to highly plastic. On the other hand, if lime is to strengthen and improve the quality of the soil, the soil should originally contain the necessary chemical compounds that will react with the lime to produce the cementing effect. In general, the more plastic clays have greater reactivity with the lime and are considerably improved by adding lime. Lime is not too effective, though, in further reducing the plasticity index of a soil originally having a low plasticity. Stabilization of granular materials with lime is difficult, if not practically impossible in some instances. Sometimes, though, granular material can be successfully stabilized with lime if a suitable clay binder or a relatively small amount of pozzolanic material is added to the soil so as to improve the cementation action.

Usually, the desired improvements in the soil can be produced by any one of the commercial grades of lime and sometimes by using locally available waste limes. Although many types of lime may be used in stabilizing a particular soil, one type of lime may be more effective than another. If more than one type of lime is economically available, all limes should be checked to determine which is the most desirable for the existing conditions. The exact amount of lime needed varies not only with the type of lime but also with the type of soil and with other factors. In general, as the amount of lime in the soil is increased, the strength and quality of the mixture is also increased, although not necessarily proportionately. Regardless of the type of lime used or the other conditions, a minimum of about 3 percent lime is needed to produce the desired results.

Another major limitation in using lime as a stabilizing material is the curing temperature. Lime-soil mixtures must be cured for some time at warm or even hot temperatures to gain proper strength and durability. This necessitates early or middle season construction. Late season construction is not desirable. Many lime-soil stabilized sections that were placed late in the season have failed during the first winter because of insufficient curing during the cool fall.

Although the properties of lime-soil mixtures have been investigated rather extensively in the laboratory, little data have been obtained from field testing. So serious is this lack of information that sometimes wrong conclusions have been drawn in evaluating this stabilizing material. For example, the literature strongly indicates that the strength which can be obtained in the laboratory under ideal temperature and other curing conditions is considerably greater than that developed in the field. If the material is being improperly evaluated in this manner higher strengths will be used in design than are actually obtained in the field. In such cases the thickness of the road could be seriously underdesigned. On the other hand, it appears that current durability tests are too harsh on lime-soil specimens. Many times these laboratory tests have indicated the performance of lime-soil mixtures to be poorer than the material has actually been in the field. Until more data are obtained and laboratory and field results are thoroughly correlated, proper design of lime-soil mixtures is seriously handicapped.

In summarizing, the literature tends to indicate certain facts that allow the following conclusions to be drawn. Some of the statements are strongly supported by existing data, whereas others are inferences drawn from limited data.

1. Lime tends to modify the undesirable characteristics of the more plastic clays. It can make the clays friable, can reduce the plasticity index of the soils and can reduce the amount of volume change.

2. In most clays, lime can produce a cementing action which will result in a higher strength and greater durability than would occur in untreated soils.

3. Lime can be used to stabilize heavy clays which cannot be stabilized economically by other types of stabilizing materials.

4. Lime cannot be successfully used with all types of soils, but is limited primarily to the stabilization of medium and highly plastic soils.

5. For soils with low or no plasticity, fly ash and other pozzolanic materials may be added to the soil with the lime to aid in the cementing action.

6. Lime-pozzolan-soil mixtures and lime-soil mixtures have similar physical characteristics.

7. It appears that most of the existing methods for testing lime-soil mixtures do not accurately evaluate the strength and durability characteristics of lime-soil mixtures.

8. The amount of lime needed to modify or stabilize a soil is relatively small. Between 1 and 10 percent, but usually not less than 3 percent lime is required.

9. For the lime to react thoroughly with the soil, there should be a curing period after the lime has been mixed into the soil and before the mixture is finally compacted.

10. The lime-soil mixture must be compacted to a high degree to have high strength and high quality.

11. Because lime-soil mixtures do not set up rapidly, sufficient time usually exists for thorough mixing and compaction.

12. Subgrades that are treated with lime are less affected by rain than untreated subgrades. In some cases this enables contractors to start work after heavy and prolonged rains sooner than they could do otherwise.

13. During construction, lime-treated bases seem to be little affected by rain. Their imperviousness also prevents falling water from flowing through them to the already compacted subgrade.

14. The gain in strength and quality of lime-soil mixtures is very slow and requires rather long periods of time and warm temperatures.

15. Warm weather is almost a necessity in adequately curing lime-soil mixtures. Cool or cold weather is not desirable, and little gain in strength will be obtained at low temperatures.

16. To adequately protect the surface of a lime-stabilized base, the surface must be covered with a surfacing material such as a seal coat or asphaltic concrete.

## SUGGESTED RESEARCH PROJECTS

In reviewing the existing literature on lime-soil mixtures, certain deficiencies in the technical knowledge become apparent that can only be rectified through additional research. A number of general research suggestions are listed herein that should increase this knowledge and enable these lime-soil mixtures to become more useful highway materials.

This list of research suggestions does not necessarily include all of the needed research, but probably does include the most important ones at this time. Some of these studies have been started and as results are reported, the list will need to be modified.

These research suggestions are not placed in any order, and definitely no priority rating has been established. The relative importance of each suggestion varies with specific circumstances and should be evaluated in the light of the existing conditions.

A. Basic research should be conducted to gain a more thorough knowledge of the reactions that take place when lime is added to soil. This includes, but is not limited to, the cementing actions, the chemical compounds that are formed in the soil and the influence of pozzolans on lime-soil mixtures.

B. Research is needed to develop a test or tests that will indicate if a soil is suitable for stabilization with lime.

C. The influence or effectiveness of the various types of limes for stabilizing soils should be investigated.

D. Studies should be made to determine the types of soils that are suitable for stabilization with lime. In addition, the optimum percentage of lime needed for each of these soil types should be determined.

E. The permanency of lime-stabilized soils should be thoroughly studied. Not only should this study include the permanency of the change in plastic limits and strengths of a lime-stabilized soil, but it should also include the effects of groundwater and leaching.

F. More knowledge on the methods of curing lime-soil mixtures is needed. Factors that improve curing, as well as the detrimental factors should be studied.

G. A suitable laboratory test is needed for evaluating the durability of lime-soil mixtures.

H. The effects of cold temperatures on lime-soil mixtures, primarily frost action and durability, should be determined through additional research.

I. The reactions that occur during the initial curing process should be studied, as well as the influence of this aging on the cementation process.

J. More controlled field tests of lime-soil mixtures are needed to determine the performance of this material under all climatic conditions.

K. Methods for correlating laboratory data and field data with the behavior of lime-soil mixtures under actual field conditions are needed.

L. A suitable rational design method for structurally designing semi-flexible pavements, such as lime-soil mixtures, should be derived.

M. Methods for improving the bond between lime-soil bases and bituminous surface treatments should be developed.

N. Additional investigations are needed to determine the types of materials, other than fly ash, that are suitable for use as pozzolans.

O. The effects of various chemical admixtures on the strength and durability of lime-soil mixtures should be determined.

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On the part of the University, the work covered in this report was carried out under the general administrative supervision of W. L. Everitt, Dean of the College of Engineering; R. J. Martin, Director of the Engineering Experiment Station; N. M. Newmark, Head of the Department of Civil Engineering; and Ellis Danner, Director of the Illinois Cooperative Highway Research Program and Professor of Highway Engineering.

On the part of the Division of Highways of the State of Illinois, the work was under the administrative direction of R. R. Bartelsmeyer, Chief Highway Engineer; T. F. Morf, Engineer of Research and Planning; and W. E. Chastain, Sr., Engineer of Physical Research.

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Representing the Illinois Division of Highways—W. E. Chastain, Sr., Engineer of Physical Research; R. K. Andrews, deceased, Soils Engineer; and Dolph Hoke, Soils Engineer.

Representing the Bureau of Public Roads—H. J. Stahl, Area Engineer; and F. P. Walton, Assistant Construction and Maintenance Engineer.

Representing the University of Illinois—T. H. Thornburn, Professor of Civil Engineering; and R. E. Grim, Research Professor of Geology.

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## ANNOTATED BIBLIOGRAPHY

The references in this bibliography are limited to articles related to stabilization of soils with lime. There are no references on lime specifications, lime production, lime characteristics or lime-pozzolan-aggregate mixtures.

Each article on lime-soil stabilization has a reference number assigned to it and a short annotated summary of what the article covers. The reference number is composed of two parts (59-1). The first part of the reference number indicates the year of publication (1959), and the second part refers to the arrangement within that particular year. The references are arranged chronologically according to the earliest year of publication and alphabetically according to authors within the particular year. Where the name of the author was not given, the article is referenced last in that year.

After a few of the references there are no annotations. These references are either not available at the University of Illinois Library or are written in foreign languages.

25-1. McCaustland, D. E. J., "Lime in Dirt Roads." Proc., National Lime Assn., 7: 12 (1925).

Indicates the possibilities of using lime for stabilizing road subgrades. Conclusions are based on laboratory results obtained at University of Missouri.

25-2. McKesson, C. L., "Report of the Rio Vista, California, Subgrade Treatment Experiments." HRB Proc., 5:Pt. I, 123 (1925).

A section of test road using a 1 to 20 hydrated lime mixture 12 in. deep, was constructed on adobe and silty clay soils. Transverse cracks 10 to 60 ft apart and several short irregular longitudinal cracks developed. Surface checking was also noted. Lineal shrinkage was reduced 2 percent. Conclusions of test were that hydrated lime was useless as a subgrade treatment.

26-1. Woods, H. W., Jr., "Lime in Earth Roads." Proc., National Lime Assn., 8:57 (1926).

A general article on the use of lime for stabilizing earth roads.

26-2. Anon., "Out of Mud with Lime." Bull. 317, National Lime Assn. (1926).

Field practice at this time indicated that the lime content should be between 2.5 to 4.0 percent. For troublesome clay soils 3 to 5 percent lime produced the desired results. In general, it was found that lime treated roads gave better service than untreated soils; and also that these lime treated soils provided a foundation for further improvements.

31-1. Rauterberg, E., "The Physico-Chemical Effect of Lime on the Soil." Fortschritte dev Landwirtschaft, 6:680 (1931).(In German).

32-1. Groditskaya, B. M., and Ipatova, A. I., "The Problem of Lime Stabilization of Soils for Roads." Sbornik Gdornii, Gruntodezhda, Vol. 3 (1932). (In Russian).

32-2. Ipatova, A. I., "Experiments in Stabilizing Chernozem Soils with Lime." Doroga i Avtomobil, (3) (1932). (In Russian).

32-3. Maffei, A., and Banchi, G., "The Displacement of Alkalis in Clays by the Action of Lime." Ann. Chim. Applicota, 22:93 (1932).

34-1. Eno, F. H., "Some Effects of Soil, Water and Climate upon the Construction Life and Maintenance of Highways." Eng. Exper. Sta. Bull. 85, Ohio State Univ. (1934).

35-1. Searle, A. N., "Limestone and Its Products." Earnest Benn Ltd., London, p. 588 (1935).

One section discusses the use of lime in treating road subgrades.

35-2. Volkov, M. I., and Kustiik, B. R., "Influence of Additions of Lime and Cement on Road-Building Properties of Clay Soils." Journal, Katkhov Highway Institute, 1:90 (1935).

36-1. Hogentogler, C. A., and Willis, E. A., "Stabilized Soil Roads." Public Roads, p. 45 (May 1936).

A general article on stabilizing soils encompassing all stabilizing agents used up to this time. Lime is referred to only briefly. Many good basic factors, especially those pertinent to all methods, are discussed.

37-1. Bykovski, N. I., "The Problem of Lime Treatment of Roads." Doroga i Avtomobil, Vol. 8 (1937). (In Russian).

37-2. Hogentogler, C. A., "Engineering Properties of the Soil." McGraw-Hill (1937).

The presence of lime in soils is briefly discussed. The calcium replaces hydrogen or sodium in the clay, thus converting an acid or alkaline clay into a more usable calcium clay. The action of lime also replaces the acidic hydrogen in humic acid forming the more stable so-called calcium humate or neutral humus.

40-1. Lesesne, S. D., "Stabilization of Clay Roadbeds with Lime." Bull. 325, National Lime Assn. (1940).

Stabilization of heavy gumbo clays was accomplished by adding lime and then compacting the mixture at optimum water content. Highest strength values were achieved when the lime-soil specimens were soaked in a capillary tank for a period of time. Further moist curing only maintained the peak value.

40-2. Lesesne, S. D., "Road Stabilizing Materials and Processes." Proc., National Lime Assn. (May 1940).

40-3. Willis, E. A., and Smith, P. C., "Chemical Treatment of Chert-Gravels for Use in Base Course Construction." Public Roads, 21:4, 65 (June 1940).

Primarily a description of the testing of chert-gravel stabilized with various admixes in a test track. Lime was one of the stabilizers and performed quite satisfactorily.

42-1. Visser, W. C., "Lime Status and Soil Structure." Landbouwkundig Tijdschriff, 54:791 (1942).

43-1. Li, M. C., "Research on Soil Stabilization." HRB Proc., 23:413 (1943).

This article deals with China's problem to develop a quick stable road surface by using admixtures of cinders, burnt clay, lime, etc. Various physical properties were determined, but little data were given on lime stabilization.

46-1. James, R. L., "Soil Stabilization—The Wet Sand Process." Contractors Record and Municipal Engineering (Feb. 6, 1946).

47-1. Dockery, W. D., and Manigault, D. E. H., "Lime Stabilization and Low Cost Road Construction." Roads and Streets, 90:91 (Aug. 1947).

The construction of various lime-soil stabilization projects in the Austin District of the Texas State Highway Department is reported. Primarily worn-out, clay-gravel roads were effectively stabilized with waste lime.

47-2. Freeborough, B. B., "Lime Treatment Permits Use of Substandard Flexible Base Materials." Public Works, 78:6, 17 (June 1947).

A general article on some of the advantages of stabilizing various soils with lime. Observations were made of projects in Texas.

47-3. Maiborodo, G. I., "Humus-Concrete Road Construction." Stroitel'stvo Dorog, (1) (1947). (In Russian).

47-4. Manigault, D. E. H., "Lime Stabilization." Roads and Streets, p. 94 (Aug. 1947).

Conclusions, obtained from laboratory investigations of the effects of lime in stabilizing soils, were given with a general discussion of the use of lime in road construction.

48-1. Aaron, H., "Report of Committee on Lime-Soil Stabilization." Tech. Bull. 147, American Road Builders' Assn. (1948).

In general the conclusions of the committe were: (1) More observations and studies are necessary before definite recommendations can be made relative to test methods and design procedures. (2) Small percentages of lime lower PI of gravel, disintegrated granite, and caliche, and increase stability. (3) A soil's physical reaction to lime should be thoroughly investigated before stabilization. (4) Control over proportioning of materials, mixing and compaction are essential during construction. (5) Curing is necessary to prevent too rapid drying of mixture.

48-2. Johnson, A. M., "Laboratory Experiments with Lime-Soil Mixtures." HRB Proc., 28:496 (1948).

Fine-grained soils, natural gravels, and gravel binder mixes were benefitted by the addition of lime. This was indicated by increased resistance to penetration (CBR) even though the maximum dry density was lowered.

48-3. Kuran, H., and Honnemann W., "Influence of Lime on the Mechanical Properties of Soil Colloids." Zeitschrift fur Pflanzenernährung and Dungung, 40:200 (1948). (In German).

48-4. McDowell, C., "The Use of Hydrated Lime for Stabilizing Roadway Materials." Proc., National Lime Assn. (1948).

An article describing the general use of lime for stabilizing soils. Specimens used for testing the strength of lime soil mixtures were moist cured for 7 days; air dried at 140 F for one day; subjected to 10 days of capillary wetting; and finally tested by the triaxial compression method.

48-5. McDowell, C., and Moore, W. H., "Improvement of Highway Subgrades and Flexible Bases by the Use of Hydrated Lime." Proc., Second International Conf. on Soil Mechanics and Foundation Engineering, 5:260 (1948).

Report of an exploratory investigation of lime stabilization with Texas soils. A history is given and preliminary conclusions are made.

48-6. Smith, W. H., "Stabilizing Texas Roads with Lime." Better Roads, 18:5, 23 (1948).

A brief record of early lime-soil stabilized projects carried out by the Texas Highway Department is given. Very good results were obtained when the proper quantities of lime, soil and water were adequately mixed, compacted and cured. In the few failures recorded, a mistake in one of the previous requisites was found. When the mistake was rectified, no further damage was recorded. One test section withstood heavy traffic and icy winters with only negligible maintenance.

48-7. Volkov, M. I., Gelmer, V. O., et al., "The Effect of the Addition of Lime and Cement on the Road Properties of Clay Soils." (Dorizdat), Moscow (1948). (In Russian).

48-8. Anon., "Lime Used in an Airfield Base." Roads and Streets, 91:1, 96 (1948).

During World War II an airstrip at Beeville, Texas was constructed with a base course of caliche stabilized with lime. After 4 1/2 yr of service the strip was in fine condition.

49-1. Huang, E. Y., "Effect of Quick-lime on the Compressive Strength and the Physical Constants of Fine-Grained Soils." Unpublished Thesis, Univ. of Utah (1949).

The changes in physical characteristics of various types of fine-grained soils produced by addition of quicklime were investigated. Results are similar to those produced by hydrated lime. The difference in the results obtained with the two types was not compared in this report because hydrated lime was not part of the investigation.

49-2. McDowell, C., "Hydrated Lime for Stabilizing Roadway Materials." Roads and Streets, 12:2, 81 (Feb. 1949).

General information concerning lime stabilization of soils in Texas. In addition to information concerning construction, plasticity and strength changes, results of freeze-thaw durability tests are given.

49-3. Spangler, M. G., and Patel, O. H., "Modification of a Gumbotil Soil by Lime and Portland Cement Admixtures." HRB Proc., 29:561 (1949).

This paper reports the results of a laboratory study of the effect of various percentages of unslaked lime (CaO) and portland cement on the engineering properties of gumbotil soil which is rather frequently encountered in highway construction in southwest Iowa. The results indicate that a marked and favorable modification of the soil in all the major properties studied is accomplished by adding lime.

49-4. Woods, K. B., "Lime as an Admixture for Bases and Subgrades." Paper presented at 31st Ann. Mtg., National Lime Assn. (May 1949).

Laboratory studies indicate that the degree to which subgrade soils can be improved (reduction in plasticity index and increase in strength) is dependent on the type of soil. The more plastic soils are improved to a greater degree than more silty soils. Tests indicated lime would also improve gravel-base material.

50-1. Minnick, L. J., and Miller, R. H., "Lime-Fly Ash Compositions for Use in Highway Construction." HRB Proc., 30:489 (1950).

A sand and several types of coarse aggregates were improved by stabilizing with lime and fly ash. The stabilized soils showed excellent resistance to wet-dry and freeze-thaw tests. Compressive strengths also were increased.

50-2. Mehra, S. R., and Uppal, H. L., "Use of Stabilized Soils in Engineering Construction." Journal, Indian Road Congress, 15:1 and 2 (1950).

50-3. Patel, O. H., "Stabilization of Gumbotil Soil for Highway Use." Journal, Indian Road Congress, 15:336 (1950).

51-1. Couillaud, E., "Substitute Binders." Rev. Mat'er Construction, No. 426, p. 77 (1951). (In French).

51-2. Gallaway, B. M., and Buchanan, S. J., "Lime Stabilization of Clay Soil." Texas Eng. Exper. Sta. Bull. 124, A and M College of Texas (1951).

A fairly basic investigation of the modifying effects that lime has on clays. The total base exchange capacity of a soil appears to give an indication of the reactivity of the soil and lime. Other methods, such as the X-ray, seemed not to be feasible. All results were given in terms of the plasticity change in the soil; no strength tests were run. An excellent theoretical analysis is given of the stabilizing reaction of soil and lime.

51-3. Mainfort, R. C., "A Summary Report on Soil Stabilization by the Use of Chemical Admixtures." Technical Development Report 136, U. S. Civil Aeronautics Admin. (1951).

This report covers a comprehensive long-time study of the stabilization of a number of different types of soils with various admixtures. When stabilized with lime, the soils had very little resistance to the laboratory freeze-thaw testing; however, the soils seemed more durable when subjected to actual field durability tests.

51-4. Anon., "Distribution Charts for Stabilized Materials." Roads and Streets, 94:8, 46 (Aug. 1951).

These charts were prepared by the Fourth Army Engineers for field use in their area and include cement as well as lime. Such charts are given as: (a) converting from percent lime to amount of lime per sq yd for specific depth, (b) rate of application, etc.

52-1. Carter, H. C., "Lime Stabilization in District Fourteen, Texas Highway Department." Tech. Bull. 185, American Road Builders' Assn. (1952).

This article is a short summary that deals with lime stabilization projects in a Texas Highway District. Primarily it covers construction procedures, but concludes with some pertinent observations.

52-2. Chopra, S. K., and Patwardhan, N. K., "Investigation on the Use of Lime-Sludge as a Soil Stabilizer." Journal of Scientific Industrial Research, India, 11B:10, 434 (1952).

52-3. Fuller, M. G., and Dabney, G. W., "Stabilizing Weak and Defective Bases with Hydrated Lime." Roads and Streets, 95:3, 64 (March 1952).

The Corps of Engineers built several test sections using lime to stabilize existing weak, poor quality, clay-gravel base courses. Field sections were successfully stabilized with only 3 percent lime. The plasticity index and percent of soil binder were reduced and high CBR values were obtained on all sections.

52-4. Goldberg, I., and Klein, A., "Some Effects of Treating Calcium Clays with Calcium Hydroxide." Symposium on Exchange Phenomena in Soils, Spec. Tech. Publ. 142 (with discussion), ASTM (1952).

After investigating the effects of lime on the expansion of two expansive clays, it was concluded that swelling was reduced with addition of lime. Above a given amount of lime, depending on the soil, little reduction in swelling was obtained with the addition of more lime. Detailed chemical analyses were also made to give indication of changes in lime and ions.

52-5. Gushosder, "Tentative Specifications for Methods of Constructing Soil-Cement and Lime-Stabilized Roads." Central Board of Highways, Moscow (Dorizdat) (1952). (In Russian).

52-6. Levchanovskii, G. N., "Lime Stabilized Soil Bases for Improved Road Surfacings." Saratov (Avtovefevat) (1952). (In Russian).

52-7. Minnick, L. J., and Miller, R. H., "Lime-Fly Ash-Soil Compositions in Highways." HRB Proc., 31:511 (1952).

The effect of lime and fly ash on the engineering properties of four types of soil was studied. A beneficial change was brought about in the properties investigated including durability.

52-8. Whitehurst, E. A., and Yoder, E. J., "Durability Tests on Lime-Stabilized Soils." HRB Proc., 31:529 (1952).

Studies were conducted on three soils, a Wisconsin drift soil, an Illinoian drift soil and a river terrace gravel, to determine the influence of lime on strength and durability properties (the latter as measured by the soniscope). Small amounts of lime did not help appreciably, but larger amounts (greater than 5 percent) significantly increase both strength and durability. Increased time of moist curing was beneficial. Greatest benefits were derived by the gravel and the least by the Wisconsin drift.

52-9. Woods, K. B., and Yoder, E. J., "Stabilization with Salt, Lime, or Calcium Chloride as an Admixture." Proc., Conf. on Soil Stabilization, Massachusetts Institute of Technology, p. 3 (June 1952).

In the lime stabilization section of this article, it was indicated that the addition of lime to soils brings about a reduction in the plasticity index in various ways depending on the soil type. Other properties were investigated; most of which were improved by the addition of lime. The mixtures were susceptible, however, to freezing and thawing.

52-10. Zube, E., "Experimental Use of Lime for Treatment of Highway Base Courses." Tech. Bull. 181, American Road Builders' Assn. (1952).

A description of construction procedures, materials, test results and performance of two lime stabilization projects in California. In both projects granular base course materials were stabilized with agricultural lime.

53-1. Barisova, E. G., "Theoretical Principles on the Binding of Soils by Lime." Sbornik MGU, Gruntovedenie, Vol. 3 (1953). (In Russian).

53-2. Levchanovski, G. N., "Soil Stabilization with Ground Unslaked Lime." Trudy SADI, Sbornik 12, Saratov (Saratovskoe Knizhn. izd-vo) (1953). (In Russian).

53-3. McDowell, C., "Road and Laboratory Experiments with Soil-Lime Stabilization." Proc., National Lime Assn. (1953).

Primarily this article reports the results of testing lime-soil specimens that were cured for long periods of time. Strength tended to increase for 2 to 4 yr, depending on lime content and other factors, and then changed little or even decreased slightly with more aging. The plastic limit also changed slightly with time.

53-4. Minnick, L. J., and Meyers, W. F., "Properties of Lime-Fly Ash-Soil Compositions Employed in Road Construction." HRB Bull. 69 (1953).

For a variety of soils studied, additions of small amounts of hydrated lime and fly ash helped to develop high strength at relatively early ages. Curing at elevated temperatures accelerated pozzolanic action. This material had good durability as indicated by the soniscope.

53-5. Wood, J. E., "Lime-Fly Ash-Soil Stabilization in Maryland." Tech. Bull. 199, American Road Builders' Assn. (1953).

A report of the first lime-fly ash stabilization project in Maryland. A fairly non-plastic pit-run gravel was combined with optimum proportions of lime and fly ash as determined by laboratory moisture-density test. It was allowed to cure open for 75 days and then it was sealed. After a year it was in fairly good condition.

53-6. Anon., "Texas Stabilizes Roads with Quicklime." Engineering News-Record, 150:38 (Feb. 5, 1953).

This article illustrated how the Texas Highway Department realized some savings in cost of treating road bases by substituting quicklime for slaked lime.

53-7. Anon., "Road Base in Texas Stabilized with Lime." Contractors and Engineers, 50:7 (July 1953).

A heavy clay hydraulic fill was stabilized and made into an accepted base, when slaked lime was added to improve the bearing value of the subbase.

54-1. Dougherty, J. R., "Low-Cost Dustless Surfacing for Secondary Roads." HRB Proc., 24:25 (1954).

An investigation into the economics of "low-cost" road construction was begun through the construction of a "low-cost" road test section. Various stabilizers, including lime, were used. No conclusions were given, but were to be made at a later date.

54-2. Misiaszek, E. T., "Lime-Fly Ash Stabilization Research; Abstract." Rock Products, 57:90 (June 1954).

A general review of research at Clarkson University on lime-fly ash stabilization of soils. Article is very brief with little technical data.

54-3. Anon., "Lime Stabilization of Roads." National Lime Assn., Washington, D. C. (1954).

An excellent publication on the use of lime for soil stabilization. Contains general discussion on construction procedures, recommended tests, and specifications for lime and lime stabilization. It also gives results of 30 different tests on fine-grained soils and 8 natural gravel and gravel-binder mixes as conducted at Purdue University. Several conclusions based on laboratory tests and experience are given in the bulletin. Lime was found to be most effective on clay-gravel or gravel-binder mixes in amounts from 2 to 5 percent. Five to 10 percent lime was considered necessary for most fine-grained clay soils. No definite conclusions were stated with respect to use of lime with fine-grained silty and loamy soils.

54-4. Anon., "Lime for the Stabilization of Road Bases." Roads and Engineering Construction, 92:96 (Sept. 1954).

A condensed version of "Lime Stabilization of Roads" by National Lime Assn. See 54-3 above.

54-5. Anon., "Lime Applied from Tankers on Texas Base Stabilization Project." Roads and Streets, 97:47 (Oct. 1954).

Lime stabilization of a Texas farm to market road was accomplished by the addition of hydrated lime in slurry form. No lime separation troubles were encountered. Normal construction procedures were followed except that a thin coat of emulsion was applied to the stabilized base to act as a dust palliative and to aid in curing before the protective surface treatment was placed.

55-1. Birulya, A. K., "Doragi iz Mestnykh Materialov." ("Roads from Local Materials.") Autotransizdat, Moscow (1955). (In Russian).

55-2. Chu, T. Y., Davidson, D. T., et al., "Soil Stabilization with Lime-Fly Ash Mixtures: Preliminary Studies with Silty and Clayey Soils." HRB Bull. 108 (1955).

A laboratory investigation of the stabilization of four various soils with lime and fly ash. Preliminary test results were given and a method was suggested for evaluating lime-fly ash stabilized soils.

55-3. Cooper, J. P., "Lime Stabilization of Base Material." Texas Highways, 29th Annual Highway Short Course, p. 86 (May 1955).

A fairly high plastic base material was stabilized with a lime slurry. Techniques were covered for preparing the slurry and its use.

55-4. Huff, T. S., "Use of Lime Stabilization on Roads of the Texas Highway System." Proc., AASHO, p. 157 (Dec. 1955).

This is a very general discussion of the use of lime in stabilizing soils. Characteristics of lime stabilization, both desirable and undesirable, and some basic suggestions for avoiding project failure were given.

55-5. Maclean, D. J., "Stabilization of Soils." Proc., 10th International Road Congress, Part B, Question II-Soils, Istanbul (1955).

55-6. McDowell, C., "Development of Lime Stabilization." Texas Highways, 29th Annual Highway Short Course, p. 79 (May 1955).

Primarily the past history and the development of lime stabilization are covered in this general article.

55-7. Mehra, S. R., and Chadda, L. R., "Use of Lime in Soil Stabilization." Journal, Indian Road Congress, 19:3, 483 (1955).

Results were given of a number of different laboratory tests on four typical loamy soils due to the effects of lime and lime with plaster of Paris. It was concluded that "lime improves compressive strength, reduces shrinkage, and increases resistance to softening action of water. Sandy loams react better to lime treatment than silty or silty clay loams." Also it was concluded that plaster of Paris should not be used with lime.

55-8. Misiaszek, E. T., "Effects of Lime and Pozzolanic Admixtures to Soils of New York State." Unpublished Thesis, Clarkson College of Technology (June 1955).

Laboratory investigations indicated that compressive strengths and durability characteristics of the three soils investigated were improved by stabilization with mixtures of lime and fly ash. The amount of improvement depended on the ratio and amounts of lime and fly ash used. Two of the soils were A-4 type and the other was an A-3 type.

55-9. Swain, M. S., "Lime Stabilization of Subgrades." Texas Highways, 29th Annual Highway Short Course, p. 83 (May 1955).

Construction experience on a Texas highway project where a clayey subgrade was stabilized with both hydrated lime and quicklime is summarized.

55-10. Uppal, H. L., "Laboratory Experiments in Sand Stabilization." Journal, Indian Road Congress, 19:2, 285 (1955).

Report of a laboratory investigation of the strength of a relatively clean river sand when stabilized with lime and with lime-molasses. Strength was little improved by lime alone, but lime-molasses increased the strength. There was little increase in strength when the combined mixtures were water soaked and there was even less strength when $CO_2$ was added to the water.

55-11. Whitehurst, E. A., "Stabilization of Tennessee Gravel and Chert Bases." HRB Bull. 108, p. 163 (1955).

Addition of lime and lime-fly ash to samples of Tennessee chert and gravel bases resulted in no improvement. Low unconfined compressive strengths and high weight loss in durability tests indicated this conclusion.

56-1. Dawson, R. F., "Special Factors in Lime Stabilization." HRB Bull. 129 (1956).

The cohesiometer was used to evaluate the strength of a clayey gravel stabilized with various amounts of lime. The cohesiometer value increased as lime content was increased to an optimum of about 5 percent lime and then decreased. In general, additional compactive effort and curing time increased the cohesiometer value.

56-2. Goecker, W. L., Moh, Z. C., et al., "Stabilization of Fine and Coarse-Grained Soils with Lime-Fly Ash Admixtures." HRB Bull. 129 (1956).

A laboratory evaluation was made of the effects of lime-fly ash on eight soils from various parts of the country. Primarily, it was a preliminary investigation dealing with mixing time, compactive effort, types of curing, time of curing and resistance to freezing-thawing and wetting-drying. The report is very comprehensive.

56-3. Laguros, J. G., Davidson, D. T., et al., "Evaluation of Lime for Stabilization of Loess." Proc., ASTM, 56:1301 (1956).

This article gives an account of research with various types of lime on loess from Iowa. Test results with lime-stabilized loess were related to the calcium:magnesium ratio of the lime and to the amount of quicklime and hydrated lime. On the basis of compressive strength, quicklime appeared to be more effective with loess than the equivalent amount of hydrated lime, and dolomitic lime was more effective than calcitic lime.

56-4. Minnick, L. J., and Williams, R., "Field Evaluation of Lime-Fly Ash-Soil Composition for Roads." HRB Bull. 129 (1956).

A number of lime-fly ash soil field projects were investigated and studied. Performance was evaluated by physical inspection and by testing of undisturbed specimens removed from the base. Results are compared with those obtained from laboratory studies that involved pozzolanic activity produced at elevated temperatures and subjected to wet-dry, freeze-thaw testing. Recommendations are made as to methods of evaluating lime-fly ash-soil mixtures.

56-5. Muse, W. W., Jr., "Lime Used to Speed Up Paving Operations." Louisiana Department of Highways (1956).

56-6. Weaver, H. C., "Lime Stabilization." Rural Roads (Nov.-Dec. 1956).

Lime was used to stabilize an inferior caliche base material. The strength of the base increased from that of a borderline base material to a good flexible base material upon stabilization with 3 percent hydrated lime.

56-7. Williamson, F., "County Builds Lime-Stabilized Roads." Better Roads, 26:6, 34 (June 1956).

To reduce the loss of gravel on county roads, lime was mixed with the gravel. Construction problems are related. After the first severe winter there was no evidence of base failure.

56-8. Anon., "Lime-Soil Stabilization; Panel Discussion." Rock Products, 59, p. 128 (June 1956).

Condensation of remarks made by members of a lime-soil stabilization panel at the annual meeting of the National Lime Association.

56-9. Anon., "Lime Stabilization Technique Makes Good Base Course in Plastic Soils." Contractors and Engineers (Nov. 1956).

Article briefly describes how lime has been used to stabilize bases on several projects in Louisiana. Highly plastic, fine-grained clays and silts have been transformed into suitable bases with the addition of 3 to 5 percent lime.

57-1. Clare, K. E., and Cruchley, A. E., "Laboratory Experiments in the Stabilization of Clays with Hydrated Lime." Geotechnique, 7:2, 97, London (1957).

A good brief resumé of the work completed on lime stabilization is covered in this article. Although ten clays were investigated, results were similar for all and data are reported for only one highly plastic clay. Effects of lime content on plasticity tests, pH value, suction/moisture and calcium hydroxide content were studied. Work covered theories of action of lime on clays and indicated that neither exchangeable base, base exchange capacity nor liquid limits provide a satisfactory means of determining suitability of soil to be stabilized with lime or what proportion of lime is needed.

57-2. Davidson, D. T., Katti, R. K., and Handy R. L., "Field Trials for Soil-Lime Flyash Paving at Detroit Edison Co., St. Clair Power Plant, St. Clair, Michigan." Unpublished report for Detroit Edison Company (1957).

57-3. Lu, L. W., Davidson, D. T., et al., "The Calcium-Magnesium Ratio in Soil-Lime Stabilization." HRB Proc., 36:794 (1957).

A laboratory study of the effects of various commercial limes and synthetic limes on various soil types. Strength (unconfined compressive and CBR) and durability properties were investigated. For the test procedure used, indications are that dolomitic quicklime gives best results for soil stabilization.

57-4. McAllister, R. W., "Report to the Mississippi Lime Company on Lime Stabilized Highway Construction." Arthur D. Little, Inc. (1957).

A general report that covers briefly the effects of lime on soils and procedures for constructing lime-soil stabilized roads. The major portion of the report deals with actual lime-stabilized soil highway projects in Illinois and Missouri.

57-5. Maclean, D. J., and Clare, K. E., "The Use of Stabilized Soil in Road Construction." Road International, 27:33 (1957/1958).

57-6. Taylor, W. H., Jr., "Stabilizing Organic Fills with Lime in Louisiana." Tech. Bull. 233, American Road Builders' Assn. (1957).

It was desired to stabilize a rather marshy soil that contained large amounts of organic matter and salt. Cement and asphalt were found to be unsatisfactory. Stabilization with lime, though, resulted in a firm subbase through which the underlying soft material did not break through on rolling.

57-7. Schofield, A. N., "Lime Stabilization of a Nodular Clayey Pea-Laterite in Nyasaland." Bull. 3, Road Research Overseas, Department of Scientific and Industrial Research, Harmondsworth, England (1957).

57-8. Viskochil, R. K., Handy, R. L., and Davidson, D. T., "Effect of Density on Strength of Lime-Flyash Stabilized Soil." HRB Bull. 183, p. 5 (1957).

The strength of lime-fly ash soils was greatly increased with increased compactive effort after 7 and 28 days of curing. The optimum lime-fly ash ratio with clays and silts resulted in a decreased percent solids for the same compactive effort and an accompanying decrease in strength.

57-9. Anon., "Lime Subgrade Stabilization on Texas Interstate Projects." Roads and Streets, 100:7, 75 (July 1957).

Lime stabilization of high PI subgrades on a Texas highway project saved 4 to 6 in. of stone usually needed to accommodate heavy wheel loads. Results of laboratory testing of soils as well as construction are covered. An unusual method of scarification aided in producing a more homogeneous mixture. Pulverization was aided by letting the lime rot in the soil for periods up to 48 hr.

57-10. Anon., "Summary Reviews of Soil Stabilization Processes, Hydrated Lime and Quicklime." Report 5, Miscellaneous Paper 3-122, Corps of Engineers, U. S. Army, Waterways Experiment Station, Vicksburg, Miss. (Aug. 1957).

The information presented in this report was obtained from available literature and thus represents the thinking of a number of investigators in the field of lime-soil stabilization. The article indicates that lime is more useful in fine-grained stabilization than in coarse-grained materials, but that reaction of lime with coarse-grained materials may be aided by "adept" material or pozzolans. Calcium chloride, zinc sterate, or salicylic acid may be added to the lime-soil mixture to increase weathering resistance. Indications are that dolomitic-type lime gives the highest strength values when used in stabilization.

57-11. Anon., "Worn-Out Road Rebuilt with Lime Stabilization; Fox Point, Wisconsin." Public Works, 88:100 (Nov. 1957).

A one-block test section of lime-stabilized road was built in Fox Point, Wisconsin. At places it was necessary to add as much as 4 in. of clay-gravel to bring the test section to grade. This material, as well as existing soil, was stabilized by the same construction procedure that is used in standard soil-cement construction except that lime was used instead of cement. Results were satisfactory.

58-1. Brand, W., "Die Bodenstabitisierung mit Kolk." ("Soil Stabilization with Lime.") Strasse und Autobahn (Nov. 1958). (In German).

58-2. Davidson, D. T., et al., "Reactivity of Four Types of Flyash with Lime." HRB Bull. 193, p. 24 (1958).

Increased lime contents resulted in increased strength of lime-fly ash mortar specimens. Time and temperature are two significant

factors that influence the pozzolanic reaction. Fly ashes that possess fineness and low carbon content permit an intimate union between the lime and the fly ash and give best results.

58-3. Dawson, R. F., and McDowell, C., "Expanded Shale as an Admixture in Lime Stabilization." HRB Bull. 183, p. 33 (1958).

An expanded shale was used as a pozzolan with lime to stabilize two gravels. Only strengths (compressive and flexural) were investigated and they were improved by using the admixture.

58-4. Eades, J. L., "Progress Report No. 2—Base and Subgrade Stabilization Experiments." Virginia Council of Highway Investigation and Research (July 1958) (For summary see 59-9).

58-5. Gutschick, K. A., "Expedite Construction with Lime Stabilization." Modern Highways (June 1958).

Advantages of using lime to stabilize soils are discussed from the construction viewpoint. The addition of lime to soil has an agglomeration action and a drying out action that help expedite construction.

58-6. Hill, A. D., "Construction Report on Experimental Hydrated Lime Treated Subgrade Sections—Cloud and Jewell Counties." State Highway Commission of Kansas, Research Department (April 1958).

This report covers the construction of two experimental lime stabilization projects in Kansas. A number of conclusions were made in regard to construction techniques concerning handling of lime, mixing, etc. Comparative costs of lime-treated material and untreated base are also given.

58-7. Hoover, J. M., Handy, R. L. and Davidson, D. T., "Durability of Soil-Lime-Fly Ash Mixes Compacted Above Standard Proctor Density." HRB Bull. 193, p. 1 (1958).

Primarily the article reported that high density tends to improve the durability of soil-lime-fly ash mixtures. In addition it was noted that the strengths of these specimens were increased during the wetting-drying test.

58-8. Jones, C. W., "Stabilization of Expansive Clays with Hydrated Lime and with Portland Cement." HRB Bull. 193, p. 40 (1958).

Laboratory tests were conducted on an expansive California clay canal soil that was treated with hydrated lime and with portland cement. Expansion on wetting, shrinkage on drying, as well as strength and durability properties were checked. Lime was superior in improving some of the properties, whereas cement was superior for others.

58-9. Jones, W. G., "Lime-Stabilized Test Sections on Route 51, Perry County, Missouri." HRB Bull. 193, p. 32 (1958).

A number of road test sections were constructed with various types of limes on different types of subgrade soils. After 4 1/2 yr of service, the conditions of these sections were surveyed. This report describes the conditions of the lime sections at the end of that time and offers some tentative conclusions.

58-10. Kelly, A. R., "Low Cost Street Construction with Lime Stabilization." Public Works, 89:113 (Oct. 14, 1958).

This is a report of stabilizing an existing city street with lime. The original street had been composed of bank-run clay-gravel which exhibited high plasticity and high shrinkage. Lime reduced the detrimental effects of the clay and resulted in a greatly improved street.

58-11. Lium, E. L., "Red River Valley Experiments with Lime Stabilization." Better Roads (Nov. 1958).

Three lime stabilization projects were constructed in the Red River Valley on existing gumbo soil. Laboratory testing of the lime-treated soil indicated it would have a high CBR strength. Also, indications were that it would resist disintegration in water.

58-12. Miller, R. H., and McNichol, W. J., "Structural Properties of Lime-Fly-ash-Agregate Compositions." HRB Bull. 193, p. 12 (1958).

The strength of soils is greatly increased by addition of lime and fly ash. This combination is more beneficial than addition of lime only. Results also show that lime-fly ash-aggregate mixtures are a superior base material even before pozzolanic action takes place.

58-13. Nichols, F. P., Jr., "Virginia's Experiments with Lime Stabilization." Tech. Bull. 236, American Road Builders' Assn. (1958).

A general discussion of one of the first lime stabilization projects in Virginia. Some laboratory testing, field construction and field testing are covered.

58-14. Snyder, J. F., "Hydrated Lime—To Improve and Strengthen Subgrade and Flexible Materials." Texas Highways (Oct. 1958).

A very general article which highlights the beneficial use of hydrated lime in highway base stabilization. Specific examples are cited to bear out the claims.

58-15. Unger, A., "Verbesserung von Schluff duch Kolk." ("Improvement of Silt by Lime.") Strasse und Autobahn (Nov. 1958). (In German).

58-16. Van Dine, W. G., "Lime Stabilization Methods and Experiences at Fort Polk, Louisiana." Roads and Streets, 101:54 (Sept. 1958).

Old clay-gravel roads at Ft. Polk, La., were stabilized with hydrated lime to combat wet weather problems. Three standard sections were adopted for use depending on subjected wheel loads. These stabilized roads were surfaced with a double surface-treatment and gave excellent service in spite of regular heavy truck traffic and occasional tank traffic.

58-17. Viskochil, R. K., Handy, R. L., and Davidson, D. T., "Effect of Density on Strength of Lime-Flyash Stabilized Soils." HRB Bull. 183, p. 5 (1958).

This laboratory investigation indicated that the strengths of lime-fly ash stabilized soil are greatly improved by increasing the density and that the lime-fly ash ratio is of little consequence up to 1:9 or 2:8. If the lime content is increased above these ratios, the percentage of solids is decreased and the strength is also decreased.

58-18. Anon., "Initial Laboratory and Field Tests of Quicklime as a Soil-Stabilizing Material." Report 2, Tech. Report 3-455, Corps of Engineers, U. S. Army, Waterways Experiment Station, Vicksburg, Miss. (Aug. 1958).

Laboratory investigations indicated that a loessial soil could be effectively stabilized with quicklime in a relatively short time. However, actual test sections did not indicate this. Construction methods were probably at fault, though, and not the materials.

59-1. Arman, A., "A Study in the Use of Lime in Highway Construction." Louisiana Department of Highways, District 7 Laboratory (Feb. 1959).

59-2. Boynton, R. S., "Lime Stabilizing Airport Runways." Paper to U. S. Air Force Pavements Conf. (July 28, 1959).

The advantages of using lime for the stabilization of plastic soils were discussed. Some information is given on the changes in physical and chemical properties that occur when clayey soils are stabilized with lime. The article also lists and discusses the use of lime in stabilizing bases and subgrades of airfields and roads on several military bases in the south and southwest.

59-3. Brand, W. and Schoenburg, W., "Impact of Stabilization of Loess with Quicklime on Highway Construction." HRB Bull. 231, p. 18 (1959).

Results are given of laboratory testing water sensitive loess with quicklime and subsequent use in actual construction. Not only was strength increased, but by adding lime to the soil that had high water content, construction was able to proceed normally.

59-4. Davidson, D. T., and Katti, R. K., "Activation of the Lime-Flyash Reaction by Trace Chemicals." HRB Bull. 231, p. 67 (1959).

The results of a laboratory investigation in which the effects of small amounts of 47 different chemicals on the strength of Ottawa sand-lime-fly ash mixtures are presented. A theoretical explanation is also offered for the strength improvement produced by the different groups of chemicals studied.

59-5. Kreusel, E., "Lime Stabilization Expedites Construction of SAC Jet Runway." Tech. Bull. 239, American Road Builders' Assn. (1959).

Lime was used to stabilize a clay subgrade during wet weather as an aid to construction. Good construction procedures were developed and reported.

59-6. Leonard, R. J., and Davidson, D. T., "Pozzolanic Reactivity Study of Flyash." HRB Bull. 231, p. 1 (1959).

A basic research on the nature of pozzolanic reaction between lime and fly ash is reported. Various techniques are used. An explanation is also made of the mechanism of the pozzolanic reaction.

59-7. Lund, O. L., and Ramsey, W. J., "Experimental Lime Stabilization in Nebraska." HRB Bull. 231, p. 24 (1959).

The Nebraska Department of Roads in 1956 performed an experiment involving the use of hydrated lime in the stabilization of plastic soils, and in the upgrading of inferior base course materials. The experiment included a preliminary laboratory study and a field construction project. The report summarizes the tests performed

on the various materials before and after adding hydrated lime, and presents the results of deflection measurements at various intervals since the construction of the field project.

59-8. McDowell, C., "Stabilization of Soils with Lime, Lime-Fly Ash and Other Lime Reactive Materials." HRB Bull. 231, p. 60 (1959).

A very general article covering the past history of lime stabilization. It discusses the types of limes used, the chemical reactions that take place and a brief summary of the testing of soil-lime mixtures. It gives some general suggestions for construction procedures and concludes with the benefits of lime stabilization.

59-9. Nichols, F. P., Jr., "Progress Report No. 3—Base and Subgrade Stabilization Experiments." Virginia Council of Highway Investigation and Research (March 1959).

This report gives the progress of the testing and performance of some bases and subgrades stabilized with lime. It summarizes data reported in previous reports (58-4) and gives detailed description of a more recent project. Performance of these test sections have indicated lime and lime-fly ash are generally quite effective for treating subgrades and bases. The degree to which they improve desirable characteristics depends on the soil type. Recommendations are made concerning the use of lime and lime-fly ash as stabilizers in construction.

59-10. Parsons, C. C., "Lime Expedites Construction and Reduces Thickness of Granular Materials Required in Highway Construction." Mississippi Highways (Feb. 1959).

59-11. Anon., "Lime Stabilized Subgrade for Kansas, I Project." Roads and Streets, 102:112 (Feb. 1959).

The addition of lime to a moderately plastic, high swelling clay helped stabilize the subgrade under a portland cement concrete pavement. The stabilized subgrade also tended to aid construction speed because it readily shed water and lost little strength during a rain.

59-12. Anon., "Lime Stabilization Construction Manual." Tech. Bull. 243, American Road Builders' Assn. (1959).

This bulletin thoroughly covers the recommended procedures for construction of lime-stabilized roads. It deals with both the dry and the slurry methods of handling and spreading lime. Related factors such as maintaining traffic during construction, lime safety precautions, etc., are also covered. It is a good publication for personnel actively engaged or closely related to this type of construction.

60-1. Anday, M. C., "Progress Report No. 3—Base and Subgrade Stabilization Experiments." Virginia Council of Highway Investigation and Research (Jan. 1960).

This report presents the results of extensive laboratory and field testings on a recently constructed lime-stabilized subgrade test section in Virginia. This test section consisted of a short section of heavy clay subgrade soils stabilized with 5 percent hydrated lime.

Changes in the physical properties of the soil, as well as an increased bearing value of the subgrade, were noted immediately after construction of the section.

60-2. Davidson, D. T., Mateos, M., and Barnes, H. F., "Improvement of Lime Stabilization of Montmorillonitic Clay Soils with Chemical Additives." HRB Bull. 262 (1960).

Results of laboratory investigations of methods of improving the strength and durability of compacted lime-montmorillonitic soil mixtures were presented. For the testing procedures used dolomitic monohydrated lime improved the immersed strength of the mixture more than high calcium hydrated lime. The effects of sodium hydroxide, sodium phosphate and sodium carbonate on the physical properties of lime-soil mixtures were discussed. Addition of small amounts of sodium hydroxide were found beneficial in accelerating and in increasing the hardness of lime-soil mixture. Sodium phosphate and sodium carbonate were not particularly beneficial in improving lime-stabilized montmorillonitic soils. In addition, the effects of these chemicals on the durability of lime-soil mixtures were presented.

60-3. Eades, J. L., and Grim, R. E., "The Reaction of Hydrated Lime with Pure Clay Minerals in Soil Stabilization." HRB Bull. 262 (1960).

A laboratory study was made of the reactions that occurred when lime was added to eight soil samples of four different types of clay minerals. The study consisted of making X-ray and differential thermal analyses of untreated and lime-treated clays after various curing times. Results indicated that kaolinites, illites, montmorillonites and mixed layered clay minerals all react with lime to give greater bearing strengths and that the quantity of lime required to produce maximum strengths for the different soils varied with the types of clay minerals present. Also, the chemical changes that take place as lime is added to these minerals are recorded.

60-4. Hilt, G. W., and Davidson, D. T., "Lime Fixation in Clayey Soils." HRB Bull. 262 (1960).

Laboratory studies were conducted on lime-soil and lime-fly ash-soil mixtures that contained montmorillonite, illite-chlorite and kaolinite clay minerals. The effects of lime on the strengths and the plastic limits of various types of clay minerals were discussed. Investigations disclosed that the minimum quantity of lime required to increase the strength in some of the clays was equal to the quantity required to increase the plastic limits to a maximum extent. This correlation, however, did not exist for soils containing illite-chlorite clay minerals. The addition of a pozzolan, fly ash, to montmorillonite and kaolinite soils was found unnecessary for strength purposes.

60-5. Ladd, C. C., Moh, Z. C., and Lambe, T. W., "Recent Soil-Lime Research at the Massachusetts Institute of Technology." HRB Bull 262 (1960).

The article contains a summary of 3-yr research on lime-soil mixtures. Investigations were conducted in four fields: the use of quicklime for wet soil stabilization, the use of lime to prevent the erosion of soils, the effects of secondary additives on lime-soil mixtures and the feasibility of using lime-soil stabilization for improving soils in Honduras. Much of the data confirmed previously reported trends. However, new data indicated that the soaked strengths of some lime-soil mixtures were considerably increased by the use of sodium compound additives. Of the compounds investigated, sodium metasilicate was found to be the most effective for the soils studied.

60-6. McDowell, C., "Progress of Lime Stabilization in Texas." Paper presented at the Annual Convention of the National Lime Assn. (May 1960).

Progress in the development and use of lime for the stabilization of soils in Texas is discussed. The quantity of lime used for soil stabilization in Texas has steadily increased during the past 15 yr. In 1959 the quantity of lime used for soil stabilization purposes was in excess of the total quantity of lime produced in Texas in 1945, and the present trend is toward even greater increased use of lime for soil stabilization. Current construction procedures are reported. Also, specifications developed by the Texas Highway Department for the construction of lime-stabilized soils and for the quality of hydrated lime for soil stabilization purposes are included in the article.

60-7. Taylor, W. H., Jr., and Arman, A., "Lime Stabilization Utilizing Preconditioned Soils." HRB Bull. 262 (1960).

Investigations of a few lime-soil stabilized bases in Louisiana indicate that most of the failures have resulted from improper mixing and from delayed compaction after initial mixing (rotting) of the lime and soil. Results of laboratory and field tests indicate that improved stabilization can be obtained by applying one-half the lime to the soil initially and then waiting 30 days and applying the remainder of the lime to the soil. Compaction of the mixtures after the final application of lime was started immediately after mixing.